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A study on the needle heating of industrial lockstitch sewing machine

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Prohlašuji, že předkládanou disertační práci jsem vypracoval samostatně pod vedením školitele Doc. Ing. Antonína Havelky, CSc., a s použitím uvedené literatury.

....

Declaration

The contents of the thesis are experimental results obtained by the author on the basis of literature and under the supervision of Doc. Ing. Antonín Havelka, CSc.

....

Dedicated to my Parents

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ABSTRACT

Sewing process is one of the most important operations in the clothing industry. It is also an important part of assembling some technical textile products. Every day, millions of products ranging from shirts to automotive airbags are sewn. Hence, even a minor improvement may result in significant commercial and performance benefits. The biggest issue with high speed sewing is the damage caused by heating of the needle on the sewing thread and the fabric. Sewing thread undergoes repeated abrasion and passes through the needle eye resulting in a friction with the needle; on the other hand the friction between the needle and the fabric during its penetration through the fabric layer(s) causes an increase in the needle temperature. This hot needle causes damage to the thread, the fabric and finally a loss in productivity. This work described in this dissertation aims at understanding the various processes causing a heating of the needle, with the needle's temperature measurement and prediction. It also explores certain methods which may possibly improve the productivity of the sewing operation by reducing the needle temperature without compromising the sewing speed.

Chapter 3 of this work covers the experimental techniques to measure the sewing needle temperature. Three methods (thermal camera, inserted thermocouple and thermocouple touch method) are compared under different sewing conditions. It was found that the thermal camera got influenced by the low emissivity of the needle and it is very difficult to measure at speeds higher than 3000r/min. Inserted thermocouple method showed repeatable results with the lowest deviation. On the other hand, the thermocouple touch method could be used to provide an estimation of the needle temperature since the delay in contact between the needle and the thermocouple provides lower values of needle temperature as compared to the inserted thermocouple method.

Chapter 4 presents the effect of different factors on the sewing needle temperature; it was observed that the sewing speed, the thread count, the sewing time, the fabric structure and thickness had major impact on sewing needle temperature. On the other hand, ambient humidity, ambient temperature, stitch density and needle parameters played a minor role in heating of the sewing needle.

Chapter 5 is based on the cooling of hot needle by a vortex stream of cold air, which is the common method in industry to decrease the needle temperature. In this research, a 10 second of cooling time was suggested at the time of machine stoppage or deceleration. This technique provides similar results as compared to the continuous vortex cooling, but significantly saves the energy consumption.

Chapter 6 presents the effect of the lubricant amount on sewing needle temperature. Lubrication is the second most common technique in industry for decreasing the needle temperature after the cooling air. Results of this research show that, to decrease needle temperature, it's not productive to use lubricants if the machine speed is less than 2500 r/min; whereas for higher machine speeds, it's recommended to add 3-4% of lubricant to the sewing thread.

In Chapter 7 the effect of the needle temperature on the tensile properties of the sewing threads is discussed. It was observed that the tensile properties of the used sewing threads decreased dramatically for machine speeds higher than 3000r/min; where about 40% loss of tensile strength was recorded for sewing threads at machine speed of 4000 r/min. The tensile properties of the sewing threads were also measured at different sections of the sewing machine to examine the effect of the needle temperature as well as the abrasion by the tension devices.

Chapter 8 presents the methodology for evenly coating the sewing needle with a diamond like carbon (DLC) layer. DLC coatings are well known for decreasing the friction properties of heavy machine parts like engines and pistons. In this research, the sewing needle (a very thin metal) was coated evenly with the DLC layer. There were minor differences observed in the properties of stitched thread after sewing using a DLC coated needle.

Finally, in Chapter 9 a simple analytical model was developed to calculate the needle temperature at its steady state from a set of parameters that includes: friction coefficients, friction forces and thread tension. A linear equation was obtained for the temperature of the needle related to the machine speed as an independent variable. It was found that the model

could predict the maximum needle temperature that can be attained during a continuous sewing process of more than 10 seconds with a reasonable accuracy. The important role of the sewing thread in contributing towards the needle temperature was also established by this simple theory which corroborates with the experimental observations.

Keywords: *Needle heating, sewing machine, needle cooling, needle temperature prediction, sewing thread, needle coating.*

ABSTRAKT

Šicí proces je jednou z nejdůležitějších operací v oděvním průmyslu. Je také důležitou součástí při sestavování některých technických textilních produktů. Každý den se ušijí miliony produktů od košil až po airbagy. Proto i malé vylepšení může mít za následek významné obchodní a výkonnostní výhody. Největším problémem při vysokorychlostním šití je poškození způsobeno zahříváním jehly na niti a materiálu. Šicí nit podléhá opakovanému oděru a prochází očkem jehly, což vede k tření s jehlou; na druhé straně tření mezi jehlou a materiálem během pronikání přes vrstvu materiálu způsobuje nárůst teploty jehly. Tato horká jehla způsobuje poškození nitě, materiálu a nakonec i ztrátu produktivity.

Tato disertační práce se zaměřuje na pochopení různých procesů způsobujících zahřívání jehly, s měřeními a predikcí teploty jehly. Práce také zkoumá určité metody, které by mohly zlepšit produktivitu šicího procesu snížením teploty jehly bez ohrožení rychlosti šití.

Kapitola 3 zahrnuje experimentální techniky pro měření teploty šicí jehly. Tři metody (termo kamera, vložený termočlánek a dotyková metoda pomocí termočlánku) jsou porovnávány při různých podmínkách šití. Bylo zjištěno, že termo kamera byla ovlivněna nízkou emisivitou jehly a je velmi obtížné provádět měření při rychlosti vyšší než 3000 ot / min. Metoda s vloženým termočlánkem ukazuje opakovatelné výsledky s nejnižší odchylkou. Na druhé straně by dotyková metoda s termočlánkem mohla být použita pro poskytnutí odhadu teploty jehly, protože zpoždění v kontaktu mezi jehlou a termočlánkem poskytuje nižší hodnoty teploty jehly ve srovnání se způsobem vloženého termočlánku.

Kapitola 4 představuje vliv různých faktorů na teplotu šicí jehly; bylo zjištěno, že rychlost šití, počet nití, čas šití, struktura materiálu a tloušťka měly hlavní vliv na teplotu šicí jehly. Na druhé straně, parametry jako okolní vlhkost, okolní teplota, hustota stehu a parametry jehly hrály menší roli v zahřívání šicí jehly.

Kapitola 5 je založena na chlazení horké jehly ve vířivém proudu studeného vzduchu, což je běžný postup používaný v průmyslu ke snížení teploty jehly. V tomto výzkumu byla navržena doba chlazení 10 sekund v okamžiku zastavení stroje nebo jeho zpomalení. Tato technika poskytuje podobné výsledky při porovnávání s kontinuálním vírovým chlazením, ale výrazně šetří spotřebu energie.

Kapitola 6 prezentuje vliv množství maziva na teplotu šicí jehly. Mazání je druhou nejčastější technikou v průmyslu pro snížení teploty jehly po chlazení vzduchem. Výsledky tohoto výzkumu ukazují, že ke snížení teploty jehly není produktivní používat lubrikanty, pokud je rychlost stroje nižší než 2500 ot / min vzhledem k tomu, že pro vyšší rychlosti stroje je doporučeno přidat 3-4% maziva do šicích nití.

Kapitola 7 pojednává o vlivu teploty jehly na tahové vlastnosti těchto šicích nití. Bylo pozorováno, že tahové vlastnosti použitých šicích nití se dramaticky snížily při rychlostech stroje vyšších než 3000 ot / min; kde asi 40% ztráta pevnosti v tahu pro šicí nitě byla zaznamenána při otáčkách stroje 4000 ot / min. Tahové vlastnosti šicích nití byly také měřeny v různých částech šicího stroje kvůli zkoumání vlivu teploty jehly, jakož i oděru pomocí napínacích zařízení.

Kapitola 8 představuje metodiku pro rovnoměrné potažení šicí jehly s tzv. "Diamond like carbon" (DLC) vrstvou. DLC povlaky jsou dobře známé pro snížení třecích vlastností různých částí těžkých strojů, jako jsou motory a písty. V tomto výzkumu, šicí jehla (velmi tenký kov) byla potažena rovnoměrně DLC vrstvou. Byly pozorovány drobné rozdíly ve vlastnostech nití v stehu, po šití s jehlou s DLC povlakem.

Na závěr byl v kapitole 9 vyvinut jednoduchý analytický model pro výpočet teploty jehly ve svém ustáleném stavu ze souboru parametrů, který obsahuje koeficienty tření, třecí síly a napětí nitě. Lineární rovnice byla získána pro teplotu jehly vztahující se k rychlosti stroje jako nezávislá proměnná. Bylo zjištěno, že model by mohl predikovat maximální teplotu jehly, která může být dosažena v průběhu kontinuálního procesu šití při více než 10 vteřinách s dostatečnou přesností. Pomocí této jednoduché teorie byla prokázána důležitá role nitě v přispívání k teplotě jehly, což potvrzuje experimentální pozorování.

Klíčová slova: *Zahřívání jehly, šicí stroj, chlazení jehly, predikce teploty jehly, šicí nit, povlak jehly*

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List of Symbols

ε	Emissivity
α	Angle of contact
T_n	Tensile property of thread from seam
F_1	Incoming force
F_2	Leaving force
μ	Coefficient of friction
K_y	Thermal conductivity of thread
P_f	Density fabric yarn
C_f	Specific heat fabric yarn
K_f	Thermal conductivity of fabric yarn
P_n	Density needle
C_n	Specific heat needle
K_n	Thermal conductivity of needle
μ_t	Friction coefficient needle and thread
μ_{fy}	Friction coefficient needle and fabric yarn
T_y	Tension thread max
v_N	Needle velocity
V_m	Machine speed
θ	Needle and thread angle of contact
F_{NF}	Frictional normal penetration force to needle from fabric
h_c	Convection coefficient
T_{01}	Initial temperature of the needle
th	Fabric thickness
σ	Stefan’s constant $5.67*10^{-8} w/m^2K^4$
e_{AB}	Seebeck voltage
$f * v$	Product of friction force of needle-fabric and velocity of needle

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Introduction

Industrial sewing is one of the most common operations in the manufacturing of garments, shoes, upholstery and technical fabrics for automobiles. Every day, millions of products ranging from shirts to automotive airbags are sewn using industrial sewing machines. Heavy industrial sewing, such as that used in the manufacture of automobile seat cushions, backs and airbags, requires not only high production but also high sewing quality (i.e. better appearance and seam strength). Typically, the material being sewn includes single and multiple plies of fabric or leather, sometimes backed with plastics, and needle heat-up is a major problem on the sewing floor. In recent years, in order to increase production, high-speed sewing has been extensively used. Currently, sewing speeds range from 1000-6000r/min. In heavy industrial sewing, typical sewing speeds range from 1000-3000r/min.

Depending on the sewing conditions, maximum needle temperatures range from 100°C~300°C [1]. This high temperature weakens the thread, since thread tensile strength is a function of temperature, resulting in decreased production [2]. In addition, the final stitched thread has 30–40% less strength than the parent threads [3]. Very high temperature of the needle can also damage the materials such as some synthetic fabrics or plastics which come in direct contact with the needle during sewing process. Since generally an increase in the machine speed is accompanied by an increase in the needle temperature, an optimization is often required. Therefore, it is important to understand the causes of the heating of needle in a sewing machine and to be able to predict the maximum needle temperature from the various parameters of the machine, process and material.

However, the temperature of the needle of a sewing machine during its operation is a difficult thing to measure since the needle moves at a very high speed and its size is generally not very big [4]. Nevertheless various methods for measuring needle temperature, such as infrared pyrometer, thermocouple and temperature sensitive waxes, have been used. Sondhelm [5] used a lacquer painted in the needle groove to observe a change of colour with temperature. Laughlin [6] tried to measure needle temperature through infrared measurement from the needle using a lead-sulphide photocell. Recently Yukseloglu et al [7] have observed the needle temperature by thermal camera for polyester blend fabrics for sewing speed of

3000r/min using chromium needle and the emissivity was considered as 0.07. For infrared temperature measurement, there is a problem in calibration because the amount of radiation emitted at higher temperature depends on the surface characteristics [8]. The emissivity of each needle must be determined individually and, indeed, the emissivity might change during high speed sewing process. Another technique using thermocouples was later developed by Dorkin and Chamberlain [9]. There are few theoretical models available to predict sewing needle temperature [4, 8, 10, 11]. Trung et al [10] used Finite Element Analysis (FEA) model, Q. Li et al and Howard [4,11] have used analytical as well as FEA models and reported that the FEA approach gives much better accuracy compared to their analytical models which had an average error of 25%. As a result of such variety of measuring methods used by various researchers, it is sometimes difficult to compare the results reported in literature. Nevertheless, as a result of improved understanding of the causes of sewing damage, many technical developments such as improved needle design [12,13] fabric finishes [14], thread lubrication and needle coolers [15,16] have taken place over the years.

Chapter 1. Literature review

A sewing machine is one of the most common machine of any clothing, automobile, footwear or home textile products. Sewing machines were invented during the first Industrial Revolution to decrease the amount of manual sewing work performed in clothing companies. Thomas Saint in 1790 is considered as the inventor of first working sewing machine [17]. Lockstitch sewing machines due to strong stitch and easy use are the major sewing machine used in any clothing industry.

Lockstitch is a stitch performed in most household and industrial sewing machines (single needle). Lockstitch is formed by interlacement of upper thread and lower thread [18] .The upper thread runs from a spool near the machine, through guides, tension devices, take-up arm, and finally runs through the needle eye. Meanwhile the lower thread is wound on the bobbin, which is inserted in the bobbin assembly located under material in lower case of the machine [19].To make one stitch, the machine moves downwards the threaded needle through the material and into the bobbin assembly, where a rotating hook catches the upper thread just after it passes near the needle. The hook assembly carries the upper thread entirely around the bobbin case, so that it has made one wrap of bobbin thread .Then the take-up arm pulls the excess upper thread to tighten the stitch. Finally the feed-dogs move the fabric along one stitch length, and the cycle is repeated similarly.

Ideally, the lockstitch is formed in the center of the thickness of the material. The thread tension mechanisms, one for the upper thread and one for the lower thread, prevent either thread from pulling the entwine point from out of the middle of the material. A small length of the needle thread (depending on stitches /cm) is consumed in the stitch formation and excess is pulled back. Therefore the needle thread passes nearly 20-25 times through the guides, tension regulator, take-up lever, needle and the fabric before becoming incorporated with the seam [20].

1.1 Basic thermal mechanism of needle heating

The actual sewing needle heating is rather a complicated process. Needle temperature rises as the sewing starts and continues to rise till the steady state is attained. During the complete process, the needle temperature varies minor at the needle penetration and withdrawal from fabric. [21]

The heat is generated from the following sources:

- Heat flux generated between fabric and needle outer surface. It is dependent on needle penetration force, withdrawing and frictional forces acting on needle by the fabric.
- Heat flow from the friction between sewing thread and needle eye. It is dependent on type of sewing thread and thermal conductivity of thread, needle and friction coefficient between yarn and needle can influence the needle temperature. The sewing needle heating thermal heating mechanism is shown in figure 1.

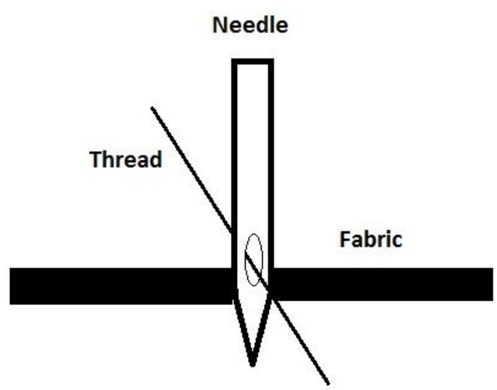

Figure 1 Sewing needle heating thermal system

On the other hand, the heat leaves the needle by: [1]

- Convection of the outer surface of the needle to the environment. Heat loss by convection is considered as the major source in cooling the needle. The convective heat flow equation can be expressed by Newton's Law of Cooling as,

  $$q = h_c A \, dT \qquad (1.1)$$

  Where

  q = heat transferred per unit time (W)

  A = heat transfer area of the surface (m^2)

  h_c= convective heat transfer coefficient of the process ($W/(m^2K)$ or $W/(m^{2o}C)$)

h_c - is dependent on the type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties.

dT = temperature difference between the surface and the bulk fluid (K or ^oC)

- The heat conduction in the needle from higher point to lower temperature points, also the heat loss to the needle holder. The conductive heat flow can be expressed by **Fourier's Law** as

  q = k A dT / s (1.2)

  Where

  q = heat transfer (W, J/s, Btu/s)

  A = heat transfer area (m^2, ft^2)

  k = thermal conductivity of the material (W/m K or W/m ^oC, Btu/(hr ^oF ft^2/ft))

  dT = temperature difference across the material (K or ^oC, ^oF)

  s = material thickness (m, ft)

- The heat of conduction from the needle to sewing thread and fabric, the needle and textile materials have great difference of thermal conductivity but still at the time of machine stoppage the ultimate contact with needle-thread and needle–fabric causes local heating and damages the textile material.

  Conductivity factor λ [W/(mºC)] cab be expressed by following equation:

  $\lambda = QL/At\ (T_1\text{-}T_2)$ (1.3)

  Where Q is heat flow, L is textile material thickness, t is time interval and T_1-T_2 is temperature difference.

- Radiation heat between the needle outer surface and the environment. According to the Howard radiation play minor role in needle cooling, due to thin size and very low emissivity [11]. The equation can be expressed by the Stefan-Boltzmann law as:

  $\boldsymbol{P = \varepsilon\sigma A(T^4\text{-}T_s^4)}$ (1.4)

  P is net radiated power

  ε is Emissivity of material

  A is radiation area

  σ is Stefan's constant $5.67*10^{-8} w/m^2K^4$

T is temperature of radiator

T_s is temperature of surrounding

1.2 Experimental techniques of measurement

There are multiple efforts in the past to experimentally observe the sewing needle heating. The experimental techniques to measure sewing needle temperature can be classifies as;

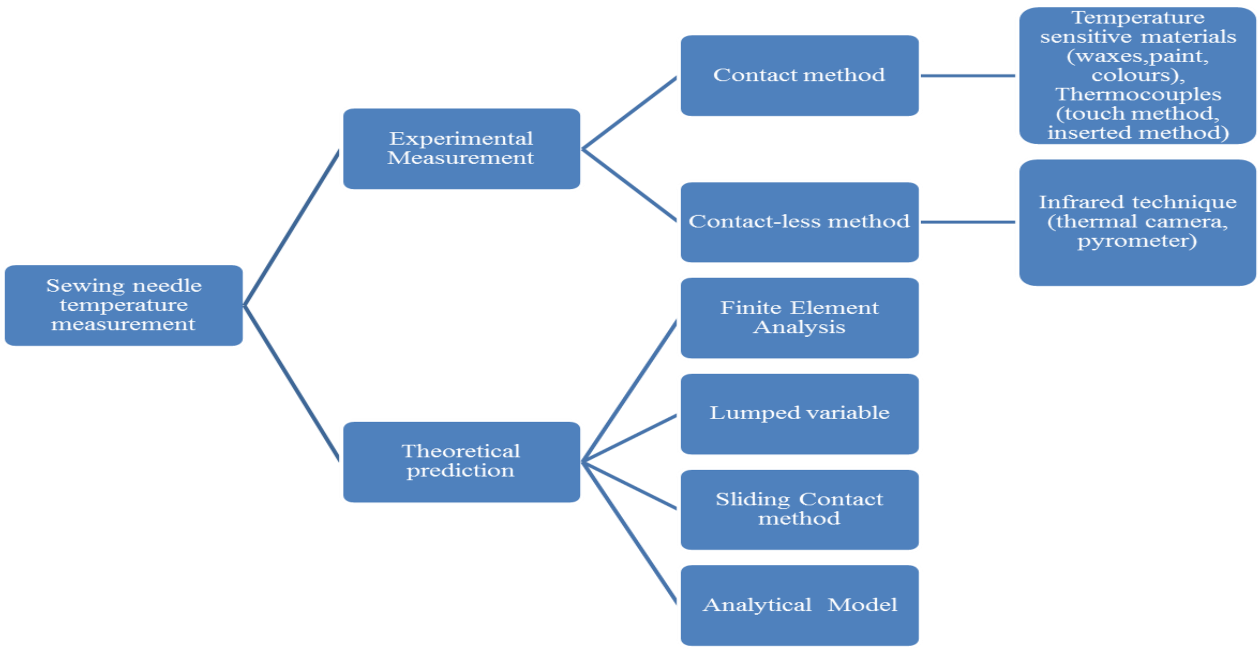

Figure 2 Classification of Sewing needle temperature measurement

1.2.1 Contact-less measurement

1.2.1.1 Thermal Radiation Principles

The intensity of the emitted energy from an object varies with temperature and radiation wavelength. In addition to emitting radiation, an object reacts to incident radiation from its surroundings by absorbing and reflecting a portion of it, or allowing some of it to pass through (as through a lens). From this physical principle, the Total Radiation Law is derived, Total radiation (Wt) can be stated with the following formula:

$$Wt = aW + rW + tW \qquad (1.5)$$

Which can be simplified to:

1 = a + r + t.

The coefficients a, r, and t describe the object's incident energy absorption (a), reflection (r), and transmission.

1.2.1.1.1 Emissivity

The radiation properties of objects are usually described in relation to a perfect blackbody (the perfect emitter). If the emitted energy from a blackbody is denoted as W_{bb}, and that of a normal object at the same temperature as W_{obj}, then the ratio between these two values describes the emissivity (ε) of the object,

$$\varepsilon = W_{obj} / W_{bb} \qquad (1.6)$$

Thus, emissivity is a number between 0 and 1. The better the radiation properties of the object, the higher its emissivity.

1.2.1.2 Temperature measurement

An object that has the same emissivity ε for all wavelengths is called a grey body.

Consequently, for a grey body, Stefan Boltzmann's law takes the form

$$\mathbf{W = \varepsilon\sigma T^4} \qquad (1.7)$$

Where

ε is Emissivity of material
σ is Stefan's constant $5.67*10^{-8} w/m^2K^4$
T is temperature of radiator

The radiation that impinges on the IR camera lens comes from three different sources. The camera receives radiation from the target object, plus radiation from its surroundings that has been reflected onto the object's surface. Both of these radiation components become attenuated when they pass through the atmosphere. Since the atmosphere absorbs part of the radiation, it will also radiate some itself (Kirchhoff's law). The total radiation power (W_{tot}) received by the camera can be written as

$$\mathbf{W_{tot} = (1 - t) \cdot W_{obj} + (1 - \varepsilon) \cdot t \cdot W_{amb} + (1 - t) \cdot W_{atm}} \qquad (1.8)$$

Where ε is the object emissivity, t is the transmission through the atmosphere, T_{amb} is the (effective) temperature of the object's surroundings, or the reflected ambient (background) temperature, and T_{atm} is the temperature of the atmosphere.

1.2.1.3 Needle temperature measurement by contact-less method

This technique is very effective for the temperature measurement of stationary object with higher emissivity. This technique includes devices like pyrometers and thermal camera which works on the IR radiation and measures the temperature based on emissivity of the surface. In case of sewing needle the small size of nearly 0.1-0.2cm, emissivity of sewing needle nearly 0.06[21] and high speed of sewing makes it complicated to measure the sewing needle temperature. Most of the researchers [8, 16, 22, 23] have used the contact less method to measure the sewing needle temperature. The major limitation of this measurement for thin metal is the emissivity of each needle must be measured individually, and, indeed, the emissivity can change during the sewing process, so there must a continuous calibration during the measurement.

1.2.2 Contact method measurement

This technique of needle temperature measuring includes thermocouples and temperature sensitive materials.

1.2.2.1 Principle of thermocouple

A thermocouple is a device made by two different wires joined at one end, called junction end or measuring end. The two wires are called thermoelements or legs of the thermocouple: the two thermoelements are distinguished as positive and negative ones. In 1821, Thomas Seebeck discovered if metals of two different materials were joined at both ends and one end was at a different temperature than the other, a current was created. This phenomenon is known as the Seebeck effect and is the basis for all thermocouples.

$$\Delta e_{AB} = a.\Delta T \qquad (1.9)$$

Where:

e_{AB} = Seebeck voltage

ΔT = temperature change at the thermocouple junction

a = Seebeck constant

1.2.2.2 Needle temperature measurement by contact method

Measurement by thermocouple is done by touching the thermocouple to the needle surface after the sewing process is stopped. The major problem with this technique is the delay and exact position in the placing the thermocouple on the needle. Dorkin and Chamberlain [9] used thermocouples to measure sewing needle temperature. Another technique of inserting thermocouple inside needle groove patent by Hes [24] still remains a novel approach to practically measure the sewing needle temperature, the techniques is not practically much used in past ,due to slow response time of thermocouples and bigger size of thermocouples available in the past.

Another way of measuring the needle temperature is to stick the temperature sensitive material, such as waxes, lacquers and melting-point crayons in the needle groove. The material melts or change colour when they reach a specific temperature. This method is surely a hit or miss method. If a wax on the needle does not melt then it must be replaced by other wax with lower melting temperature. If the wax melts, it must be replaced by higher melting temperature wax. In this way, it is possible to indicate the maximum temperature needle can reach under specific conditions. Sondheim [5] used a lacquer painted in the needle groove to observe a change of colour with temperature. The placement of heat sensitive material on needle and the material not to be removed by the thread or fabric interaction is always a great issue in this methodology.

1.3 Theoretical models

1.3.1 Sliding and Lumped Model by Li [1]

Due to complexity and shortcomings of the experimental methods, an analytical simulation of needle heating is much desired. Theoretical models like Lumped variable, sliding contact and finite element analysis are proposed by different researchers. Howard [11] and Hersh [25] examined important factors that influence needle heating. In Howard work a model was established considering conduction, convection and radiation from the needle at the equilibrium state, He matched his theoretical results with the infrared measurement technique. Whereas Hersh considered the needle fabric interaction and measured the heating of needle by the penetration force of needle and fabric.

Li [1] used the sliding contact and lumped variable model to predict the needle temperature in these models, the needle geometry is assumed as an infinite cylinder and the heating by thread is ignored. The sliding contact model is based on the theory of moving heat source and temperature at a sliding contact [16].The basic model for sliding contact model is shown in figure 3.

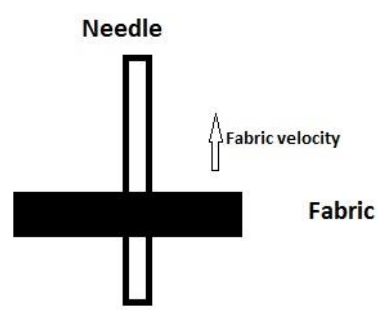

Figure 3 Sliding contact model [1]

Using principle of Sliding contact model Li [1] made two equations, firstly showing needle heating by needle and fabric friction and secondly representing the cooling of needle by convection.

$\mathbf{T=T_{01} + (1.064 * \gamma q/K)*(\alpha.l /v)^{1/2}}$ by Li [1] (1.10)

Where

T is heat gained by needle

T_{01} is initial temperature of the needle

γq is friction heat absorbed by the needle

K is thermal conductivity of needle

α is material diffusivity

l is contact length with fabric

v is relative velocity of the needle

Cooling of needle by convection in Sliding Contact model is given by Li[1] as below

$$\mathbf{T = T_{\infty} + (T_i - T_{\infty}) \exp(- hc.F/\rho.c.V_{ol})} \qquad (1.11)$$

Where

T_{∞} is ambient temperature

T_i is initial temperature when cooling begins

h_c is convection coefficient

F is cooling area

V_{ol} is volume to cool down

ρ is density of needle

c is specific heat of needle

The heat generation equation and cooling equation for the Sliding Contact Model were simulated for continuous strokes of sewing process to examine the heat gain by fabric friction and loss by convection during the sewing process.

While the lumped model shown in figure 4 is based in the basic heat transfer principles, these simplifies models are examined for needle heating phenomena in one stitch between needle and fabric, formulated heating and cooling equation. Then computer software is used to carry the calculation for the needle temperature build-up in the whole sewing process.

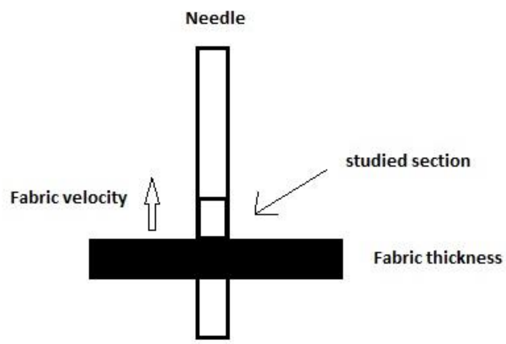

Figure 4 Lumped variable model [1]

Both the models (Sliding Contact and Lumped Model) can be used for low speed of sewing, thickness of fabric less than 8mm and heating by thread is ignored. The author (Li. [1]) concludes that their model has **20-25% error.**

1.3.2 Finite Element Analysis

Finite element analysis (FEA) demands much more complex computation to predict the needle temperature. Researchers [7, 10] have reported that FEA shows better accuracy as compared to other models to predict the needle temperature. Due to complex computation cannot be easily used at sewing floor and the models are experimentally compared with the infrared temperature measurement technique.

The heat flux generated by the friction power was shown by the equation below

$$q_{flux} = f * v / A \qquad (1.12)$$

Where

q_{flux} is heat flux generated by friction force

$f * v$ is product of friction force of needle-fabric and velocity of needle ($f*v$)

A is area of contact

The friction force for the flat needle part going through the fabric is given by

$$f = 2\pi\, r.th.p.u \qquad (1.13)$$

The heat generation when needle flat surface goes through the fabric the heat flux was expressed as

$$q_{flux\text{-}flat} = p.u.spd \qquad (1.14)$$

Where p is unit normal force that fabric act on the needle

r is needle radius

th is fabric thickness

μ is friction coefficient

spd is needle penetration force

The friction heat generated by the thread and needle interaction was given as

$$Q_t = \mu t.T.\cos\theta.V_t \qquad (1.15)$$

μt is coefficient of friction between needle and thread

T is tension of sewing thread with the needle

θ is thread angle of contact

V_t is thread velocity

The heat loss was from the needle was determined by the Newton's law of cooling for convection loss and Fourier's law of conduction.

1.3.3 Regression Analysis

Regression analysis is also performed by some research [7, 23, 27] based on their experimental measurement by IR-camera and pyrometers. The factors like machine speed, time of sewing and fabric thickness are considered in this analysis, but the use of IR-camera for measuring needle temperature thin fast needle moving is always questionable.

Muge [7] measured the needle temperature polyester upholstery fabric using thermal camera and shows following regression equation.

$$y = -24.8 + 10.8\, x_1 + 0.616\, x_2 + 0.0658\, x_3 \qquad (1.16)$$

$r^2 = 93.8\%$

Where y- needle temperature, °C;

x_1 – fabric thickness, (mm);

x_2 – thread count, (tex)

x_3 – machine speed. r/min

All the previous efforts in experiment and theoretical analysis shows very important information, which gives a valid start for measuring the sewing needle temperature experimentally using different techniques and compare different methods of measurement and also to theoretically analyse the sewing needle heat up. From the previous researchers results it can be concluded that.

- Sewing speed is the most important factor in needle heating, but has minor effect on needle penetration force.
- Radiation plays a minor role in needle heat dissipation.
- Needle characteristics (like needle structure, needle finish, needle point shape, the needle finish) are the only factors that affect the equilibrium temperature of the needle.
- Fabric properties (including fabric finish and fabric composition) plays a big role in needle temperature. The needle temperature is function of needle to fabric friction properties which depends on surface finish and fabric tightness.
- Properly installed cooling system has obvious results in decreasing needle temperature.

1.4 Effectiveness of the cooling techniques to decrease needle temperature

The three industrial methods to decrease needle temperature are:

- Vortex/forced air cooling
- Thread lubricant
- Surface coating

There are few more methods like fabric finishes [14, 15, 28, 29] and increasing throat plate needle hole size [12], but are not used on industrial scale as the change fabric finishes is never acceptable by the customer and this process is always an extra addition in terms of money and time to the complete sewing process, whereas changing in throat plate needle hole causes more air go with the needle penetration but it causes the loose or faulty stitches. Coating the needle with low fiction coefficient can also be used to decrease needle temperature by decreasing the friction heat between needle and textile material.

1.4.1 Vortex / forced air cooling

The Ranque-Hilsch vortex tube [30, 31] has been used for many years in various engineering applications like cooling suits, refrigerators, airplanes, etc. Other practical applications include cooling of laboratory equipment and sewing machines. Because of its compact design and little maintenance requirements the vortex tube is increasing its industrial use day by day. Compressed air is sent through the inlet nozzle (Figure 5). Swirl generators at the inlet plane create the vortex motion inside the tube. As the vortex moves along the tube, a temperature separation is formed. Hot air moves along the tube periphery, and cold air is in motion in the inner core. The hot air is then allowed to pass through the cone valve at the far end of the tube, while the cold air exits from the other side near the air inlet [32].

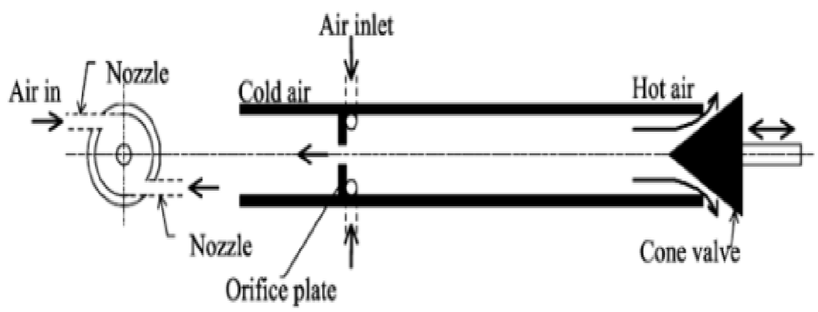

Figure 5 Vortex tube [33]

It is considered that the vortex tube or forced air is an effective way of cooling the hot sewing needle [34], but still there is no research available which shows the difference in needle temperature by the use of vortex tube. In our research we have measured the effect of vortex cooling on sewing needle and also shown the impact on tensile strength of sewing thread. The vortex cooling time is also optimised in our research to save energy consumption.

1.4.2 Thread lubrication

In the sewing process, the sewing thread undergoes friction between fabric, guides, tension devices on machine, bobbin thread and the sewing needle. The performance of sewing thread in apparel industry has become extremely important. Lubricants causes the decrease in friction coefficient of sewing threads and are commonly used in sewing industries [35]. The lubricant improves the surface finish which causes the decrease of friction between yarn and the metal object. Most lubrication is intended to decrease yarn to metal friction. In recent publication, it was reported that the amount of lubricant used have a profound effect on friction [36].Sewing thread lubricant always contains silicon, because silicon provides the heat protection and friction reduction in sewing threads. It is accepted that silicones are poor conductor of heat but good release agent and causes reduction in friction [37].The application of paraffin wax reduce the value of friction coefficient by approximately 50%, however at higher needle temperature it begins to soften due to local heat, caused by the friction, then forms an undesirable grease film and actually leads to an increase in friction. [35]

Due to high strength and durability of PET-PET core-spun thread, it is the most common sewing thread used in apparel industry. High amount of lubricant are applied for PET sewing threads to decrease friction and needle temperature [38-41].The Eytelwein's law should be used for the calculating the friction for threads sliding over a cylindrical guide, which is derived from the column law, where F_1 is the incoming force, F_2 is the leaving force, μ is the coefficient of friction and α is the angle of contact.

$$\mathbf{F_2/F_1 = e^{\mu\alpha}} \qquad (1.17)$$

$$\boldsymbol{\mu = 1/\alpha . \ln (F_2/F_1)} \qquad (1.18)$$

The effect of lubricant surely decreases the friction coefficient of threads but still there is no research concerning the effect on needle temperature and amount suitable for sewing threads. Till now the sewing thread are lubricated by a small bucket places above the sewing machine from which the sewing thread passes and get laminated by the sewing lubricant (lubricant holder),This method applies lubricant unevenly based on the machine speed and thread type. The contact time of lubricant and thread is very small at high speed of sewing whereas at machine stoppage the thread part remains immersed inside the lubricant .The effect of different mount of lubricant on needle heating and tensile properties of sewing thread is discussed in our work.

1.4.3 Surface coatings

Sewing needles are commonly made from steel, there are different variety of needle finishes like polishing, chrome coating, titanium nitride coating, Nickel plating, Teflon coating and ceramic coatings.

Polishing is simplest surface finish by rubbing the surface with the polishing medium, Chromium and Nickel plating provides high abrasion resistance and increase the life time of needle by abrasion protection, Titanium nitride layer on to the sewing machine needle surface provides homogenous, hard and smooth surface. Nowadays most the needles are coated with chromium finish to reduce the surface friction. The special design Titanium nitride coated needles are also popular in sewing of technical textile due to their hardness, better design and surface finish.

1.5 Effect of Needle heat on the tensile properties of sewing thread

Sewing threads plays a vital role in determining the seam strength, its durability and appearance. The mechanical properties of this thread are very important for its performance and durability. Machine stoppage due to thread breakage, rework due to poor sewing thread can greatly increase the production cost. Since very high strain are imposed on the thread during the high-speed sewing on modern machines, sewing thread requires high elasticity and for satisfactory performance [42]. To achieve good sewing performance, sewing thread, sewing thread must possess required mechanical and physical properties governed by its size and type chosen according to the fabric characteristic and end-use of the material.

During sewing at high speed, the needle thread is subjected to repeated tensile stresses, bending, pressure torsion, wearing and heat. These forces act on the sewing thread repeatedly and the thread has to pass through needle eye, fabric and the bobbin case mechanism 50-80 times before becoming part of the seam [43].the rubbing at the top of needle eye can cause local abrasion and cutting of the thread [44].In early research work Crow [45] reported 60%

reduction in thread strength after sewing. Later a number of researcher observed that there can be 30-40% strength reduction in the cotton thread after sewing [46-49].In a recent research on the tensile properties of mercerized cotton thread, nearly 30% strength reduction is reported [50].further more closer estimation of the seam strength was also possible after considering the loss in sewing thread strength [51, 52].A number of researcher also studies the dynamic loading of the sewing thread during high speed sewing process [53-57]. The mechanical performance of threads is governed by the properties of constituent fibres and their arrangement. In the course of tensile loading the tension induced by applied strain is transferred to the fibres through the interfacial shear stress, which leads to substantial changes in the yarn structure and fibre mechanical properties [58]. The friction, bending, and compression during the sewing process cause damage/pull-out of surface fibres resulting in a loss in mechanical properties. Heating of the needle cause synthetic fibres to soften or melt, leaving a weakened thread after sewing. The majority of these loadings are cyclic by nature and therefore cause the fibre fatigue [59, 60].

In our research rather than just measuring the seam strength or the thread strength in the seam, we sectioned the sewing thread in 4 section after sewing and measured the tensile properties of each section, each section gets different amount of abrasion and from thread cone till becoming part of the seam, whereas the last 2 section gets abrasion through guides and also acquire the needle heat.

1.6 Present State of Problem

1.6.1 The role of sewing thread

There are two different school of thoughts for the cause of sewing needle heating. Some researcher [2, 9, 25] believe sewing thread as a heat sink taking heat away from the hot needle. It is reported that needle decreases when sewing thread is used, friction between needle and fabric is considered as the major source of the needle heating.

On the other hand the researchers [7,8,21] report the increase in needle temperature when sewing thread is used, showing the sewing thread as heat source and applies the friction heat to the needle. It is reported that the needle temperature rises before the needle punctures the fabric.

Therefore, it's necessary to examine the role of sewing thread in needle heating.

1.6.2 Experimental techniques

The experimental verification by most of the researchers is done by the infrared or pyrometer method, which get influenced by the low emissivity of needle, changing emissivity of needle during the process and bigger measurement spot of the infrared heat measurement devices. First of all, it's necessary to experimentally verify the needle temperature using different techniques and observe the major factors that cause the increase of needle temperature.

Therefore, emissivity with contactless and discontinuity of measurement with the contact method is an unavoidable limitation.

1.6.3 Effectiveness of cooling techniques

The effect of forced air cooling on needle temperature needs more investigation in terms of the required temperature of air and the time of exposure. Similarly, the amount of lubricant to decrease the needle temperature should be studied as this amount might affect the tensile properties of the sewing thread.

Therefore, the effect of cooling by air and lubrication needs more investigation.

Chapter 2. Objectives

- Develop an experimental technique to measure the sewing needle temperature.
- Determine the factors affecting the needle temperature.
- Evaluate the effectiveness of common methods used for industrial needle cooling.
- Examine the effects of needle heat on sewing thread.
- Analyze theoretically the sewing needle temperature.

2.1 Develop an experimental technique to measure the sewing needle temperature

- Apply the three described measuring methods (thermal camera, inserted thermocouple method and thermocouple touch method)**.**
- Study the effectiveness of each method**.**
- Compare mentioned methods at different conditions**.**
- Recommend the optimum and limiting operating conditions for each method.

2.2 Determine the factors affecting the needle temperature.

- Select affecting parameters based on the available literature and the practical experience.
- Design experimental procedure for studying the effect of each parameter.
- Analyze the significance effect of each factor and the interaction between them.

2.3 Evaluate the effectiveness of common methods used for industrial needle cooling.

- Applying the cooling methods.
- Measuring the dynamic needle's temperature as well as the tensile properties of the sewing thread.
- Optimize the operating cooling conditions.

2.4 Examine the effects of needle heat on sewing thread.

- Study the factors affecting the tensile properties of sewing thread (heat and abrasion).
- Evaluate the tensile properties at different sections of the sewing machine.
- Examine the indirect effect of the machine speed on the tensile properties.

2.5 Analysing theoretically the sewing needle temperature

- Develop an analytical model for predicting the needle temperature.
- Conduct experimental verification for the model.
- Compare the model's results with literature values.

Chapter 3. Experimental techniques to measure the sewing needle temperature

In our research we measured needle temperature at high speed sewing by three methods (thermal camera, inserted thermocouple method and thermocouple touch method). Conditions for all experiments were kept constant at 26^{o}C and 65% RH. The devices used for the experiments are listed below:

- Lockstitch machine (Brother Company, DD7100-905).
- Thermal camera P60 and X6450 from the FLIR Company.
- Thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) for the inserted method.
- Thermocouple by Omega (5SC-GG-(K)-30-36) for the touch method.
- Thermocouple by Omega -wireless device and receiver (MWTC-D-K-868).
- Needles (Groz-Becker 100/16) R- type.
- Relevant parameters of the sewing thread are shown in Table 1.
- Relevant parameters of the denim fabric are shown in Table 2.

Table 1 Sewing thread used for the experiments

Thread type	Company name	Fineness (Tex)	Twist (t/m)	Twist direction (ply/single)	Coefficient of friction μ
Polyester–polyester core spun	AMANN-Saba C-80	20*2	660	Z/S	0.13

Table 2 Fabric used for the experiments

Fabric type	Weave	Weight	Ends/cm	Picks/cm	Fabric thickness
100%cotton Denim	2/1 Twill	257 g/m^2	25	20	0.035cm

All methods were tested 20 times each and the results were statistically analysed. Maximum sewing time was 60 seconds for all techniques. The stitch density was kept constant at 5 stitches/cm and the sewing process was done both with and without thread to determine the temperature difference caused by the sewing thread. All three methods are compared to determine the suitable method of needle temperature measurement.

3.1 Thermal camera

The FLIR P60 is a manual thermal camera that measure temperature as triggered by the operator, whereas the FLIR X6450 is a continuous filming camera. Therefore, the FLIR P60 was used for the emissivity measurement for the sewing process. All thermal cameras work on the principal of emissivity of the object. For this test, the emissivity of the needle was calculated by ASTM standard E 1933 – 99a [61] by painting a portion of needle with known emissivity as shown in figure 6, and determined to be 0.08 for a chromium polished needle at 37^{o}C. As the needle is thin and shiny, it is complicated to determine the exact emissivity, and most researchers adopt the emissivity of the needle as that for polished chromium, which is 0.06 [7]. Even with knowing the emissivity of the needle, measurement is extremely difficult, as the sewing process is fast and the needle moves at a rate of 1000-6000r/min. Another problem is that the emission of the needle changes during the sewing process, as the surface characteristics change [8]. Therefore, the FLIR P60 was used for the emissivity measurement for the sewing process, and the X6450 was used for measuring the needle temperature during the sewing process.

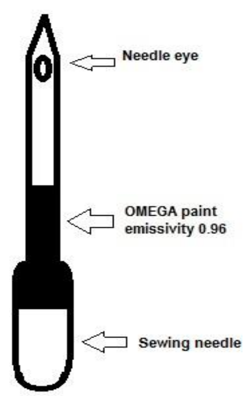

Figure 6 Needle temperature/emissivity measurement

The first experiment was conducted without thread at speeds of 1000-3000r/min; the standard deviation increased sharply at 3000r/min. It is not possible to use the camera at speeds higher than that as the needle is moving more than 3500r/min, which makes it impossible to focus the camera on the needle. When the experiment was performed with thread even at 2,000 r/m, it was difficult to measure the needle temperature, as the thread, which has an emissivity of nearly 0.95 [62], significantly affects the needle measurement, which has extremely low emissivity, as shown in Figure 7.

Figure 8 Thermal camera FLIR P60 with Lockstitch machine

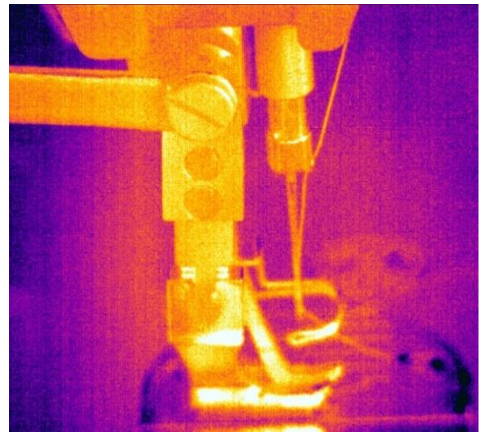

Figure 7 Needle eye temperature measured by camera

Figure 9 shows the needle temperature measured by the thermal camera with an increase of sewing speed. The maximum machine speed used was 3000 r/min, as after this speed, it was not possible to focus on the needle. Even at 3000 r/min the standard deviation was much higher than at slower speeds. It can be seen that after 15 seconds of sewing, there was not much difference in the needle temperature as the process stabilizes with the surroundings. The needle temperature was higher compared to that measured when sewing without thread. The mean needle temperature reached 135^{o}C at speed of 3000 r/min, with thread after 60 seconds of sewing.

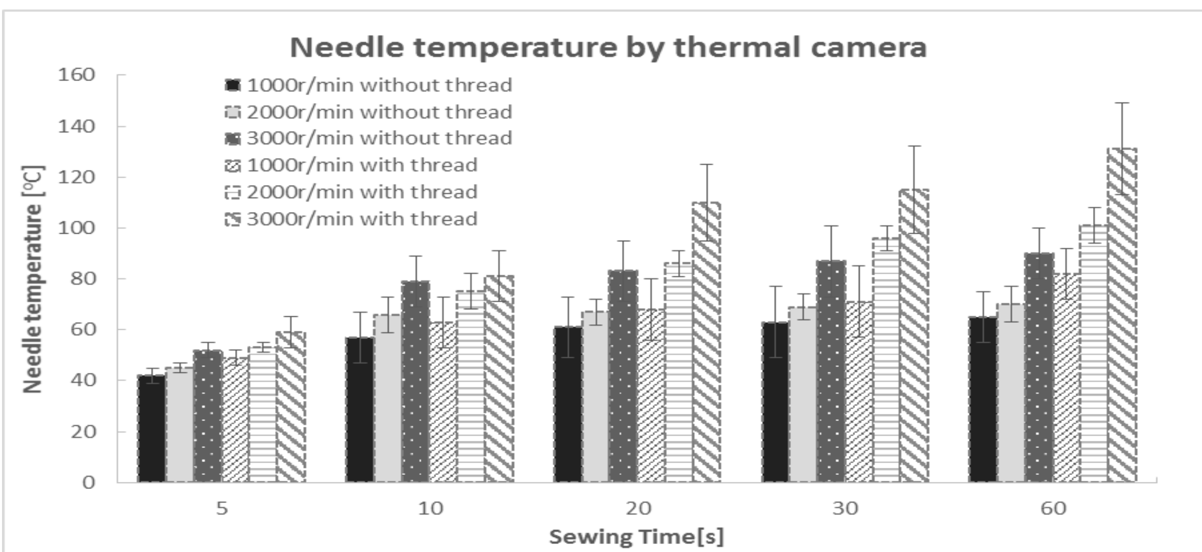

Figure 9 Needle temperature measured by thermal camera

The thermal camera was placed at position B, as shown in Figure 10. Even changing the position from A or C caused a significant change in the recorded needle temperature; this might be attributed to the surrounding energy sources, which receive reflection from the shiny needle. These energy sources are quiet hard to omit, and performing the sewing process under an enclosed black box is not suitable for determining the exact needle temperature as the surrounding conditions will not be same as those on the sewing floor. In our research we covered the surrounding with black fabric to minimise the energy sources from other object to get reflected from sewing needle.

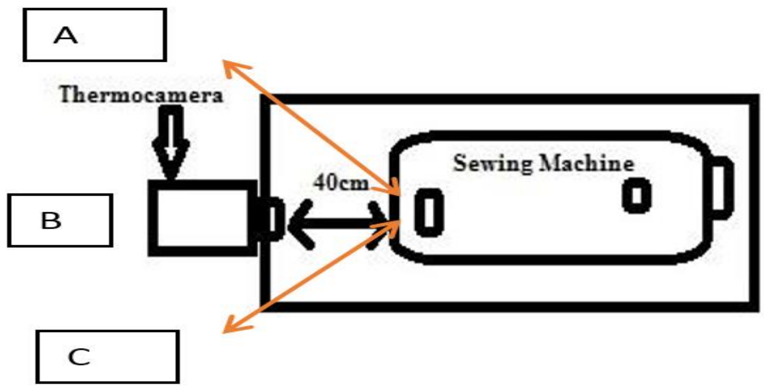

Figure 10 Placement of thermal camera

3.2 Thermocouple touch method

In this method, a thermocouple by Omega (5SC-GG-(K)-30-36) was used to measure the sewing needle temperature. The sewing process was done for 10-, 20-, 30- and 60-second time periods, and the thermocouple was manually touched to the eye of the needle to measure its temperature. This method involved a degree of human error, as the thermocouple was applied to the needle just after the sewing process finished. Being quick when applying the thermocouple and taking multiple observations for each time period reduces the percentage of error, however, the needle temperature results were still much lower when compared with the other methods, as the needle dropped heat very quickly. Figure 11 shows the thermocouple and the placement of the thermocouple after each sewing process interval.

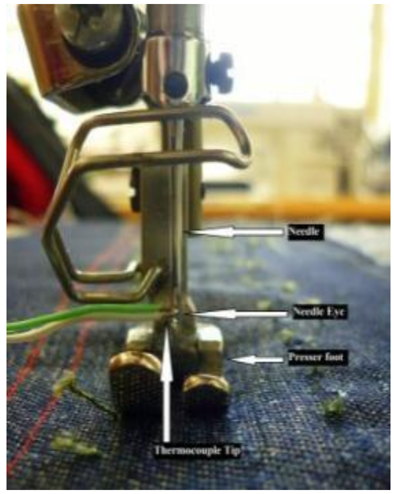

Figure 11 Thermocouple placement for thermocouple touch method

Figure 12 shows the needle temperature at the different sewing speeds; the maximum machine speed was 4000 r/min, which shows a mean temperature of 98°C after 60 seconds of sewing without thread, whereas the needle temperature of 122°C is recorded for sewing with thread under same conditions. It is observed that the needle temperature rises with higher sewing speed and sewing time .The needle temperature with thread is higher as compared to dry sewing (without thread).

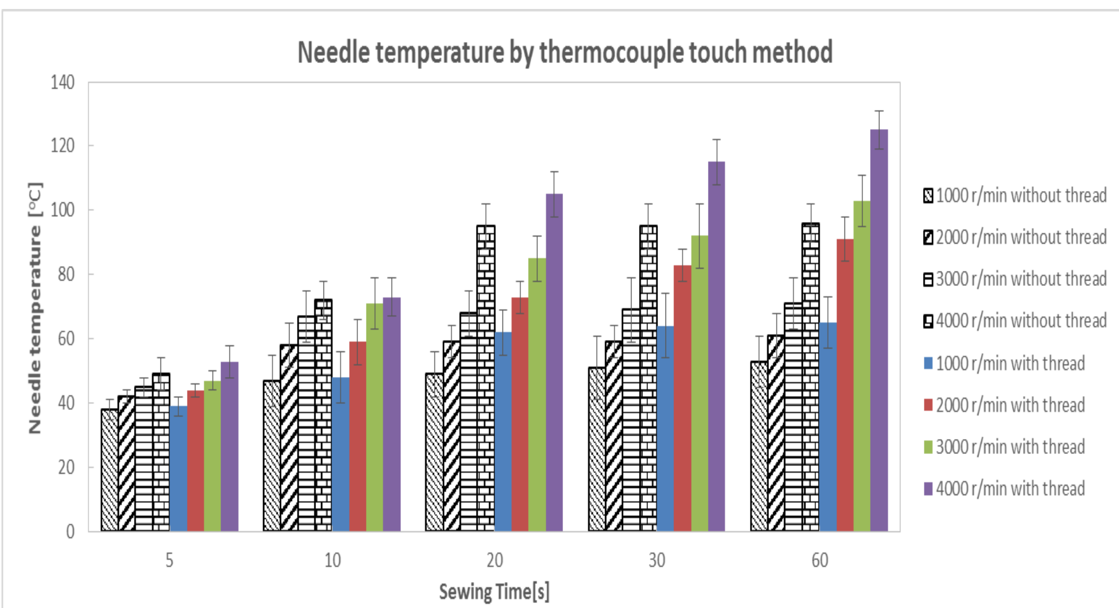

Figure 12 Needle temperature measured by the thermocouple touch method

3.3 Inserted thermocouple method

In this method for measuring sewing needle temperature, a thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) was inserted into the groove of the sewing needle and soldered. The thermocouple was located near the eye of the needle to measure the exact needle temperature, and the temperature was measured at different sewing speeds. This method proved to be very efficient as it provided continuous changes in needle temperature every second and it had a low standard deviation. Figures 13 show the placement of the thermocouple inside the needle groove. The thermocouple remained inside the needle groove during the sewing process and measurements were recorded wirelessly on a computer through a wireless end device (MWTC-D-K-868).The Figure 14 shows the inserted thermocouple measurement method during the sewing process the legend 1 is thermocouple wire, 2 is needle groove ,3 is sewing thread and 4 is the needle eye.

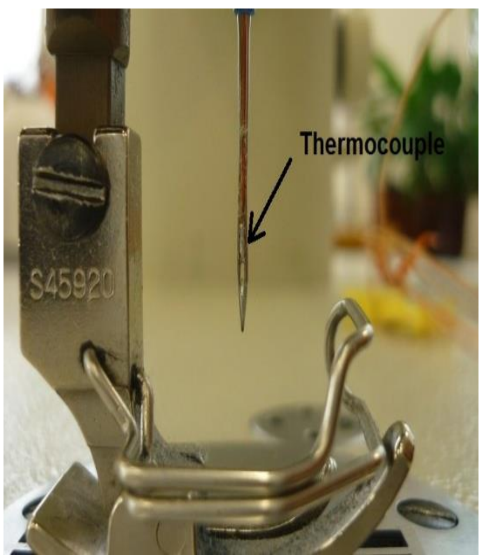

Figure 14 Sewing needle with thermocouple

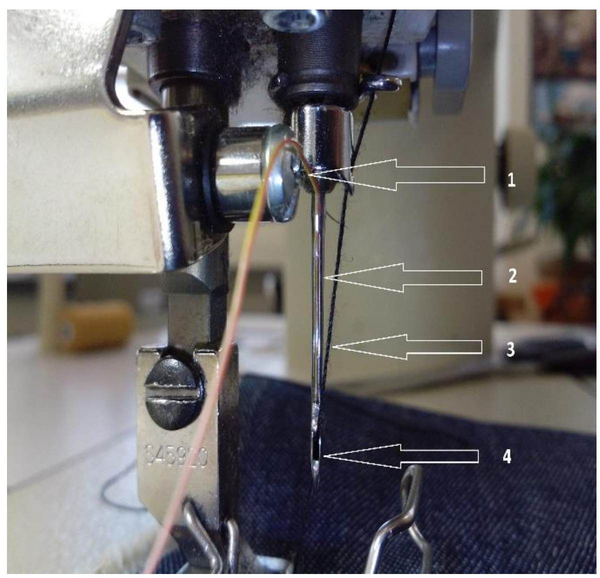

Figure 13 Placement of the thermocouple

Figure 15 shows the needle temperature measured by the inserted thermocouple at sewing machine speed 1000-4000 r/min for both sewing with and without thread. This method proved to be efficient for the different machine speeds and had a lower standard deviation as compared to the other methods of measurement.

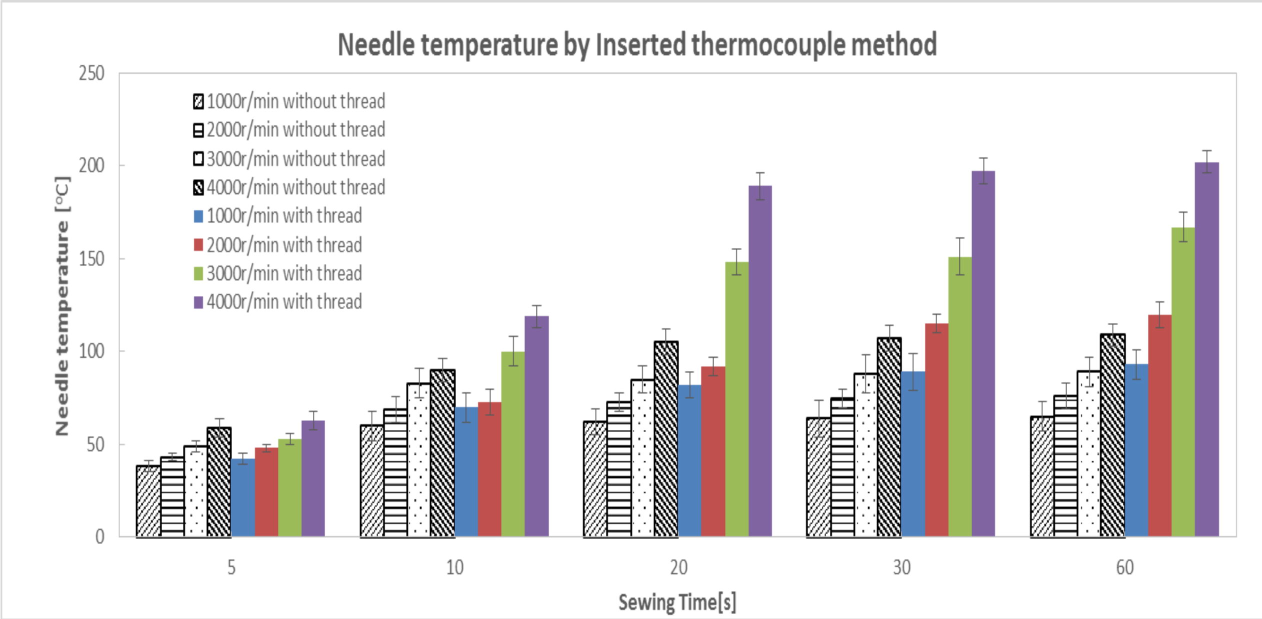

Figure 15 Needle temperature measured by the inserted thermocouple method

Figure 16 shows the needle temperature (with thread) comparison for the different methods of measurement at a machine speed of 3000 r/min. The inserted thermocouple method shows the highest needle temperature after 60 seconds of sewing with the lowest standard deviation, followed by the thermal camera measurement, which had the highest standard deviation. The thermocouple touch method shows the lowest temperature of the three methods of measurement. It was impossible to measure the needle temperature with the thermal camera at speeds higher than 3000 r/min; therefore, the thermocouple touch method and the inserted thermocouple method were used to measure needle temperatures at sewing speeds of 4000 r/min, both with and without thread. The inserted thermocouple method shows significant temperature differences between the tests performed with and without thread. Each experiment was repeated for 30 times.

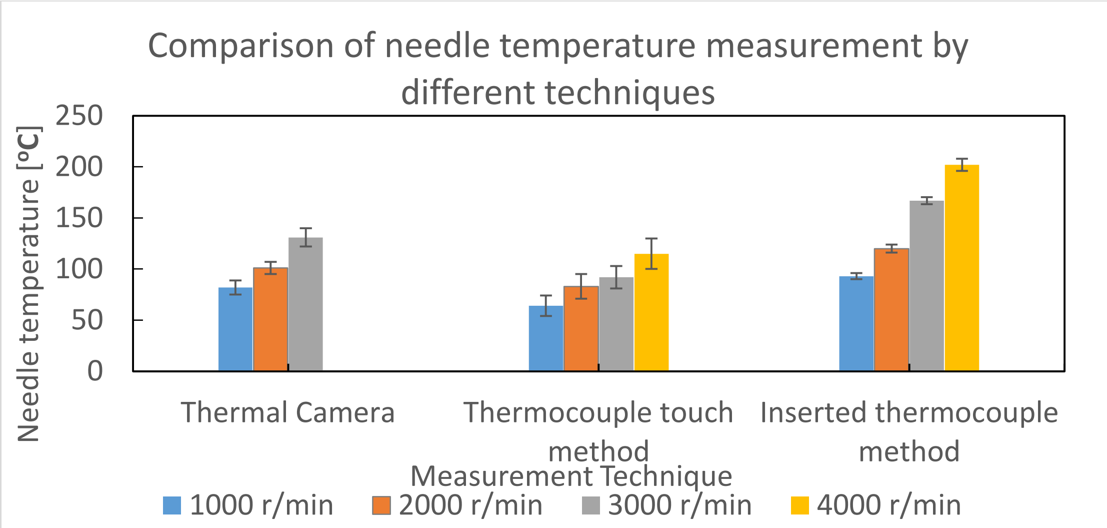

Figure 16 Comparison of the needle (with thread) temperature measurement methods

3.4 Summary

Thermal camera was not a suitable method for measurement of sewing needle temperature. The emissivity of the needle posed a major problem and changed the surface properties [8]; during the normal sewing process, surrounding energy sources reflected off the needle surface. Keeping the same emissivity caused a large standard deviation in the needle temperature measurement, and it was even higher when sewing was done with thread. The thermal camera works on emissivity, and a needle with low emissivity and thread with high emissivity are too close differentiate by the thermal camera. All three methods of needle temperature measurement shows that the needle temperature was higher when sewing with thread as compared to dry sewing.

The thermocouple touch method resulted in the lowest measured needle temperature, which was most likely due to measurement time delays.

The inserted thermocouple appeared to be an efficient method of measurement. Wireless data transfer makes it possible to record needle temperatures each second at all sewing speeds.

All three methods of needle temperature measurement shows that the needle temperature was higher when sewing with thread as compared to dry sewing.

Chapter 4. Factors affecting needle temperature

As shown in last chapter, the inserted thermocouple method showed repeatable results with minimum deviation, so this method is used to examine the effect of different factors on sewing needle temperature. Some of the factors are also reported by previous researchers [4, 7, 8, 23], but there are many factors which influences the needle temperature and not been discussed before. In this research some very common industrial sewing thread as shown in table 3 were tested under different sewing conditions to observe the effects of different factors on sewing needle temperature.

Table 3 Common industrial sewing threads used for the experiment

Thread Name	Composition	Thread count tex	Coef. of friction µ
Merciful 24/2	long-staple mercerised cotton	70	0.40
Mercifil 40	long-staple mercerised cotton	50	0.20
Mercifil 50	long-staple mercerised cotton	40	0.14
Rasant 35	Polyester-cotton corespun	80	0.30
Rasant 50	Polyester-cotton corespun	60	0.18
Rasant 75	Polyester-cotton corespun	40	0.14
Saba C35	Polyester-Polyester corespun thread	80	0.30
Saba C50	Polyester-Polyester corespun thread	60	0.17
Sabab C80	Polyester-Polyester corespun thread	40	0.13
Ctech 80	polyester filament +Carbon	35	0.11

Figure 17 shows that needle temperature rises with longer time of sewing but the increase is dramatic till 10 s of sewing, as after this time the needle system get stabilize with the environment temperature. The needle temperature also rises with the increase of sewing speed. The maximum needle temperature was recorded for the sewing threads made from cotton, as cotton has higher hairiness to cause more friction at the needle eye, which causes higher frictional heat. This needle heat is dissipated to surrounding through conduction to needle holder and also by convection through airflow (surrounding airflow and air forced at the needle eye with the sewing thread), whereas the heat dissipation through radiation might be very low as needle is thin and shiny with emissivity of less than 0.08 [8].

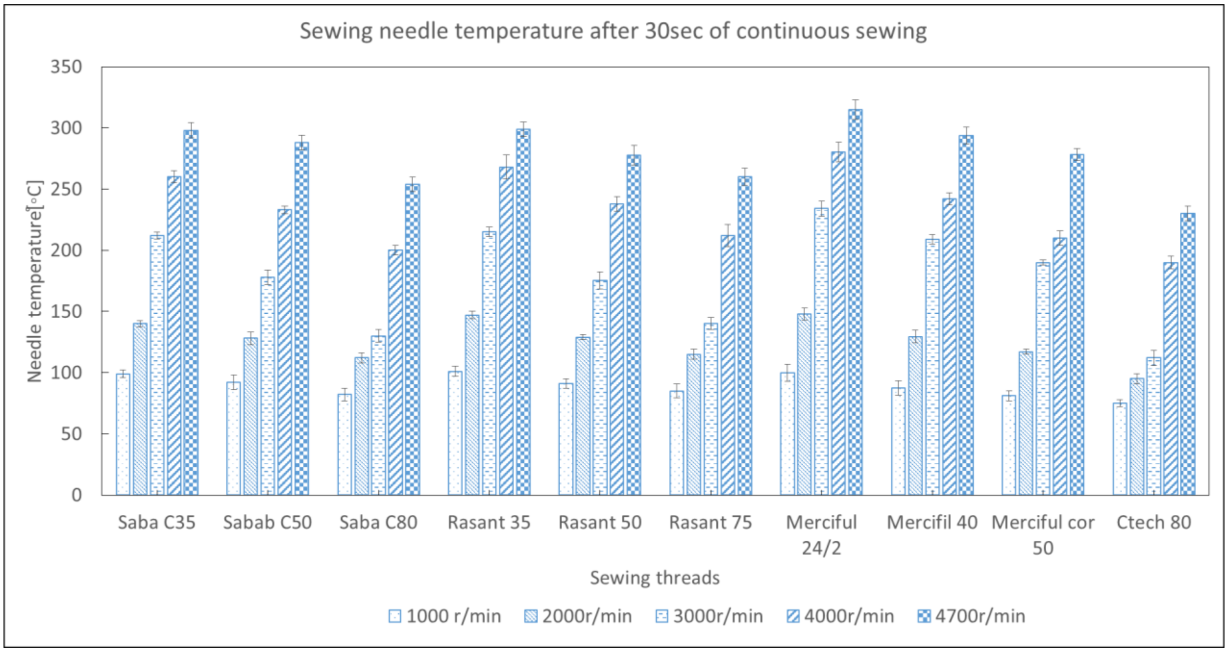

Figure 17 Needle temperature under different sewing conditions

The SEM images of each type of sewing thread after 4700r/min of sewing is shown in Figure 18.The broken and protruding fibers are visible on each thread, the melting of the fibers can be observed for the polyester based threads.

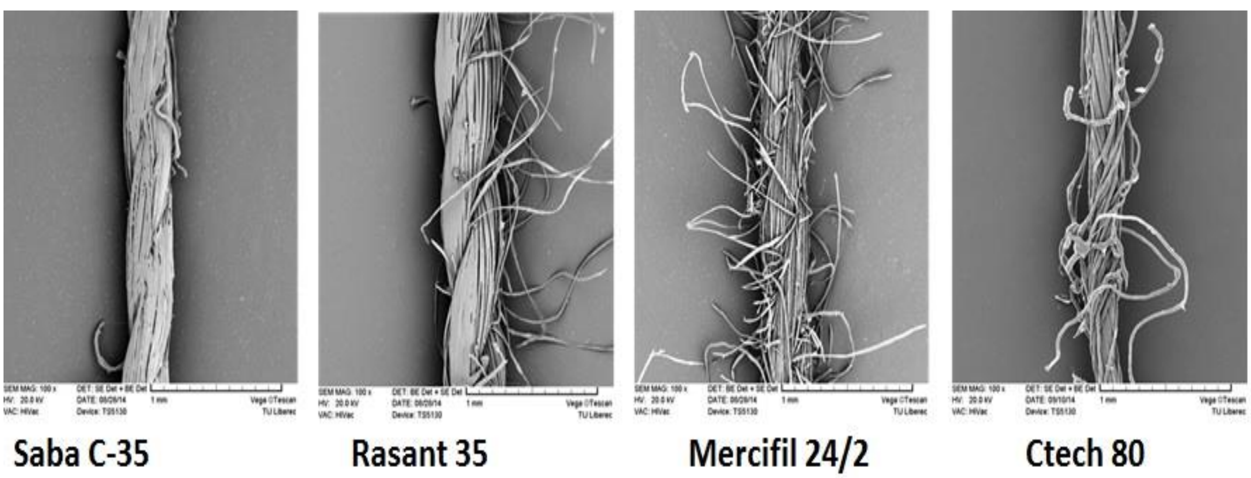

Figure 18 SEM images of the threads after sewing (machine speed 4700r/min)

4.1 Factors affecting needle temperature

The effect of different factors effecting needle temperature included in our research are discusses as below:

4.1.1 Effect of sewing speed

In our research the machine speed of 1000-4700r/min is tested for different threads and it is concluded that the needle temperature rises linearly with the increase of sewing speed. The higher the speed, the more heat goes to the needle during the unit time, hence resulting in an early high peak temperature. The more heat is taken by the needle within unit time, the faster it reaches it stability temperature, because the heat absorption rate decreases when the machine speed is going higher. The important reason for this needle temperature rise is also due to the higher thermal conductivity of the needle as compared to the textile material and more friction heat goes in to the needle during each cycle with higher sewing speed.

4.1.2 Effect of fabric thickness

In this research work, it is observed that the fabric thickness plays an important role in the needle heating, with the thinner fabrics or low number of layers the peak temperature is decreased greatly. With each new layer of fabric the temperature is increased by nearly 8^{o}C. One reason is obvious that that there will be low friction generated by thin fabrics. The other reasons are that the needle takes in much more friction heat in the same time period and make bigger temperature difference for different fabric thickness. This allows the operator to do the sewing for longer time for thin or low number of layers of fabric as the peak temperature is less and temperature stability is reached much earlier as compared to heavy or multi-layered fabrics.

4.1.3 Effect of Material

Both needle and textile material affect the peak temperature of needle, the parameters which greatly influence in terms of material property are friction coefficient and thermal conductivity and any change in these two property will dramatically influence the needle temperature.

With the increase of thermal conductivity of textile material the needle temperature will decrease to some degrees, which is due to the heat conduction of needle to the textile material and friction heat partition ratio is dependent on the thermal conductivity, fabric density and specific heat of the material.

4.1.4 Effect of needle geometry

An industrial sewing needle is defined by nearly 15 parameters. There are number of parameters that determine the behaviour of needle heating, the parameters include: The needle eye position, size, length of needle groove, needle diameter needle punching length.

In this research, different diameter of needles (90 to 120Nm), which are universal needles for denim fabric sewing were used. The friction heat increases with needle diameter increase, but the convection heat also will increase with the increase in the needle surface area. Therefore the net effect is almost negligible.

4.1.5 Thread properties

Three most common industrial threads with three different counts of 40, 60 and 80 tex were tested. It is observed that there is an increase in needle temperature with the increase of thread count. The higher count possesses larger contact area with the needle eye and causes the needle temperature to rise. It was also seen that the cotton threads has higher coefficient of friction and provide highest needle temperature to sewing needle as compared to other tested threads.

4.1.6 Stitch density

In this research all sewing threads shown in table 3 are tested for the stitch density of 3-6 stitches/cm with various machine speed (1000-4700 r/min) and multiple fabric layers; it is found that there is a negligible change of needle temperature with the change of stitch density. It is due to that the number of insertion per unit time depends on the speed of the machine not on the displacement between these insertions (i.e. stitch density), therefore the generated heat due to friction will remain the same.

4.1.7 Vortex cooling

Vortex cooling/forced air cooling is one of the most common industrial techniques to decrease the needle temperature. From our experimental analysis, for all sewing threads the needle temperature is decrease by nearly 60-100^{o}C depending on machine speed and parameters of the vortex tube air. The method is very effective to decrease the needle temperature but this must be taken into account that most of the clothing industries do not prefer to use this method because of the additional cost of continuous compressed air supply.

4.1.8 Ambient humidity and temperature

The ambient temperature affect the needle temperature and almost 5 ^{o}C temperature rise of needle was noted when ambient temperature is increased from 26 to 36 ^{o}C, whereas the ambient humidity has negligible impact on needle temperature for the polymer sewing threads, but the cotton spun sewing thread shows a minor decrease in needle temperature with respect to the increase of ambient humidity. This might be due to the moisture regain of natural thread which causes change in their thermal conductivity.

4.1.9 Thread Lubrication

Thread lubrication is the second most common method to decrease the needle temperature at any sewing companies. The lubricant decrease the coefficient of metal to yarn friction and causes the needle temperature to decrease .It is also concluded from our research that the needle temperature is decreased by nearly 30% for sewing thread with lubricant (silicon lubricant).

4.1.10 Time of sewing

Sewing time is also a very important factor that influence the needle temperature, it is observed that the needle temperature reached to stability within 10-15 seconds of a continuous sewing, Needle gains the temperature through thread and fabric friction whereas the major heat loss is by conduction to needle holder and convection through the needle surface. There is a rapid increase in needle temperature till 10sec of sewing after that there is a minor increase in needle temperature and peak temperature is mostly observed at 15 to 20seconds of sewing. The cooling time should also be considered at the sewing floor, needle takes nearly 30-45 seconds to cool down to room temperature.

4.2 Preliminary investigation

The denim fabric and polyester core-spun thread is a widely used thread in the clothing industry and most of the previous researchers have used this this thread for their research, which makes the PET corespun thread the main subject of our study. Three-level four factorial Box–Behnken experimental design (constructed using Minitab 16) was used to evaluate the effects of the selected independent variables on the response. The number of experiments required to investigate the previously noted four factors at three levels would be 81. However, this was reduced to 27 by using a Box–Behnken experimental design. The results from this limited number of experiments provided a statistical model, which can help to find the optimum experimental conditions and the relationships between experimental results and parameters. The table 4 shows the thread properties used for the experiment, properties of denim fabric used for the experiment is shown in table 2.

Table 4 Thread used for the experiment

Thread type	Company name/product	Thread Count (tex)	Twist (t/m)	Twist direction (ply/single)	Coefficient of friction μ
Polyester/polyester core spun	AMANN/Saba C-80	20*2	660	Z/S	0.13

The significant variables like stitch, speed of sewing, layer of fabric, and the time were chosen as the critical variables and designated the symbols as X_1, X_2, X_3, and X_4, respectively. The low, middle, and high levels of each variable were designated as −1, 0, and +1, respectively, as shown in Table 5-6.

Table 5 Factors and factor levels studied in Box-Behnken experimental design

	Levels		
Factors	-1	0	1
X_1=number of stitches /2.54cm	10	12	14
X_2=Speed of Sewing (stitches/60 s)	1000	2000	3000
X_3=Number of Denim fabric layers	2	3	4
X_4=Time of Sewing (s)	10	20	30

Table 6 The design of the experiment

Trial No.	X_1	X_2	X_3	X_4

1	-1	-1	0	0
2	-1	1	0	0
3	1	-1	0	0
4	1	1	0	0
5	0	0	-1	-1
6	0	0	-1	1
7	0	0	1	-1
8	0	0	1	1
9	-1	0	0	-1
10	-1	0	0	1
11	1	0	0	-1
12	1	0	0	1
13	0	-1	-1	0
14	0	-1	1	0
15	0	1	-1	0
16	0	1	1	0
17	-1	0	-1	0
18	-1	0	1	0
19	1	0	-1	0
20	1	0	1	0
21	0	-1	0	-1
22	0	-1	0	1
23	0	1	0	-1
24	0	1	0	1
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0

In a system involving four significant independent variables X_1, X_2, X_3, and X_4 the mathematical relationship of the response on these variables can be approximated by the quadratic polynomial equation:

$$\begin{aligned} Y = {} & \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + a_4 x_4 + \alpha_{12} x_1 x_2 + \alpha_{13} x_1 x_3 + \alpha_{14} x_1 x_4 \\ & + \alpha_{23} x_2 x_3 + \alpha_{24} x_2 x_4 + \alpha_{34} x_3 x_4 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{33} x_3^2 + \alpha_{44} x_4^2 \\ & + a_5 x_1 x_2 x_3 + a_6 x_1 x_2 x_4 + a_7 x_1 x_3 x_4 + a_8 x_2 x_3 x_4 + a_9 x_1 x_2 x_3 x_4 \end{aligned} \tag{4.1}$$

Where,

Y is estimate response, α_0 is constant, α_1, α_2, α_3, and α_4 are coefficients of linear variables, α_{12}, α_{13}, and α_{23} are interaction coefficients between the three factors, α_{11}, α_{22}, and α_{33} are coefficients of quadratic factors.

In this model given in equation (4.1), interactions higher than second-order have been neglected based on their significance value. A multiple regression analysis is done to obtain the coefficients and the derived equation (4.2) can be used to predict the response.

$$\mathbf{Y = -26+1.375X_1-0.0262X_1^2+1.2*10^{-5}x_2^2+0.2134X_3X_4+0.00123X_2X_4} \quad (4.2)$$

Where,

Y=needle temperature (°C)

Adjusted $R^2 = 0.994$ and P-value = $1.24*10^{-24} \approx 0$

In order to gain a better understanding of the interaction effects of variables on needle temperature, selective three dimensional surface plots for the measured responses were studied.

Figure 19 shows the 3D-surface plot for impact of number of layers and stitch density on needle temperature, it was observed that needle temperature is highly impacted by number of layers of fabrics, because with the increase of fabric thickness, higher friction occurs between needle and the fabric. Whereas the stitch density causes a minor increase in needle temperature. It is due to reason that with change of stitch density the number of insertion per unit time remains the same and so is the friction heat.

Figure 20 shows that the needle temperature rises substantially with the increase of the sewing speed. There is more stitches made at higher speeds, which makes higher needle-yarn and needle-fabric friction. The more gain in temperature for higher speed than 50 r/s (3000r/min) can be due to higher dynamic loading of thread at higher speed and this increase in thread tension causes the higher frictional heat between needle and thread.

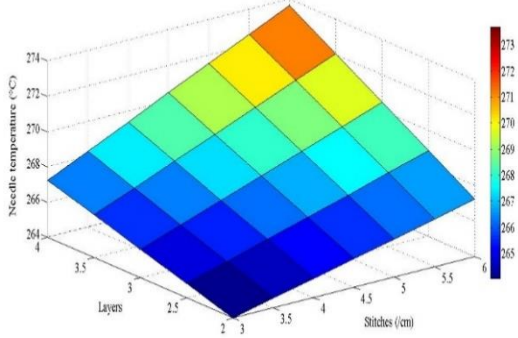

Figure 19 Effect of number of fabric layer and stitch density on needle's temperature

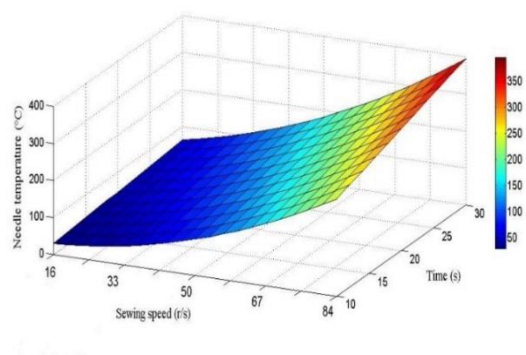

Figure 20 Effect of Sewing speed and sewing time on needle's temperature

Figure 21 shows the comparison of needle temperature at different speed of sewing by experiment, and the predicted values by the model developed. It is visible that needle temperature rises linearly with the increase of sewing speed. There is nearly 15^{o}C rise in needle temperature with each 10r/s increase in sewing speed.

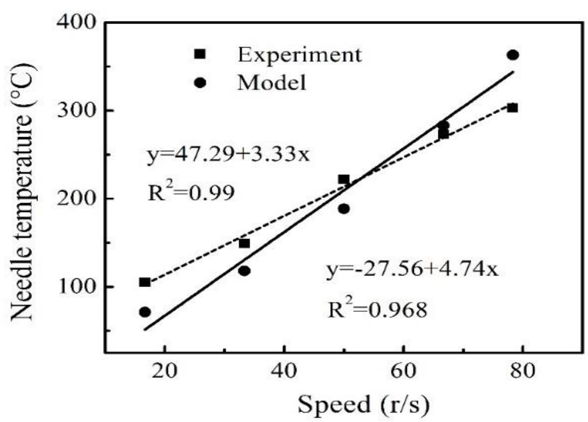

Figure 21 Comparison of Experimental and predicted Needle temperature for different speeds of sewing

Figure 22 shows the comparison of needle temperature measured by experiment and by regression analysis. The needle temperature is shown for sewing speed of 50r/sec (3000r/min) at sewing time of 10, 20 and 30 seconds for 2,3 and 4 layer of denim fabric. The secondary y-axis on the right side of graph shows the average percentage difference between the predicted and the experimental results. Results confirm that the model has error percent of less than 10% for all factors.

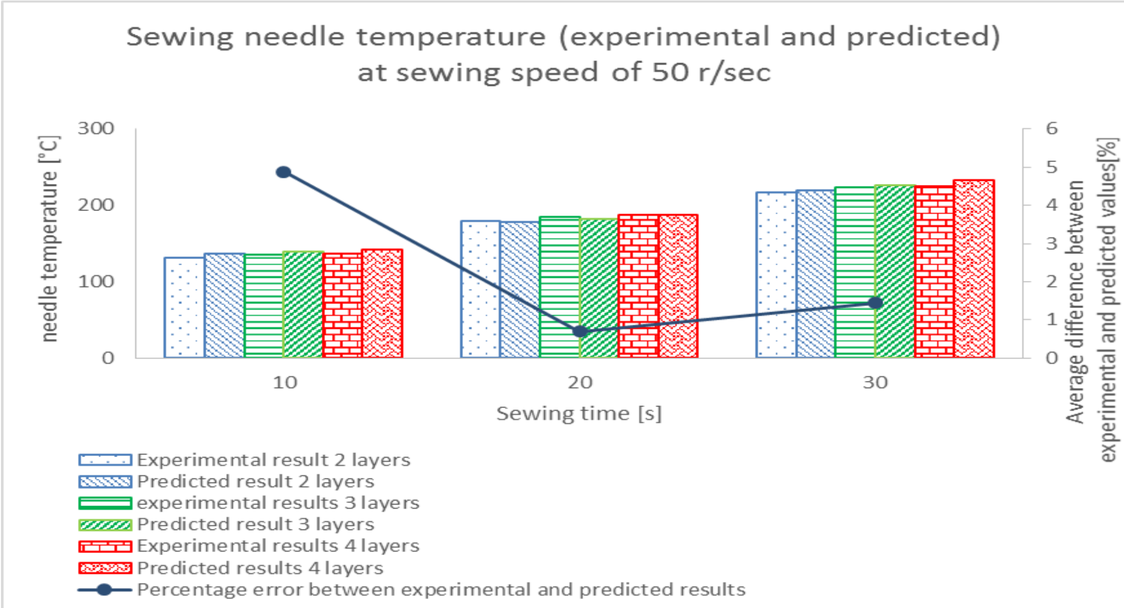

Figure 22 Prediction of model at 50 r/sec (3000r/min) of sewing

4.3 Summary

This research work presents a discussion on the effect of different factors on the sewing needle temperature; it was observed that the sewing speed, the thread count, the sewing time, the fabric thickness had major impact on sewing needle temperature. On the other hand, ambient humidity, ambient temperature, stitch density and needle parameters played a minor role in heating of the sewing needle.Needle temperature for denim fabric is also measured at different speeds of sewing, sewing time, stitch density and number of fabric layers. A multiple regression analysis is done to obtain the coefficients, and the derived equation was used to predict the needle temperature.

Chapter 5. Effect of vortex cooling on sewing needle temperature

Cooling needle by cold air is one of the most common method in cooling the hot needle. In this chapter the effect of Cold air by vortex tube is examined under different sewing conditions.

5.1 Experimental method

5.1.1 Materials and devices

For this research, sewing was performed for 30 sec with two common industrial polyester threads, and the needle temperature was measured using the inserted thermocouple method for the different speeds of sewing, ranging from 1000 to 4000 r/min. Finally, the tensile properties, like the initial modulus, breaking elongation and the tenacity of the thread, were measured at the different speeds and cooling times. The conditions for all of the experiments were kept constant at 26°C and 65% RH. The devices used for the experiments are listed below:

- Lockstitch machine (Brother Company, DD7100-905).
- Needles (Groz-Becker 100/16) R-type.
- Sewing thread properties are shown in Table 7.
- Properties of denim fabric used for the experiment is shown in table 2
- Forced air cooling device (Properties shown in Table 8).

Table 7 Properties of the sewing thread

Thread type	Producer/ product name	Yarn Count (tex)	Twist (t/m)	Twist direction (ply/single)	Tenacity (cN/tex)	Elongation at break (%)	Initial modulus (N/tex)	Coefficient of friction, μ (-)
PES–PES core spun	AMANN/Saba C-35	40 ×2	534	Z/S	50	18	4.4	0.30
PES–PES core spun	AMANN/Saba C-80	20 ×2	660	Z/S	45	21	3.26	0.13

Table 8 Vortex tube efficiency

Company	Input air pressure (kPa)	Output air temperature (°C)
Festo	500	7

The sewing process was performed for 30 sec of continuous stitching on 2 layers of fabric with needle cooling, without needle cooling and with the optimised cooling time. Each thread was observed 20 times at each of the different speeds of sewing. The stitch length was kept constant at 5 stitches/cm.

5.1.2 Needle cooling setup

Figure 23 shows the placement of the cooling tube near the sewing machine; the distance between the needle and the cold air tube is 4 cm. The cooling setup is shown in figure 23.

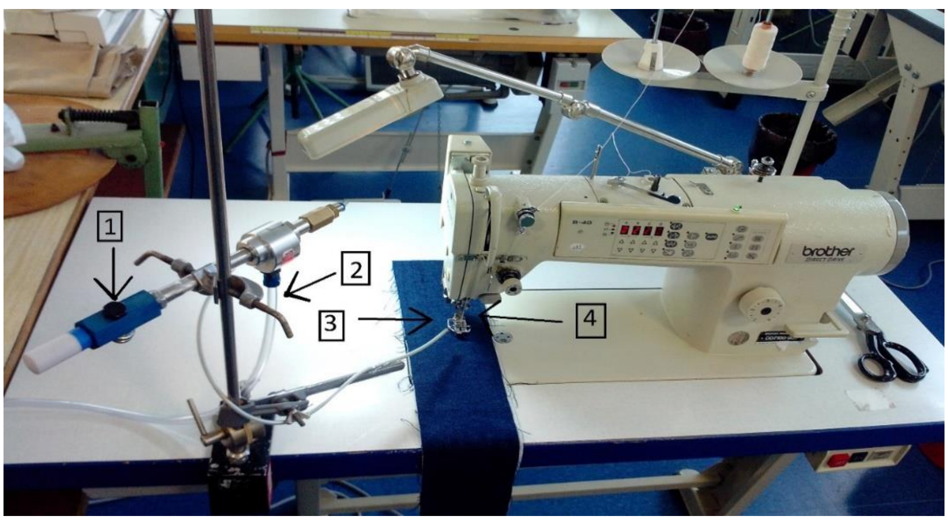

Figure 23 Sewing machine with needle cooling setup.

Point 1- vortex tube, Point 2- air inlet from compressor, Point 3- cold air outlet, Point 4- sewing needle

5.1.3 Tensile properties measurement

After each 30 sec of the sewing cycle, the thread was cut from the needle guide point and a sufficient amount of seam thread was pulled out precisely by cutting the bobbin thread. Twenty observations were performed for each speed of the machine under three conditions; with cooling, without cooling and with the optimised cooling time, respectively. Tensile testing of the sewing thread was conducted on an Instron tensile tester as per ASTM standard D2256, with a gauge length of 250 mm.

The change (%) in the tensile properties with respect to the parent thread was calculated by the following expression:

$$\boldsymbol{Change}\ (\%) = \frac{\boldsymbol{Tn-T}}{\boldsymbol{T}} * \mathbf{100} \tag{5.1}$$

Where Tn is the tensile property of the thread pulled out from the seam, with n = 1, 2, and 3 corresponding to sewing without cooling, with cooling and with the optimized cooling time, respectively. T is the tensile property of the parent thread. A negative sign (–) indicates a loss in tensile property.

5.1.4 Cooling time of the needle

First, the sewing process was performed without cooling, and all of the observations of the needle temperature and the tensile properties of the final seam thread were recorded at the different speeds of sewing. Next, the sewing process was performed with continuous cooling, and the cooling of the needle was begun a few seconds before the beginning of the sewing process. Finally, the sewing process was performed with a partial cooling time of only 5 sec before and 5 sec after the stoppage of the sewing process. In total, 10 sec of cold air was pumped manually at the sewing needle beginning at 25 sec of stitching and finishing 5 sec after the stoppage of the sewing. The reason for choosing this timing was mainly to protect the thread from damage at the time of the machine stoppage, where the contact time between the thread and the hot needle was much higher when compared to sewing at high speeds.

5.2 Results and discussion

5.2.1 Needle temperature (without cooling)

Sewing needle temperature is measured by the inserted thermocouple method for a continuous sewing process of 30 seconds, after the sewing process the needle is allowed to cool down without any forced air flow. Figures 24-25 shows the needle temperature for both threads at the different speeds of sewing, without the air cooling. The needle temperature is higher for the higher count thread, thread Saba C-35 shows a nearly 20°C higher temperature than the Saba C-80.

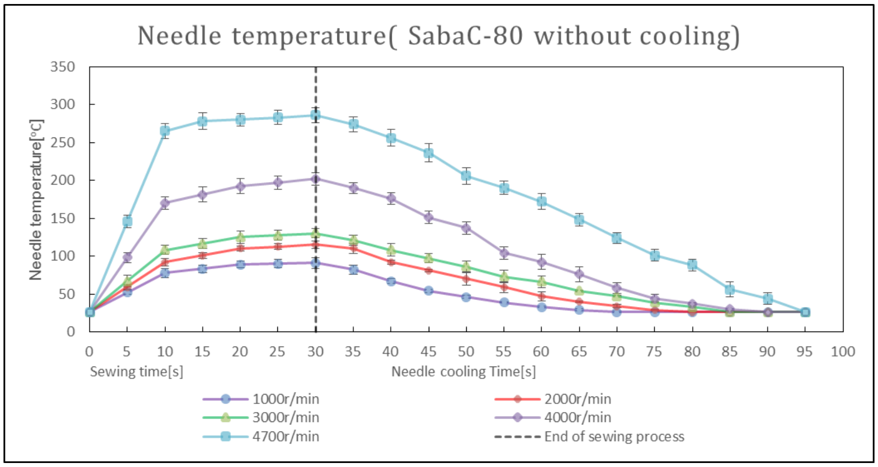

Figure 24 Needle temperature (Saba c-80) without cooling.

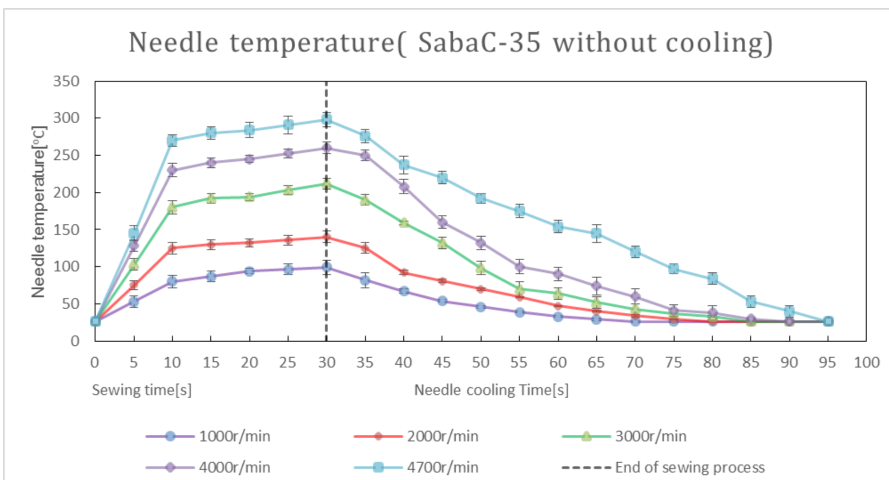

Figure 25 Needle temperature (Saba c-35) without cooling.

The needle temperature at 1000 and 2000 r/min was less than 150°C after 30 sec of continuous sewing; therefore, 3000 and 4000 r/min was selected for the comparison of the needle temperature with cooling, without cooling and at the optimised cooling time.

5.2.2 Comparison of needle temperature

Figures 26–29 show the comparison of the needle temperatures for the sewing thread at different speeds of sewing for all 3 cooling times. The legends for Figures 26-29 are described in Table 9.

Table 9 Description of legends used in Figures 23-26

Legends	Description
A	Needle temperature with continuous cooling
B	Needle temperature with partial cooling (cooling starts at 25 sec and ends at 35 sec)
C	Needle temperature without cooling
D	Dotted line at 30 sec indicates the end of sewing process

Figure 26 shows a nearly 40°C difference between sewing with air cooling and sewing without cooling for Sewing thread (Saba C-80). The optimised cooling time of 10 sec, beginning at 25 sec of the sewing process, causes the needle temperature to decrease dramatically, and in just 10 sec of cooling the needle temperature is decreased by nearly 30°C.

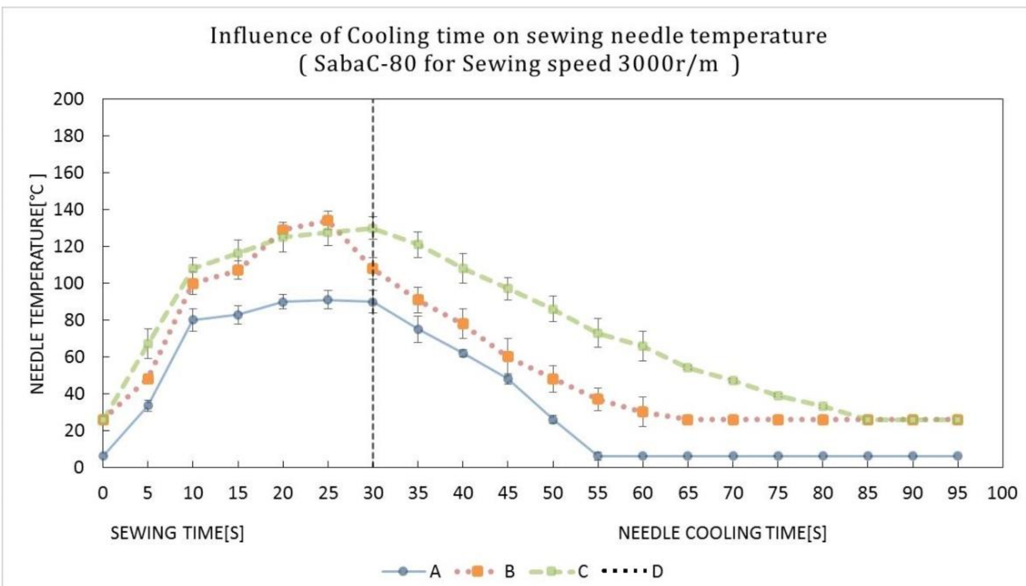

Figure 26 Influence of cooling time on temperature of sewing needle

Figure 27 shows the needle temperature at 4000 r/min of sewing speed with different cooling times for Sewing thread (Saba C-80). The optimised cooling time shows a nearly 50°C decrease in temperature with only 10 sec of cooling. The needle takes almost 60 sec to reach room temperature for sewing without cooling, whereas it takes just 20 sec of continuous cooling to cool the needle and 30 sec with the optimised cooling time.

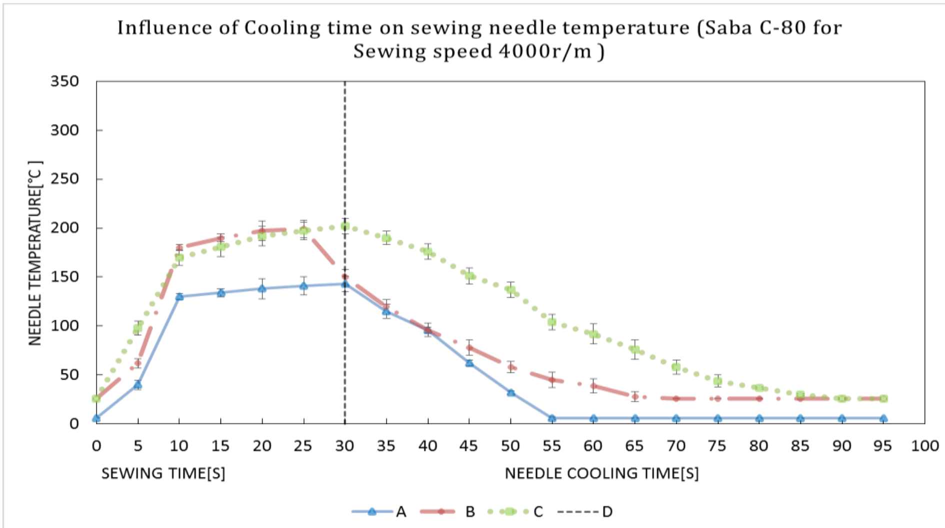

Figure 27 Influence of cooling time on sewing needle temperature (Saba C-80) at 4000 r/min.

Figures 28-29 show the needle temperature for the (Saba C-35) thread at different sewing speeds and with different cooling times.

Figure 28 shows the needle temperature (Saba C-35) at 3000 r/min with different cooling times. The optimised cooling time shows a nearly 60°C decrease in temperature. The needle takes almost 40 sec to reach room temperature for sewing without cooling, whereas it takes just 20 sec of continuous cooling to cool the needle and 25 sec using the optimised cooling time.

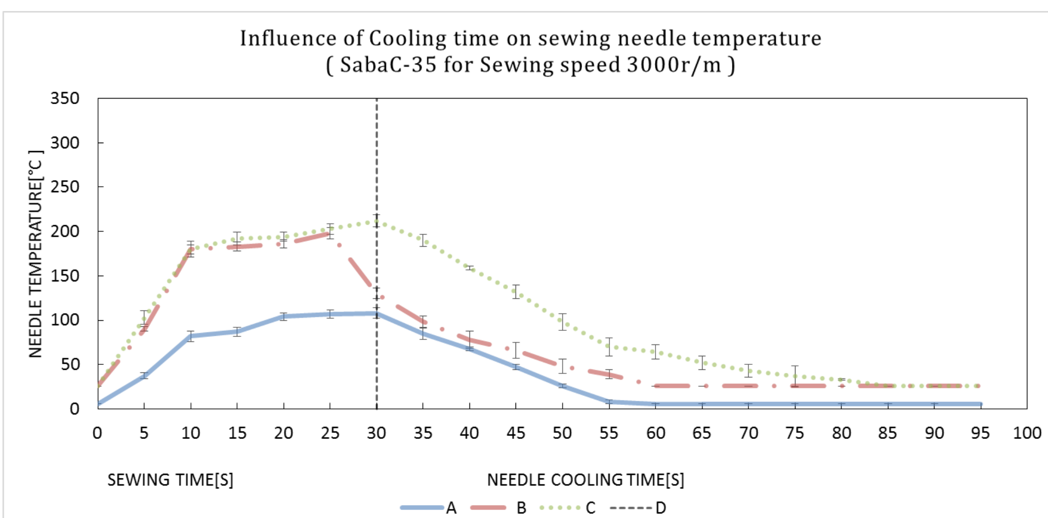

Figure 28 Influence of cooling time on sewing needle temperature (Saba C-35) at 3000 r/min.

Figure 29 shows the needle temperature (Saba C-35) at 4000 r/min with different cooling times. The optimised cooling time shows nearly 90°C of decrease in temperature. The needle takes almost 50 sec to reach room temperature for sewing without cooling, whereas it takes just 20 sec by continuous cooling to cool the needle and 35 sec with the optimised cooling time.

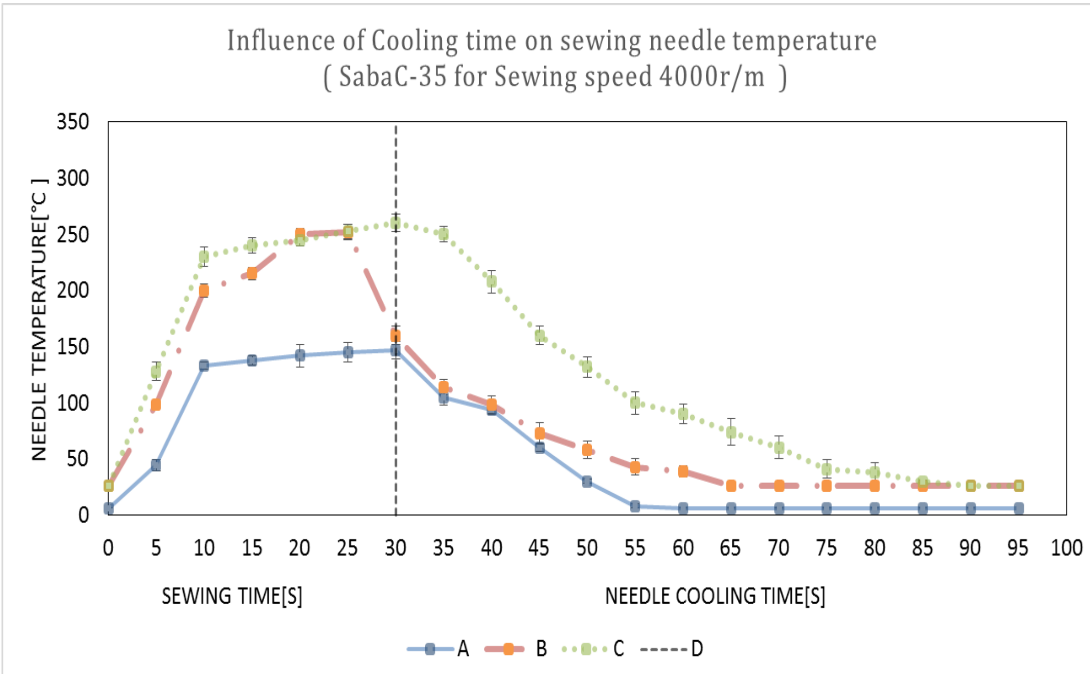

Figure 29 Influence of cooling time on sewing needle temperature (Saba C-35) at 4000 r/min.

5.2.3 Influence of cooling time on tensile properties of thread

Hot needle greatly influences the tensile properties of sewing thread. To measure the impact the needle thread is pulled out of the seam by precisely cutting the bobbin thread. Tensile properties like tenacity, initial modulus and breaking elongation of the thread were tested 20 times each to observe the effect of the cooling time on the thread strength. It was seen that sewing without cooling showed the weakest thread, where the tenacity was decreased to 26% at 4700 r/min for the sewing thread (Saba C-80); however, the sewing with continuous cooling and partial cooling (10 sec) showed almost the same tenacity of the seam thread. Figure 30 shows the tenacity of the thread for the Saba c-80 at different speeds and cooling times. The effect of the needle heat is quite visible at speeds higher than 3000 r/min.

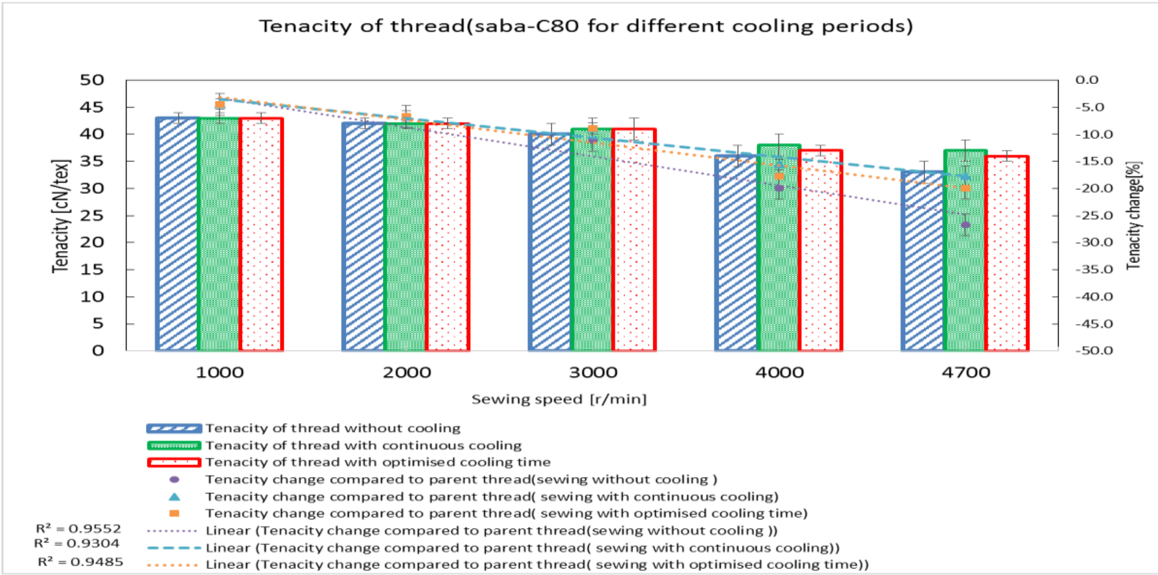

Figure 30 Tenacity of thread (Saba C-80) at different speeds and cooling times.

Figure 31 shows the tenacity of the thread (Sabac-35), sewing without cooling shows the weakest thread, where the tenacity of the thread is decreased to 30% at 4700 r/min, which is 4% higher than the thread Saba C-80; however, sewing with continuous cooling and partial cooling (10 sec) shows a minor difference in tenacity of the seam thread. The effect of the needle heat is quite visible for 3000 r/min and higher.

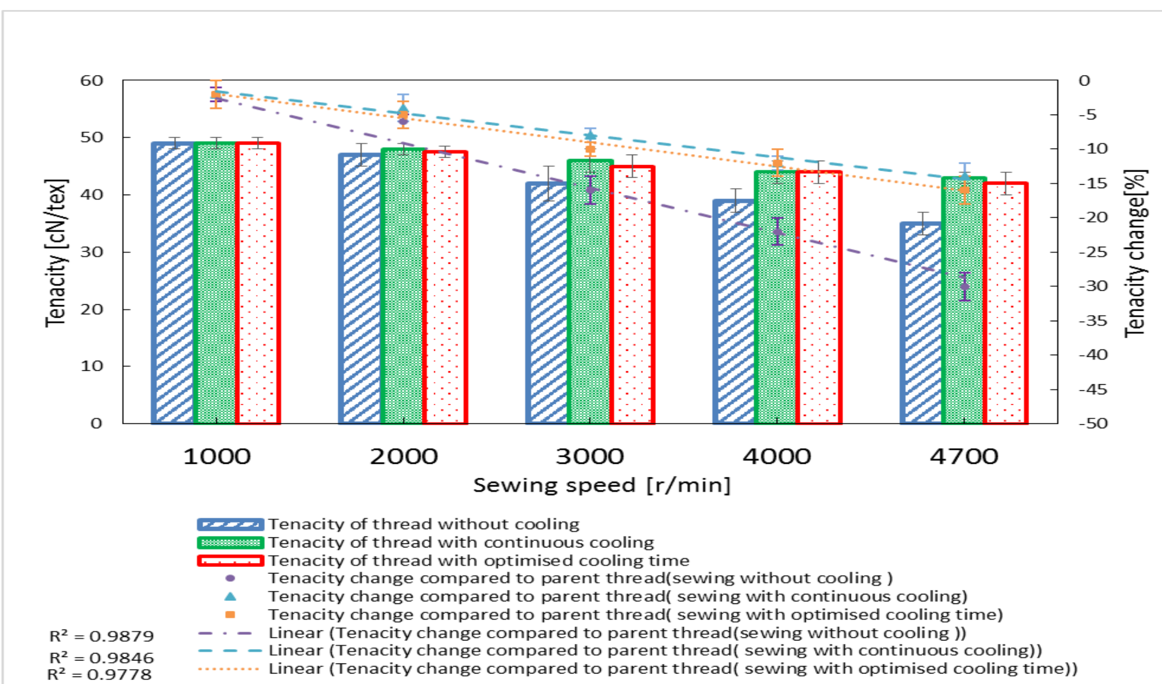

Figure 31 Tenacity of thread (Saba c-35) at different speeds and cooling times.

Table 10 shows the tensile properties of the thread, like tenacity, initial modulus and breaking elongation, of the Saba C-35 and Saba C-80 sewing thread. The percentage change in the property is also calculated according to equation 5.1. It shows that the thread tenacity, initial modulus and breaking elongation are more decreased for Saba C-35, when compared to Saba C-80, which is due to a higher needle temperature during the sewing process for Saba C-35.

The tensile properties of the thread are greatly decreased at 3000 r/min and higher. At 4700 r/min, for the Saba C-35, the initial modulus of the thread compared to the parent thread was 26% less for sewing without cooling, followed by 22% with the optimised cooling time and 21% using continuous cooling. For Saba C-80, the initial modulus decreases by 22% for sewing without cooling, followed by 20% with the optimised cooling time and 19% using continuous cooling.

Breaking elongation of the seam thread for 4700 r/min for Saba C-35 was 21% less for sewing without cooling, followed by 16.7% with the optimised cooling time and continuous cooling. For the Saba C-80, the breaking elongation decreased by 20% for sewing without cooling, followed by 16% with an optimised cooling time and continuous cooling.

Table 10 Tensile properties of threads at different speeds of sewing.

			Sabac-35						Sabac-80				
Property			speed of machine						speed of machine				
			1000 rpm	**2000 rpm**	**3000 rpm**	**4000 rpm**	**4700 rpm**		**1000 rpm**	**2000 rpm**	**3000 rpm**	**4000 rpm**	**4700 rpm**
Tenacity [cN/tex]		Parent thread	**50**	**50**	**50**	**50**	**50**		**45**	**45**	**45**	**45**	**45**
	Sewing without cooling	T1	**49**	**47**	**42***	**39***	**35***		**43**	**42***	**40***	**36***	**33***
		X	**-2**	**-6**	**-16**	**-22**	**-30**		**-4.4**	**-6.7**	**-11.1**	**-20.0**	**-26.7**
	Sewing with continuous cooling	T2	**49**	**48**	**46***	**44***	**43***		**43**	**42***	**41.2***	**38***	**37***
		X	**-2**	**-4**	**-8**	**-12**	**-14**		**-4.4**	**-6.7**	**-8.4**	**-15.6**	**-17.8**
	Sewing	T3	**49**	**47.5**	**45***	**44***	**42***		**43**	**42***	**41***	**37***	**36***

	with optimized cooling time	X	**-2**	**-5**	**-10**	**-12**	**-16**		**-4.4**	**-6.7**	**-8.9**	**-17.8**	**-20.0**
Breaking elongation [%]		Parent thread	**18**	**18**	**18**	**18**	**18**		**21**	**21**	**21**	**21**	**21**
	Sewing without cooling	B1	**17.6**	**16.2***	**15.6***	**14.6***	**14.2***		**19.6**	**19***	**18.2***	**17.3***	**16.8***
		X	**-2.2**	**-10.0**	**-13.3**	**-18.9**	**-21.1**		**-6.7**	**-9.5**	**-13.3**	**-17.6**	**-20.0**
	Sewing with continuous cooling	B2	**17.7**	**16***	**16.4***	**15.4***	**15***		**19.7**	**19.2***	**18.8***	**18***	**17.6***
		X	**-1.7**	**-11.1**	**-8.9**	**-14.4**	**-16.7**		**-6.2**	**-8.6**	**-10.5**	**-14.3**	**-16.2**
	Sewing with optimized cooling time	B3	**17.6**	**16.1***	**15.9***	**15.5***	**15***		**19.6**	**19.2***	**18.6***	**17.8***	**17.6***
		X	**-2.2**	**-10.6**	**-11.7**	**-13.9**	**-16.7**		**-6.7**	**-8.6**	**-11.4**	**-15.2**	**-16.2**
Initial Modulus [N/tex]		Parent thread	**4.5**	**4.5**	**4.5**	**4.5**	**4.5**		**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
	Sewing without cooling	I1	**4.4**	**4.4**	**4.1***	**3.6***	**3.3***		**3.1**	**3.1**	**3***	**2.8**	**2.5**
		X	**-2.2**	**-2.2**	**-8.9**	**-20.0**	**-26.7**		**-3.1**	**-3.1**	**-6.3**	**-12.5**	**-21.9**
	Sewing with continuous cooling	I2	**4.5**	**4.3**	**4.1***	**4***	**3.6***		**3.1**	**3.1**	**3.1***	**2.7***	**2.6***
		X	**0.0**	**-4.4**	**-8.9**	**-11.1**	**-20.0**		**-3.1**	**-3.1**	**-3.1**	**-15.6**	**-18.8**
	Sewing with optimized cooling time	I3	**4.4**	**4.3**	**4.2***	**3.95***	**3.5***		**3.1**	**3.05**	**3***	**2.8***	**2.55***
		X	**-2.2**	**-4.4**	**-6.7**	**-12.2**	**-22.2**		**-3.1**	**-4.7**	**-6.3**	**-12.5**	**-20.3**

Where:

- *X=percentage change with respect to parent thread property [%].(calculated according to Equation 1.)*
- *T1, T2 and T3 show the tenacity [cN/tex] of the threads without cooling, with continuous cooling and with an optimized cooling time, respectively.*
- *B1, B2 and B3 show the breaking elongation [%] of threads without cooling, with continuous cooling and with an optimized cooling time, respectively.*
- *I1, I2 and I3 show the initial modulus [N/tex] of the threads without cooling, with continuous cooling and with an optimized cooling time, respectively.*
- ** shows the significant difference of means at a 95% confidence interval from parent thread.*

5.3 Summary

The major outcomes from this part are highlighted below:

- Air cooling (Vortex) is an effective way of decreasing needle temperature, and the continuous cooling method decreases the needle temperature by nearly 100°C at 4000 r/min and 4700 r/min; whereas the 10 sec cooling at the time of machine stoppage decreases the needle temperature by 92°C at 4000 r/min and 4700 r/min.
- At high speed sewing, the contact time between the thread and needle is very low, but as the machine comes to a complete stop, the contact time of the thread and needle is relatively higher, which causes damage to the sewing thread. The results represents that cooling at the time of machine stoppage and continuous cooling show the same results in terms of thread tensile properties.
- Cooling only at the time of machine stoppage can also cause decrease in energy consumption at sewing industry due to low usage of compressed air.
- Industrial sewing machine producers must operate the air cooling device with the machine speed pedal, which operates at 3000r/min and higher, and at the time of machine deceleration.
- Cooling only at time of machine stoppage can be used for sewing operations like on bed sheets, curtain or long length stitches, where a straight long time sewing is made and cooling at time of machine stoppage can save energy consumption.

Chapter 6. Effect of lubricant on sewing needle temperature

Lubricants cause the decrease in friction coefficient of sewing threads and are commonly used in sewing industries [9]. The lubricant improves the surface finish which causes the decrease of friction between yarn and the metal object and most lubrication is intended to decrease yarn to metal friction. In recent publication, it was reported that the amount of lubricant used have a profound effect on friction, and lubricants linearly decreases the coefficient of friction in sewing threads [63-65]. Sewing thread lubricant always contains silicon, because silicon provides the heat protection and friction reduction in sewing threads. It is accepted that silicones are poor conductor of heat but good release agent and causes reduction in coefficient of friction for sewing threads [38].

Due to high strength and durability of polyester-polyester (PET-PET) core-spun thread, it is the most common sewing thread used in apparel industry. High amount of lubricant are applied to decrease friction and needle temperature [37]. In our research we measured the effect of different amount of lubricant on needle temperature, coefficient of friction and breaking tenacity of PET-PET core-spun thread.

6.1 Experimental method

In this research, PET-PET core-spun thread with three different count and nine lubricant amounts (0-7%) are used for the experiment. Silicone lubricated threads are obtained from company AMANN .The properties of sewing thread are shows in Table 11 and the properties of fabric used for the sewing process are shown in Table 2.

Table 11 Sewing thread used for the experiments

Thread type	Company name/product name	Fineness [tex]	Twist (t/m)	Twist direction (ply/single)
Polyester–polyester core spun	AMANN/Saba C-80	40(20*2)	660	Z/S
Polyester–polyester core spun	AMANN/Saba C-50	60(30*2)	640	Z/S
Polyester–polyester core spun	AMANN/Saba C-35	80(40*2)	534	Z/S

6.1.1 Sewing thread friction testing

All sewing thread friction properties are tested before the sewing process. Thread to metal coefficient of friction is measured for all threads with instrument CTT-LH401 (Company Lawson-Hemphill) according to standard ASTM D-3108 for 100m/min and contact angle of 180^{o}.The measured friction characteristics of sewing thread are shown in Table 12.

Table 12 Thread to metal coefficient of friction

Product name	AMANN/Saba C-35	AMANN/Saba C-50	AMANN/Saba C-80
Thread count	80tex	60tex	40tex
Lubrication amount[%]	µ	µ	**µ**
0	0.29	0.19	0.14
1.6	0.26	0.17	0.12
2	0.25	0.16	0.12
3	0.21	0.16	0.11
3.5	0.21	0.15	0.11
4	0.2	0.15	0.11
4.5	0.2	0.15	0.11
5	0.19	0.14	0.10
7	0.16	0.13	0.10

6.1.2 Needle temperature measurement

The inserted thermocouple method is used for measuring the needle temperature during the sewing process. Lockstitch machine (Brother Company, DD7100-905).Needles (Groz-Becker 100Nm for Saba C-80 and C-60, 110Nm for Saba C-40) are used for the sewing. Needle temperature is measured 5 times each for each threads and the results are statistically analysed. Maximum sewing time was 15 seconds for different speeds of sewing process. The stitch length was kept constant at 5 stitches/cm.

6.1.3 Tensile properties measurement

The breaking tenacity and elongation values of the sewing thread are measured using INSTRON Tensile strength tester according to standard ASTM 2256 [66]. All sewing threads with different amount of lubricant are tested before sewing and after sewing process, the sewing thread is carefully removed from the seam by cutting the bobbin thread. Each thread is measured 10 times each for all speeds of sewing.

6.1.4 Experimental design

A Box–Behnken experimental design (constructed using Minitab 16) was used to evaluate the effects of the selected independent variables on the response. The number of experiments required to investigate the previously noted three factors at three levels would be 27. However, this was reduced to 15 by using a Box–Behnken experimental design as shown in table 14. The results from this limited number of experiments provided a statistical model, which can help to find the optimum experimental conditions and the relationships between experimental results and parameters. The significant variables like stitch, speed of sewing, layer of fabric, and the time were chosen as the critical variables and designated as X_1, X_2 and X_3, respectively. The low, middle, and high levels of each variable were designated as −1, 0, and +1, respectively, as shown in Table 13-14.

Table 13 Factors and factor levels studied in Box-Behnken experimental design

Factors	Levels		
	-1	0	1
X_1=Sewing speed [r/min]	2000	3000	4000
X_2= Lubricant amount [%]	0	3.5	7
X_3=Thread count [tex]	40	60	80

Table 14 The design of the experiment

Trial No.	X1	X2	X3
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1

6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

6.2 Results

6.2.1 Effect of lubricant amount on Coefficient of friction

The yarn /metal friction is tested on instrument CTT-LH401 (Company Lawson-Hemphill) according to standard ASTM D-3108 for 100m/min and contact angle of 180^{o}.It is observed that coefficient of friction decreases with the increase in lubricant amount. There is nearly 35% decrease in coefficient of friction when the lubricant amount is 7%. The lubricant improves the surface finish which causes the decrease of friction between yarn and the metal object. Lubrication is intended to decrease yarn to metal friction. In recent publication, it was reported that the amount of lubricant used have a profound effect on friction properties [37, 38, 63, 64]. Sewing thread lubricant always contains silicon, because silicon provides the heat protection and friction reduction in sewing threads. It is accepted that silicones are poor conductor of heat but good release agent and causes reduction in friction [37]. Figure 32 shows the effect of lubricant amount on the friction coefficient of sewing threads. The increase in the lubricant amount causes decrease in metal to yarn coefficient of friction, this effect is already known and these results are further used to examine the effect of decrease on in coefficient of friction on the needle temperature.

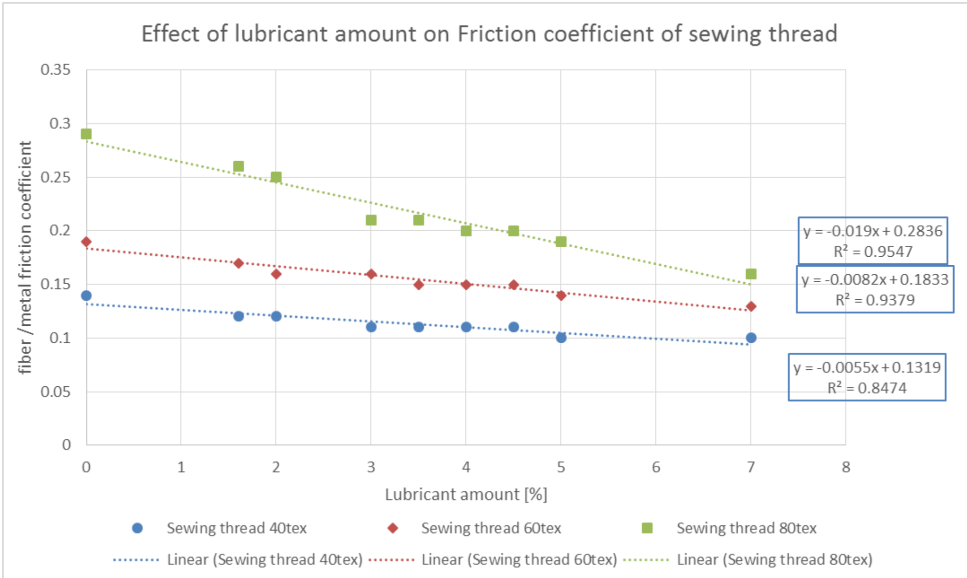

Figure 32 Effect of lubricant amount on coefficient of friction

6.2.2 Effect of lubricant amount on sewing needle temperature

The lubricant causes the reduction in yarn to metal friction (as shown in Figure 32).This reduction in friction causes needle temperature to decrease. Figures 33-35 shows the needle temperature at different speeds of sewing from 1000 r/min to 4000 r/min, Continuous stitching is performed for 15seconds with all sewing thread for 5 times respectively.

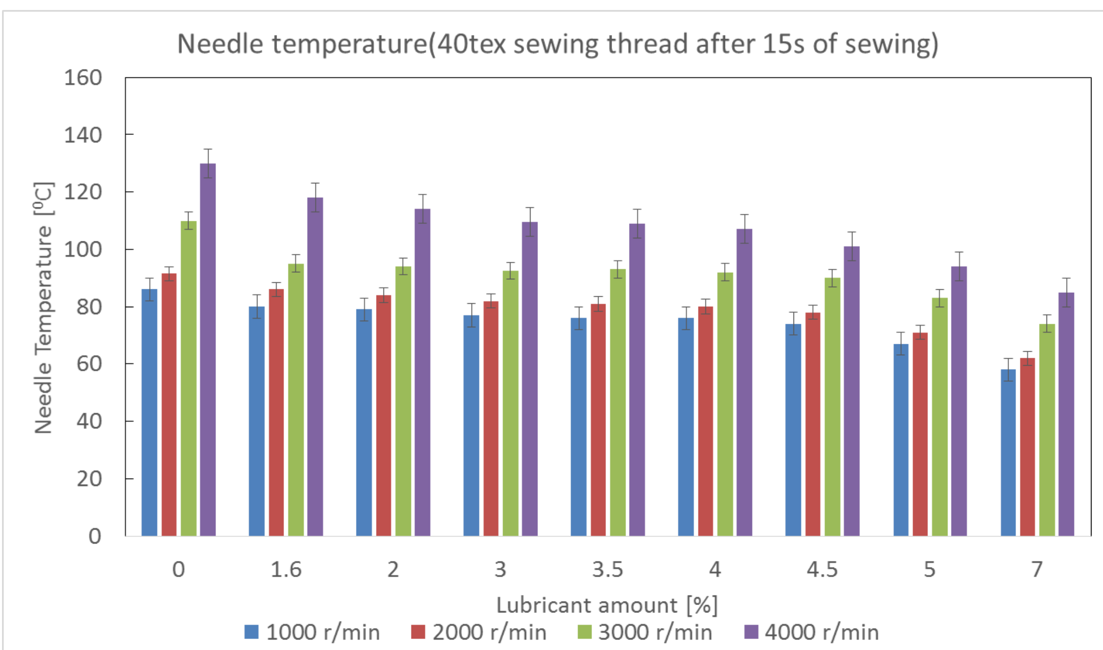

Figure 33 Needle temperature at different speeds of sewing (40tex thread with different amount of lubricant)

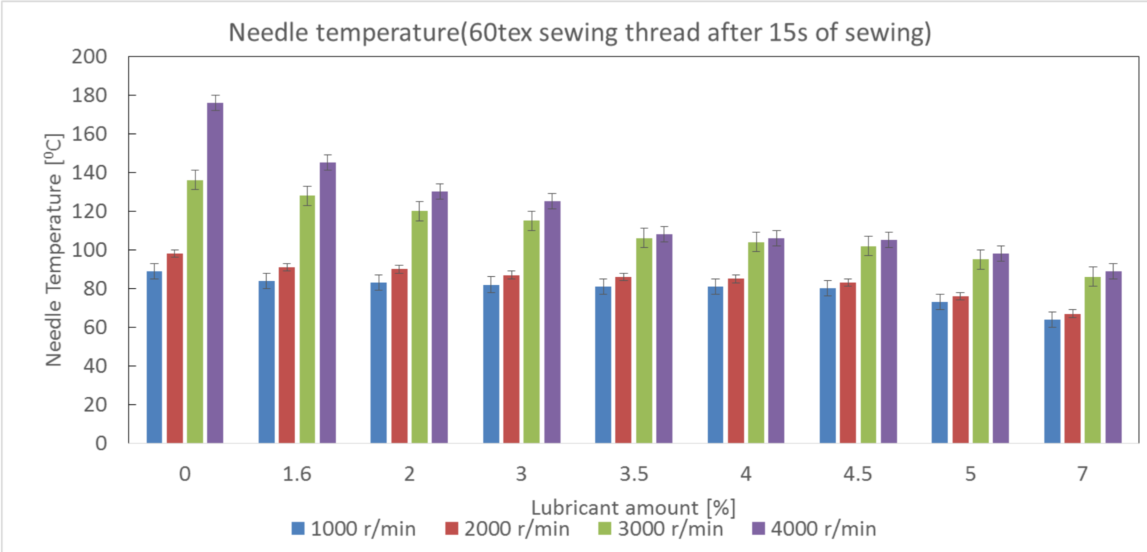

Figure 34 .Needle temperature at different speeds of sewing (60tex thread with different amount of lubricant)

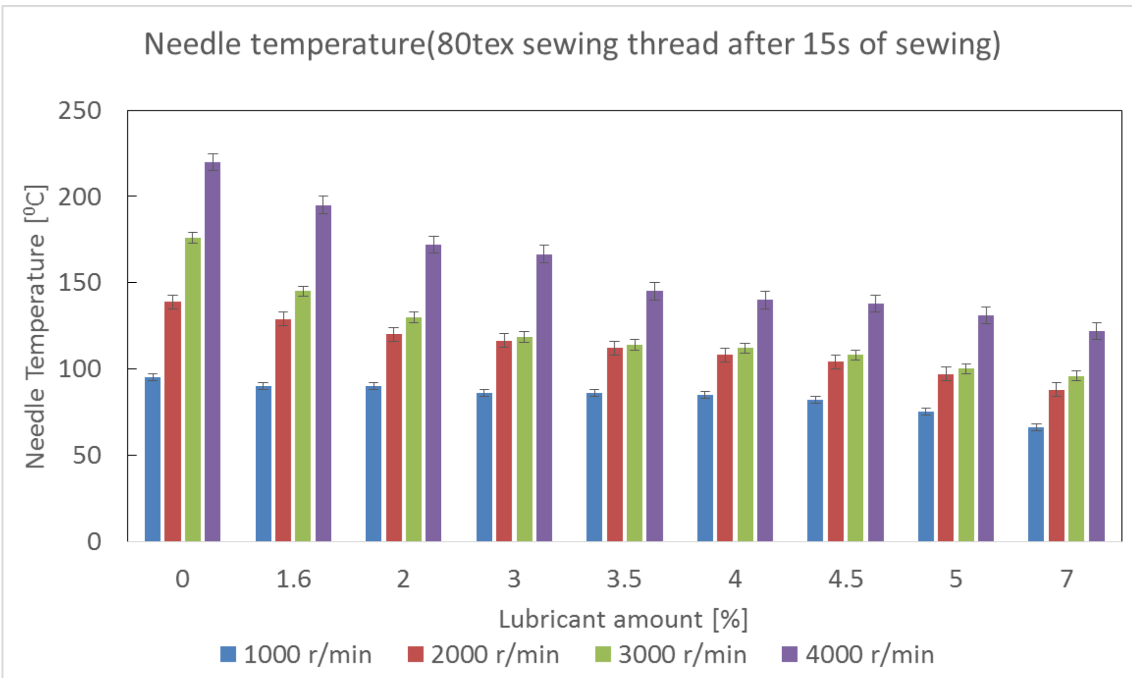

Figure 35 Needle temperature at different speeds of sewing (80tex thread with different amount of lubricant)

As shown in the Figure 33-35, the sewing needle temperature decreases with the higher amount of lubricant. It is also visible that the sewing needle temperature rises with the higher speed of sewing and higher count of sewing thread. Needle temperature decreases linearly with the increase of lubricant amount, there is nearly 30% reduction in needle temperature when lubricant amount is 7% as compared to needle temperature of sewing thread without lubricant. This reduction of needle temperature is very important for heavy industry sewing where sewing speed is higher than 3000 r/min. The use of lubricant decreases the needle temperature and can increase productivity of sewing industries.

6.2.3 Effect of lubricant amount on sewing thread breaking tenacity

The tensile properties of sewing threads are the key parameter at sewing floor is. In our research we measured the breaking tenacity and elongation at break of the sewing thread using INSTRON Tensile strength tester according to standard ASTM 2256 [66]. All sewing threads with different amount of lubricant are tested before sewing and after sewing process, the stitched thread is carefully removed from the seam by cutting the bobbin thread for tensile testing. Each thread is measured 10 times each for all speeds of sewing respectively. Figure 36 shows the effect of lubricant amount on breaking tenacity of sewing thread before sewing.

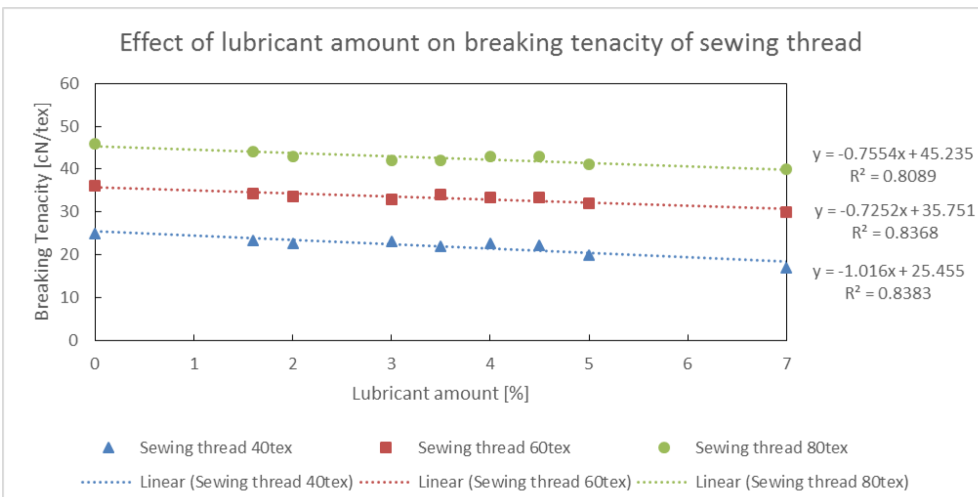

Figure 36 Effect of lubricant amount on breaking tenacity of sewing thread (before sewing).

It is visible that breaking tenacity decreases with the amount of lubricant. As the lubricant might penetrates inside the yarn, it might decreases the fiber to fiber friction and make it slippery for the fibers to hold each other. As shown in figure 36 the breaking tenacity of thread is decreases by nearly 4-7% when the lubricant amount is 7%.There is a linear decrease in breaking tenacity of thread for all thread counts with increase of lubricant amount.

6.2.4 Feasible (optimum) conditions of sewing

In a system involving three significant independent variables X_1, X_2 and X_3 the mathematical relationship of the response on these variables can be approximated by the quadratic polynomial equation:

$$\mathbf{Y=\alpha_0+\alpha_1x_1+\ \alpha_2x_2+\ \alpha_3x_{3+}\ \alpha_{11}x_1^2+\ \alpha_{22}x_2^2\ \alpha_{33}x_3^2+\ \alpha_{12}x_1x_2\ +\ \alpha_{13}x_1x_{3+}\ \alpha_{23}x_2x_3\ +\alpha_4x_1x_2x_3} \quad (6.1)$$

Where:

Y is estimate response, α_0 is constant, α_1, α_2, and α_3 are linear coefficients, α_{12}, α_{13}, and α_{23} are interaction coefficients between the three factors, α_{11}, α_{22}, and α_{33} are quadratic coefficients.

In this model given in equation (6.1), a multiple regression analysis is done for Thread tenacity, needle temperature and extension at break to obtain the coefficients, and the equation can be used to predict the response.

Breaking tenacity

$$\mathbf{Y = 30.54-0.002X_1-0.16X_2+0.118X_3-0.174X_2^2+0.0001X_1X_2+0.005\ X_2X_3} \quad (6.2)$$

Where;

Y= Breaking tenacity [cN/tex]

X_1=Sewing speed [r/min]

X_2= Lubricant amount [%]

X_3= Thread count [tex]

Adjusted R^2=0.976 and P-value=1.24*10-24 ≈ 0

Needle temperature

$$\mathbf{Y = =-45.1+0.049X_1+14.21X_2+0.48X_3-0.004X_1X_2\ -0.164X_2X_3} \quad (6.3)$$

Where;

Y= Needle temperature [°C]

Adjusted R^2= 0.98 and P-value≈ 0

Extension at break

$$\mathbf{Y=9.17-0.0009X_1+0.826X_2+0.3117X_3-0.076X_2^2-0.0017X_3^2-0.015X_2X_3-0.0001X_1X_2} \quad (6.4)$$

Where;

Y= Extension at break [%]

Adjusted R^2= 0.945 and P-value ≈ 0

A contour plot is a graphical technique for representing a 3-dimensional surface by plotting constant z slices, called contours, on a 2-dimensional format. The effect of lubricant amount on needle temperature, tenacity and breaking extension of sewing thread is plotted as contour lines, which are laid one above each other to determine the feasible region of sewing process and lubricant amount.

Figure 37-39 shows the contour plots of needle temperature, breaking tenacity and extension at break of stitched thread laid one above each other. This graphical representation shows the effect of lubricant amount and sewing speed on needle temperature, thread tenacity and extension at break. It is visible from the contour plots that it's not economical to use lubricant if sewing speed is less than 2000r/min, whereas for sewing speed of 2500r/min and higher the most feasible region of sewing is for lubricant amount of 2-4%(feasible region of sewing is shown by purple colour lines in contour plots).The higher amount of lubricant decreases the needle temperature and thread tenacity. To obtain highest tensile properties and maximum sewing speed it is recommended to use 2-4% of lubricant amount, but if it's necessary to achieve lower needle temperature due to synthetic fabrics then lubricant amount of more than 3% can be used. The effect is same for all three counts of PET-PET cores-pun thread.

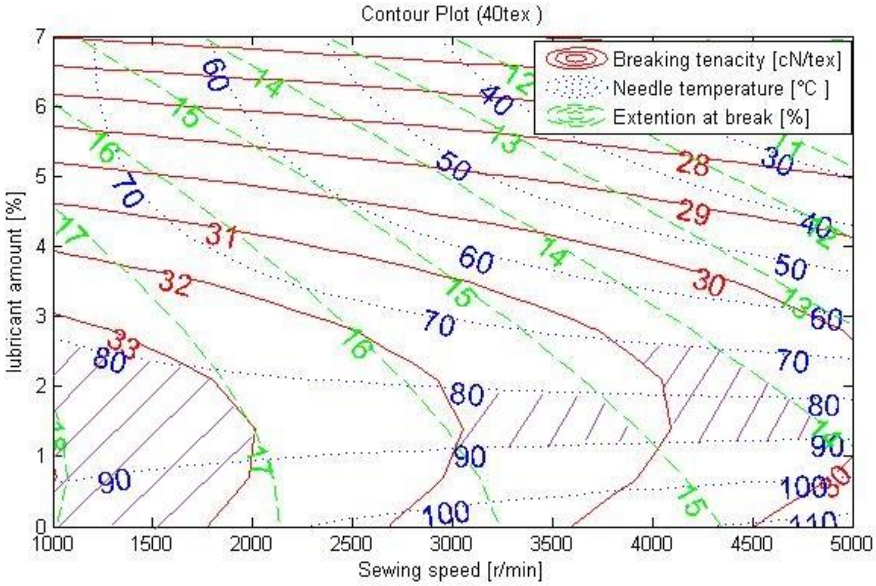

Figure 37 Effect of lubricant amount and sewing speed on needle temperature, tenacity and breaking extension of sewing thread (40 tex)

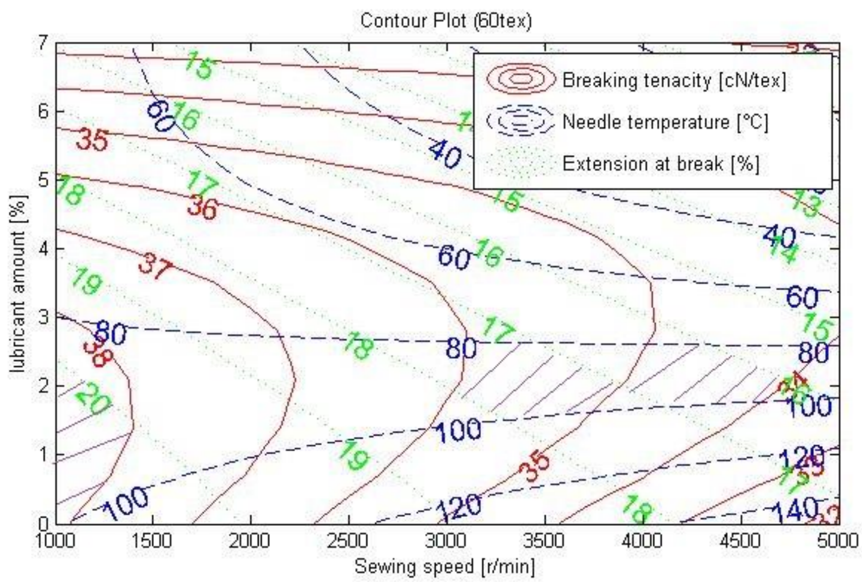

Figure 38 Effect of lubricant amount and sewing speed on needle temperature, tenacity and breaking extension of sewing thread (60 tex)

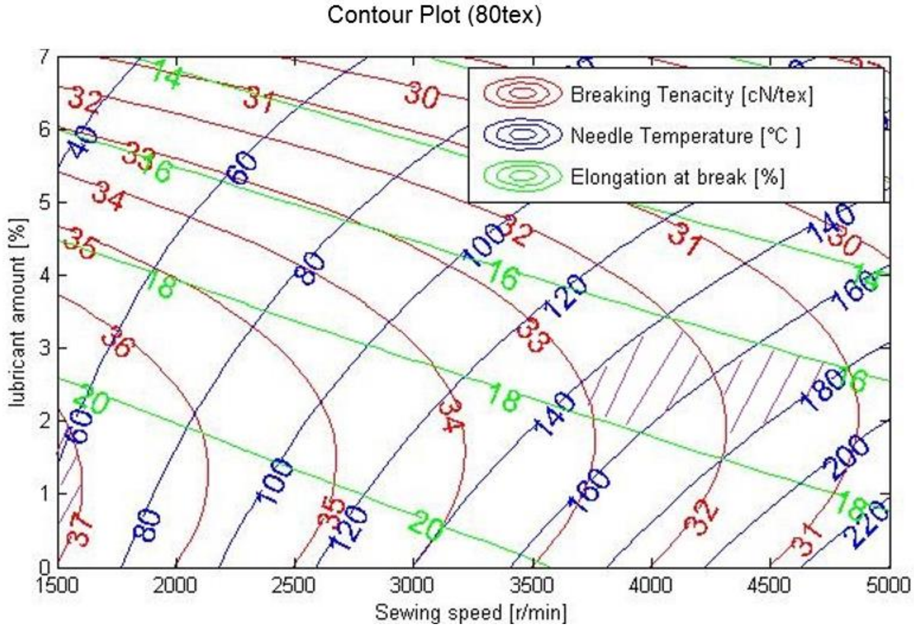

Figure 39 Effect of lubricant amount and sewing speed on needle temperature, tenacity and breaking extension of sewing thread (80 tex)

Figure 40-41 shows the SEM images of 80tex (Saba-C35) lubricated and non-lubricated thread after 4000 r/min of sewing speed. The lubricated thread fibers are more intact with the thread body whereas the non-lubricated thread shows broken and protruding fibers.

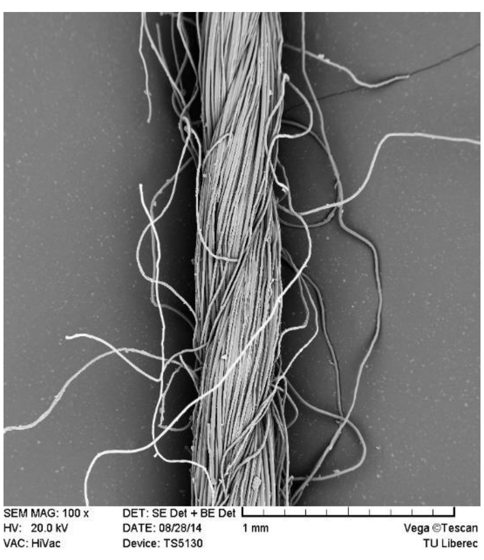

Figure 40 Saba c-35 with 0% lubricant

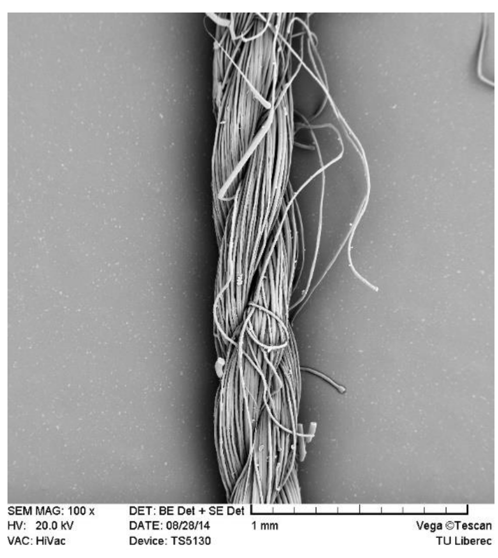

Figure 41 Saba c-35 with 4% lubricant

6.3 Summary

Lubricants are mainly used for reduction of coefficient of friction for sewing thread. It is true that the coefficient of friction of sewing threads and needle temperature decreases with the increase of lubricant amount, It might be possible that higher amount of lubricant decrease the friction between fiber to fiber inside the thread, this slippery condition between fiber to fiber causes the decrease of breaking tenacity of sewing thread.

In this work, it is visible that there is minor decrease in breaking tenacity of stitched thread with the addition of lubricant for sewing speeds till 2500r/min. From economical point of view it's not wise to use lubricant if sewing speed is less than 2000r/min whereas for sewing speed of 2500r/min and higher the most feasible condition of sewing is for lubricant amount of 2-4%.The needle temperature is less than 130°C at this sewing speed and has insignificant effect on the sewing thread.

It is advised to use the lubricant when sewing speed is 2500r/min and higher. The higher amount of lubricant decreases the needle temperature and thread tenacity .To obtain highest tensile properties and maximum sewing speed it is recommended to use 2-4% of lubricant amount, but if it's necessary to achieve lower needle temperature due to synthetic fabrics then lubricant amount of more than 3% can be used.

It is observed that coefficient of friction decreases with the increase in lubricant amount. There is nearly 35% decrease in coefficient of friction when the lubricant amount is 7%.

Needle temperature decreases linearly with the increase of lubricant amount, there is nearly 30% reduction in needle temperature when lubricant amount is 7% as compared to needle temperature without lubricant on sewing thread.

Chapter 7. Effect of needle temperature on tensile properties of sewing thread

The mechanical properties of the thread are very important for its performance and durability. Machine stoppage due to thread breakage, rework due to poor sewing thread can greatly increase the production cost. Since very high strain are imposed on the thread during the high-speed sewing on modern machines, sewing thread requires high elasticity and for satisfactory performance [42]. The mechanical performance of threads is governed by the properties of constituent fibres and their arrangement. In the course of tensile loading the tension induced by applied strain is transferred to the fibres through the interfacial shear stress, which leads to substantial changes in the yarn structure and fibre mechanical properties [58]. The friction, bending, and compression during the sewing process cause damage/pull-out of surface fibres resulting in a loss in mechanical properties. Heating of the needle cause synthetic fibres to soften or melt, leaving a weakened thread after sewing. The majority of these loadings are cyclic by nature and therefore cause the fibre fatigue [59, 60].

In our research rather than just measuring the seam strength or the thread strength in the seam, we sectioned the sewing thread in 4 section after sewing and measured the tensile properties of each section, each section different amount of abrasion and from thread cone till becoming part of the seam, whereas the last 2 section gets abrasion through guides and also acquire the needle heat.

7.1 Stages of sewing thread for tensile properties measurement

The sewing thread was divided in to four sections as shown in Figure 42.For tensile testing of sewing thread Instron tensile tester as per ASTM standard D2256 [66] was used. Tensile testing of the parent thread corresponds to that of section S1. For tensile testing of thread in zone S2, 250 mm length of thread from mark A towards G2 is mounted in the jaws. For tensile testing of thread in zone S3, a length of 250 mm from mark **A** towards point **B** is mounted in the jaws. A sufficient length of thread was removed from the seam for gripping in the lower jaw. Whereas section S4 thread is pulled out precisely from the seam by cutting the bobbin thread.30 samples of each section (S1, S2, S3, S4) are tested for tensile properties at each speed of machine respectively. Details of the figure 42 is as below

S1- same as parent thread.
G1 to G6- guides for thread.
T1 toT3- Tension devices.
S2 –Section of thread from A towards point G1
S3 –Section of thread from Point A towards point B.
PointA-12cm from needle eye.
Point B-22cm from needle eye in the seam.
S4 –Thread in the seam (pulled out precisely by cutting the bobbin thread)
The change (%) of tensile properties at different stages is calculated by following expression.

$$Change\ (\%) = \frac{Tn - T1}{T1} * 100 \qquad (7.1)$$

Where T_n is the tensile property at different sewing stages, with n = 2, 3, and 4 corresponding to sewing stage S2, S3, and S4 respectively. T1 is the tensile property of the parent thread, at sewing stage S1. Negative (–) change (%) indicates the loss in tensile property.

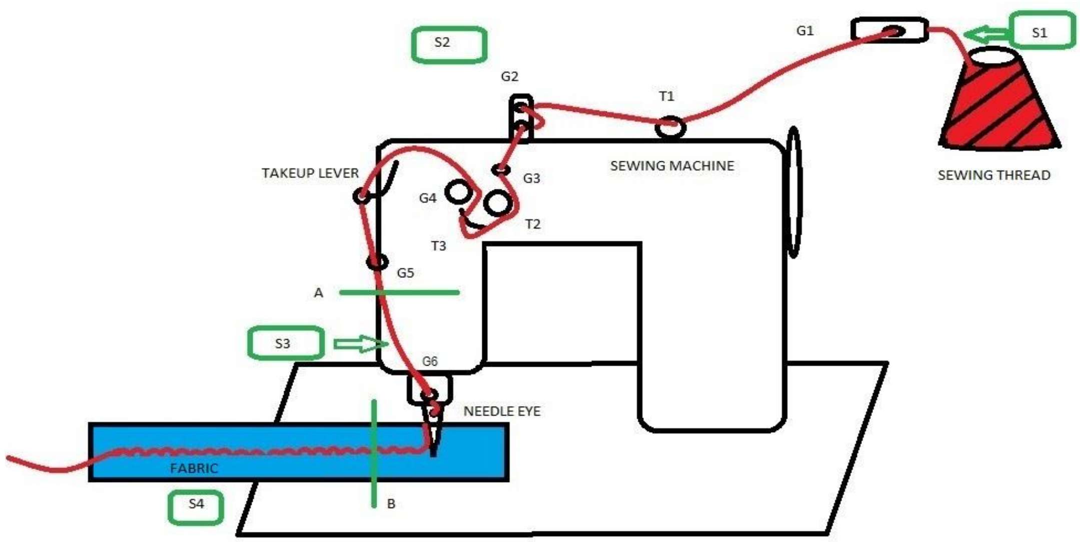

Figure 42 passage of sewing thread through the sewing machine

7.2 Effect of needle temperature at section S3

Section S3 thread undergoes maximum needle heat after machine stoppage as thread is indirect contact with the hot needle. Tenacity of thread is more affected for higher count thread (Saba C-35) as the needle temperature is higher with higher count threads. Figure 43 shows the needle temperature and tenacity of thread at section S3 for different speeds of sewing, it shows that needle temperature is causing a great damage to the sewing thread tensile property. For Saba C-35 the thread decreases tenacity by 78% followed by Saba C-80 which shows 46% decrease in tenacity at 4700 rpm of sewing speed. Saba C-35 is higher count thread and shows higher needle temperature which might be because of higher friction between needle-eye and thread. The graph shows the needle temperature at primary left axis and secondary axis on right side of graph shows the tenacity of both threads at different speed of sewing.

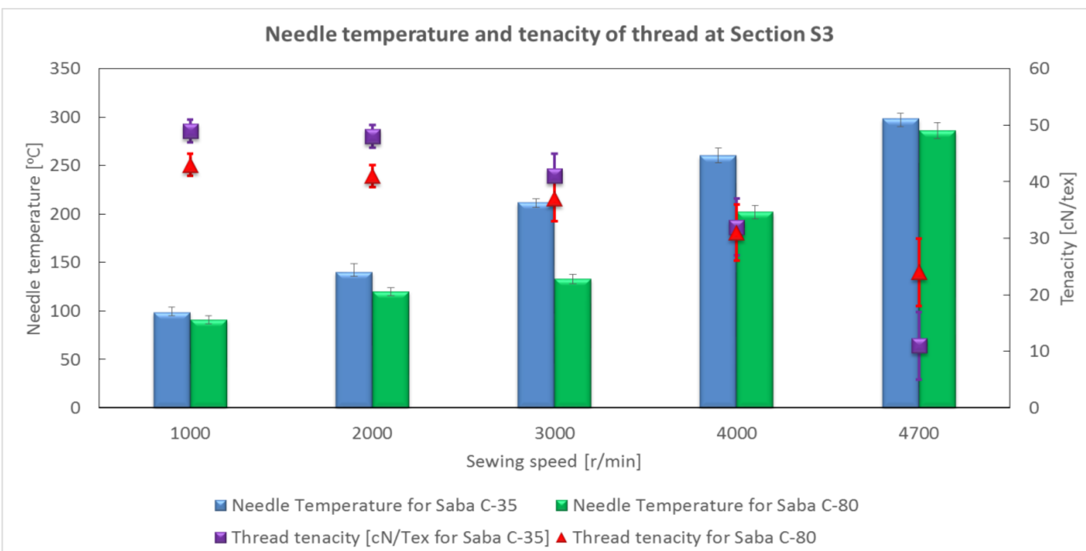

Figure 43 Needle temperatures and tenacity of threads at section S3 for thread Saba C-80

7.3 Effect of sewing speed on thread tensile properties

Table 15 shows the Tenacity, Initial modulus and breaking elongation for the both thread Sabac-35 and Saba c-80 at different speeds of sewing machine and different sections of sewing thread (S1, S2, S3 and S4). Change (%) is calculated according to Equation 7.1 and Table 15 shows that the maximum loss of tensile property is at section S3 where for Sabac-80 thread tenacity is decreased to 46.7% and for Saba c-35 the tenacity is decreased by 78% at 4700 rpm of machine. Thread at section S3 gets maximum needle heat after machine stoppage and cause the biggest change in thread tensile properties.

Breaking elongation [%] property decreased more for Saba C-35 as compared to Saba C-80, but again the impact is maximum at the section S3 where breaking elongation shows 72% decrease for Saba c-35 and 41% for Saba C-80 at 4700 rpm of machine.

Initial modulus of Saba C-80 decreases by 51% as compared to 40% of Saba c-35 at section S3 for 4700 rpm of machine.

Table 15 Mean values of mechanical properties of sewing threads

		Sabac-35 (80Tex)						Sabac-80 (40Tex)				
Property		speed of machine						speed of machine				
		1000 rpm	2000 rpm	3000 rpm	4000 rpm	4700 rpm		1000 rpm	2000 rpm	3000 rpm	4000 rpm	4700 rpm
Tenacity [cN/Tex]	S1	**50**	**50**	**50**	**50**	**50**		**45**	**45**	**45**	**45**	**45**
	S2	**50**	**50**	**48**	**47***	**45***		**45**	**44**	**43***	**43***	**42***
	percentage change with respect to S1[%]	**0**	**0**	**-4**	**-6**	**-10**		**0.0**	**-2.2**	**-4.4**	**-4.4**	**-6.7**
	S3	**49**	**48**	**41***	**32***	**11***		**43**	**41**	**37***	**31***	**24**
	percentage change with respect to S1[%]	**-2**	**-4**	**-18**	**-36**	**-78**		**-4.4**	**-8.9**	**-17.8**	**-31.1**	**-46.7**
	S4	**49**	**48**	**44***	**43***	**41***		**43**	**42**	**40***	**37***	**36***
	percentage change with respect to S1[%]	**-2**	**-4**	**-12**	**-14**	**-18**		**-4.4**	**-6.7**	**-11.1**	**-17.8**	**-20.0**
Breaking Elongation [%]	S1	**18**	**18**	**18**	**18**	**18**		**21**	**21**	**21**	**21**	**21**
	S2	**18**	**17.9**	**17.6**	**17.2**	**17***		**20.8**	**20.4**	**20.1**	**19.2***	**19***
	percentage change with respect to S1[%]	**0.0**	**-0.6**	**-2.2**	**-4.4**	**-5.6**		**-1.0**	**-2.9**	**-4.3**	**-8.6**	**-9.5**
	S3	**17.5**	**17.2***	**13.6***	**12.2***	**5***		**20**	**19.5***	**17.4***	**14.5***	**12.4***

	percentage change with respect to S1[%]	**-2.8**	**-4.4**	**-24.4**	**-32.2**	**-72.2**		**-4.8**	**-7.1**	**-17.1**	**-31.0**	**-41.0**
	S4	**17.6**	**16.2**	**16***	**15.7***	**14.3***		**19.6**	**19***	**18.2***	**17.3***	**16.8***
	percentage change with respect to S1[%]	**-2.2**	**-10.0**	**-11.1**	**-12.8**	**-20.6**		**-6.7**	**-9.5**	**-13.3**	**-17.6**	**-20.0**
Initial Modulus [N/tex]	S1	**4.5**	**4.5**	**4.5**	**4.5**	**4.5**		**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
	S2	**4.5**	**4.45**	**4.4**	**4.5**	**4.35**		**3.2**	**3.15**	**3.183**	**3.1**	**3***
	percentage change with respect to S1[%]	**0.0**	**-1.1**	**-2.2**	**0.0**	**-3.3**		**0.0**	**-1.6**	**-0.5**	**-3.1**	**-6.3**
	S3	**4.4**	**4.3***	**4***	**3.1***	**2.7***		**3.1**	**3.1**	**2.85***	**1.8***	**1.4***
	percentage change with respect to S1[%]	**-2.2**	**-4.4**	**-11.1**	**-31.1**	**-40.0**		**-3.1**	**-3.1**	**-10.9**	**-43.8**	**-56.3**
	S4	**4.4**	**4.4**	**4.2***	**3.6***	**3.3***		**3.1**	**3.1**	**3***	**2.2***	**2.1***
	percentage change with respect to S1[%]	**-2.2**	**-2.2**	**-6.7**	**-20.0**	**-26.7**		**-3.1**	**-3.1**	**-6.3**	**-31.3**	**-34.4**

* *The significant difference of means at a 95% confidence interval from stage S1*

7.4 Sewing speed, needle temperature and tenacity of sewing thread

Figure 44 shows that there is a strong linear relation between needle temperature and speed of machine, experimental result also shows a strong negative linear relationship between speed of machine and tenacity of sewing thread, at 4700 rpm of machine the sewing thread exhibit nearly 50% decrease in tenacity.

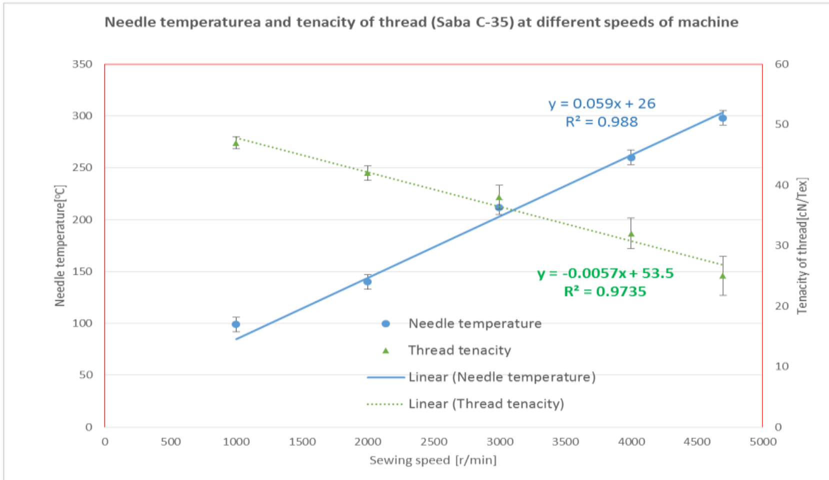

Figure 44 Needle temperature and Tenacity of sewing thread

Figure 45 shows the images of sewing thread (Saba c-35) after continuous sewing of 15 seconds for different sewing speeds, the melted fibers can be easily seen In the SEM image of sewing speed of 4700r/min.

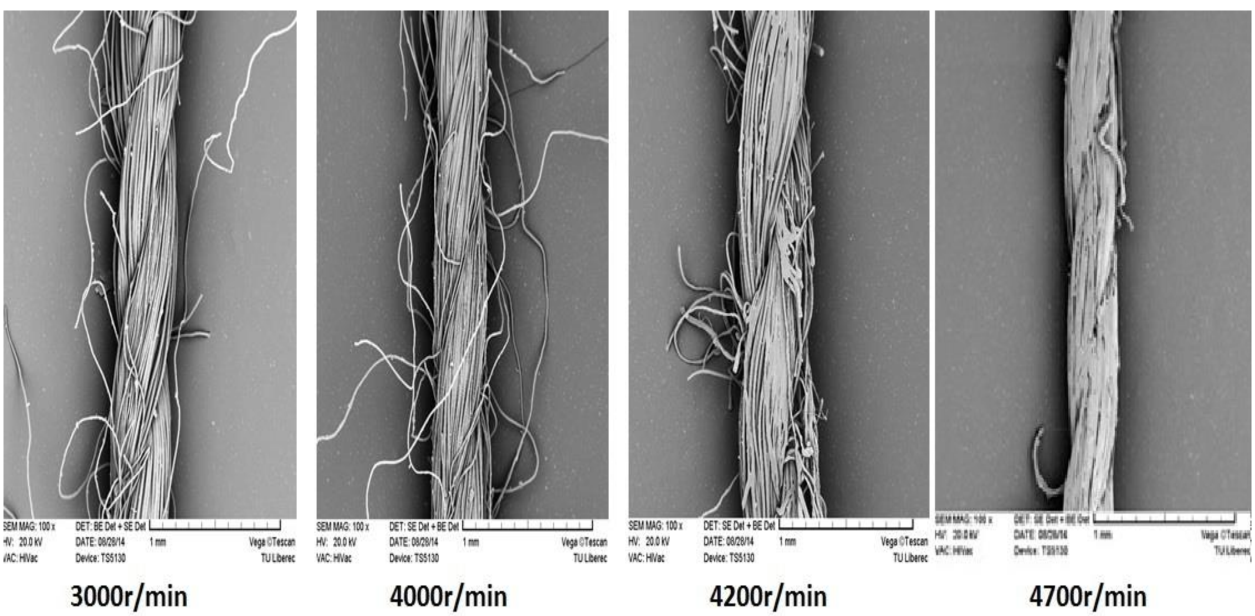

Figure 45 SEM images of sewing thread (Saba c-35) at different machine speeds at S3

7.5 Summary

This research shows that needle temperature has a dominant influence on the strength of sewing thread, the hot needle mainly damages the thread when the machine stops after sewing and needle is in direct contact with the thread. This needle-heat damaged thread eventually becomes part of the next seam and causes loss in seam strength. It is recommended to waste 20 cm of the thread after one complete sewing, so that the thread damaged at the needle eye after machine stoppage should not be part of the next seam.

As thread moves from cone to the seam, it undergoes various stresses and strain such as dynamic stress at section S2, there is a marginal decrease in tensile strength for thread at 1000 and 2000 r/m of machine, whereas loss of tensile strength of thread is much significant from 3000 r/m of machine and higher.

Bobbin thread interaction and needle heat are the two main causes of reduction of tensile strength, breaking elongation and initial modulus of thread. The loss was greater for Saba C-35(80 tex) polyester core spun thread followed by Saba C-80(40 tex) thread (see Table 15). Which can be because of higher friction between needle and thicker thread and causing needle temperature to increase. Needle temperature is nearly 20 ^{o}C higher for Saba C-35 for all observations as compared to Saba C-80.

Thread at section S3 gets maximum needle heat after machine stoppage and cause the biggest change in thread tensile properties. That is why this section thread exhibit the maximum loss of tensile property. For Sabac-80 thread tenacity is decreased to 46.7% and for Saba C-35 the tenacity is decreased by 78% at 4700 rpm of machine. Breaking elongation decreased more for Saba C-35 as compared to Saba C-80, but again the impact is maximum at the section S3 where breaking elongation shows 72% decrease for Saba c-35 and 41% for Saba C-80 at 4700 rpm of machine. Initial modulus of Saba C-80 decreases by 51% as compared to 40% of Saba c-35 at section S3 for 4700 rpm of machine.

Section S4 thread is the seam thread, pulled out precisely by cutting the bobbin thread. In this section the loss of tensile strength is mainly due to bobbin thread interaction and friction of guides and tension devices on machine, but due to high speed of machine the contact time between thread and needle is much less to impact. That is why the thread at section S4 shows higher tensile properties as compared to section S3.

Chapter 8. DLC coating of sewing needles

DLC (Diamond like Carbon) coating possesses a small friction coefficient and high wear resistance. Therefore they have been used to improve the service characteristics of various metal parts [67]. In this research we coated the needles with DLC to examine the sewing performance which includes needle temperature and tensile properties of stitched sewing thread. Diamond-like carbon (DLC) coating is widely used because of its good tribological characteristics and aesthetic value [67]. Tribology consists of three parts, i.e., friction, wear, and lubrication. DLC can be used as a solid lubricant. Some parts cannot be lubricated by wet lubricants; therefore, DLC can be useful on specific applications, such as food processing, chemical pumps, biological applications, space technology and hard disks [68]. Most modern mechanical systems are operated under high loads, high temperature, and corrosive environment [69]. DLC-coated machine parts can be operated under high load, high temperature (close to 400^{o}C), and under corrosive environment. DLC coating is also becoming commercially attractive because of some of its inherent properties, such as low friction, high wear resistance, and high hardness. In mechanical systems, low friction signifies highly efficient system, which consumes lower energy. Therefore, various studies have been performed in different mechanical components, such as automotive valve train application [70, 71], bearings, [72] gears, [73, 74] piston rings, [75, 76] piston pins, direct-injection fuel systems, and cutting and forming tools [77], these components can be coated with DLC.

8.1 Experimental part

In this research, Needles (100Nm) are coated with DLC layer by radio frequency plasma assisted chemical vapour deposition/magnetron sputtering (RF/PACVD/MS) method. The coated needles are further compared with the non-coated needles in terms of needle temperature during sewing, surface roughness and sewing performance.

8.1.1 DLC coating of sewing needles

During the last 20 years DLC coatings became a very attractive material in many industrial application. In our research we coated the needles (Grozbeckert-100Nm, R type)using RF/PAVCD/MS method .The system consists of a cylindrical chamber 290mm in diameter and 190mm high, with water cooled bottom electrode connected through a impedance matching network to the radio frequency of 13.56 MHz power generator. The magnetron equipped with 50mm Ti-cathode is mounted in the chamber top cover. The parameters and steps of sample preparation are as below.

Sample cleaning: The specimens (needles) were ultrasonically cleaned in methanol for 20 min before deposition. The base pressure of the reaction chamber is kept less than 10^{-3} Pa.

Etching: The samples mounted on R.F electrode are etched in argon plasma for 10min at self-bias voltage = - 500 V, pressure = 4 Pa and Argon gas flow rate of 10sccm.

Deposition of Ti coating: Firstly the Ti layer is deposited by DC magnetron sputtering for 5 min with pressure of 1.2 Pa, self-bias voltage of - 300 V, flow rate of Ar. was 10sccm and power on Ti sputtered target was 1025 W

Deposition of DLC coating: The DLC layer synthesis is conducted by RF/PACVD process for 20 min with methane gas at a constant flow rate of 20sccm, pressure of 20 Pa and self-bias voltage of - 600 V.

Figure 46 shows the needle after DLC coating. The needle colour changes to greyish-black due to DLC-layer.

Figure 46 Needle after DLC coating

8.1.2 Needle temperature measurement

Thermal camera is used to record the needle temperature during high speed sewing. The emissivity of the needle was calculated by ASTM standard E 1933 – 99a and found to be 0.71 for a DLC-coated needle at 37^{o}C. Lockstitch machine (Brother Company, DD7100-905) is run at high speed of 3000 and 4000r/min and needle temperature is measured with thermal camera (FLIR X6450), whereas the needle temperature of non-coated needles is measured by inserted thermocouple method, as its difficult to find the emissivity of shinny chromium needle. In this research, PET-PET core-spun thread with two different counts is used for the experiment. The properties of sewing thread are shows in Table 16. The properties of denim fabric used for the sewing process are shown in Table 2.

Table 16 Sewing thread used for the experiments

Thread type	Company name/product name	Fineness [tex]	Twist (t/m)	Twist direction (ply/single)	Coefficient of friction μ
Polyester–polyester core spun	AMANN/Saba C-80	40(20*2)	660	Z/S	0.20
Polyester–polyester core spun	AMANN/Saba C-50	60(30*2)	640	Z/S	0.23

8.1.3 Tensile properties measurement

The breaking tenacity and elongation values of the sewing thread are measured using INSTRON Tensile strength tester according to standard ISO 2256. Tensile properties of all sewing threads are tested before sewing and after sewing process, the sewing thread is carefully removed from the seam by cutting the bobbin thread. Each thread is measured 10 times each for all speeds of sewing respectively. This experiment is necessary to compare the effect of normal and DLC-coated needle on the sewing threads after sewing process.

8.2 Results and discussion

8.2.1 Comparison of sewing needle temperature

The industrial lock stitch machine is run at speed of 3000 and 4000r/min for 15 seconds and needle temperature of DLC-coated needles is measured using thermal camera and inserted thermocouple method for the non-coated needles .It was observed that the needle temperature is 12^{o}C higher for normal needles as compared to coated needles 40tex thread 8^{o}C higher for 60tex thread; this effect is insignificant (calculated at 95%confidence interval). The low surface roughness and friction properties of DLC-coated needles causes a decrease in the frictional heat between needle and the fabric but it's impossible to determine the surface properties of inside part of needle's eye, which is the major contact for the thread to the needle. The diamond polish is the final step of DLC coated needles for better smooth surface, but in case of the needle it’s impossible to polish the inside of needle eye due to complex and small shape.

8.2.2 Comparison of Tensile properties for DLC-coated and normal needles

Tensile properties of all sewing threads are tested before sewing and after sewing process. Sewing process is performed for 15 seconds and sewing thread is carefully removed from the seam by cutting the bobbin thread. Each thread is measured 10 times each for all thread types respectively. This experiment is necessary to compare normal and DLC-coated needle for the effect of needle temperature and friction on tensile properties of sewing thread. It is visible in Figure 47-48 that there is a minor increase in tensile properties of sewing thread with DLC-coated needles as compared to normal needles. This is due to low friction properties of sewing needle coated with DLC which reduces the frictional heat.

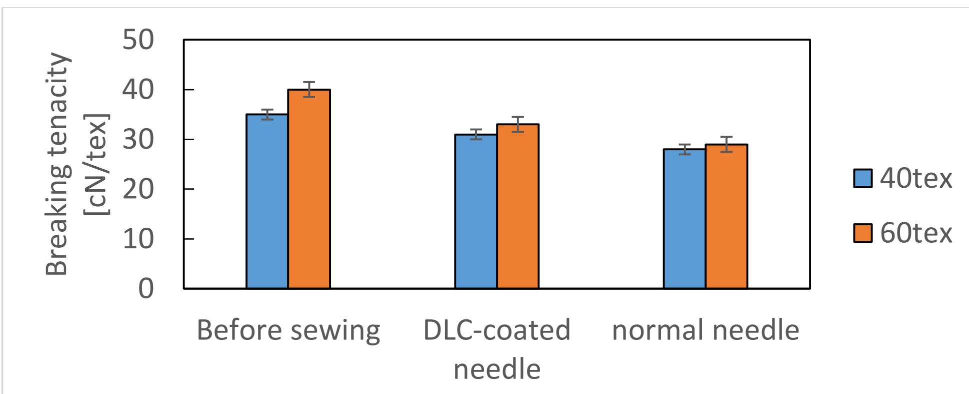

Figure 47 Comparison of breaking tenacity of sewing threads.

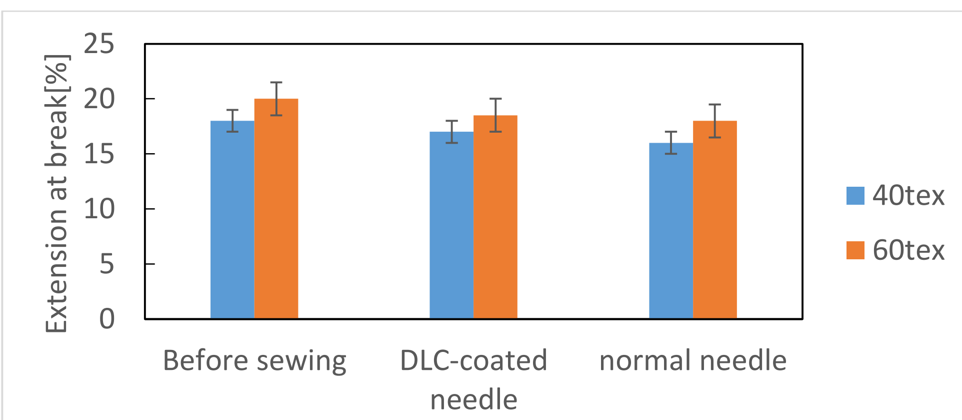

Figure 48 Comparison of breaking extension of sewing threads.

8.2.3 Surface properties of needle

The DLC thickness was measured using Scanning Electron Microscopy (SEM) and found to be 960nm, whereas the Ti-gradient layer was found to be nearly 150nm. The results (Table 17) obtained from the Atomic Force Microscopy (AFM) shows that DLC-coated needles exhibit less average roughness parameters as compared to normal needles.

Table 17 Surface properties by AFM

	Normal needle	DLC-coated needle
Average roughness R_a	689.6 nm	657.7 nm
RMS roughness R_q	802.6 nm	763.2 nm
Peak to valley roughness R_t	3.864 µm	3.837 µm

Figure 49-52 shows the surface topography of normal needle and DLC-coated needle surface by AFM. DLC-coated needles shows better roughness property as compared to normal needles by AFM measurement. The heat is generated in needle due to friction of fabric to needle surface and secondly by the rubbing of sewing thread to the needle eye. The better roughness properties of needle causes decrease in the needle temperature.

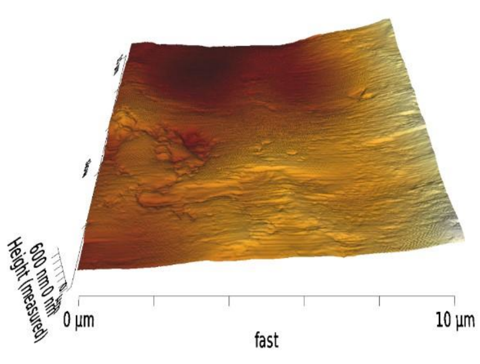

Figure 49 Surface image DLC coated needle (10*10 µm)

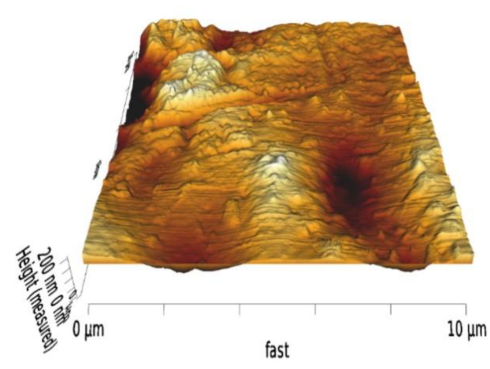

Figure 50 Surface image uncoated needle (10*10 µm)

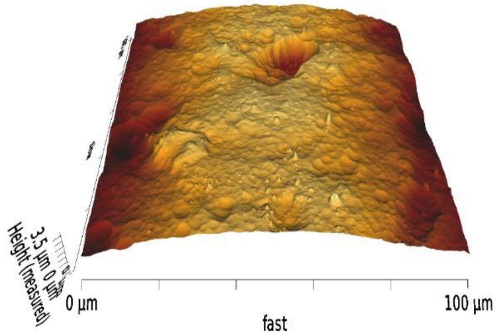

Figure 51 Surface image uncoated needle (100*100 µm)

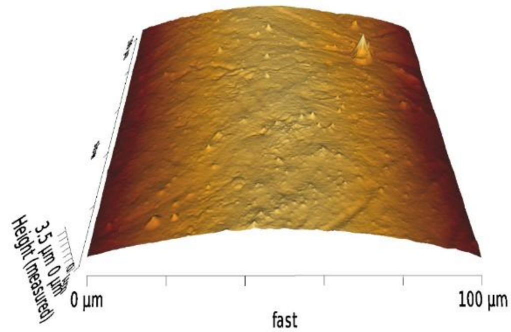

Figure 52 Surface image DLC coated needle (100*100 µm)

8.3 Summary

DLC-coating is getting popular rapidly while its use in textile industry is still unknown. From our research we conclude that;

It's possible to cover the needle with DLC coating but the needle eye complex shape make it impossible to determine if the coating is evenly applied at the inside part of the needle's eye. DLC-coated needles along length shows better roughness property as compared to normal needles by AFM measurement. Diamond polish is also important step in bringing better surface properties of martial but the needle eye due to complex shape was not possible to be diamond polished. There was a small improvement noted in terms of tensile properties and needle temperature for DLC coated needles.

Chapter 9. Theoretical Model

Analytical models offer simplicity and less computational demands with reasonable accuracy, on the other hand, numerical simulation gives better accuracy but is complicated and time consuming. In this study, unlike the previous models, two sources of frictional heating have been considered as a general case. The two sources are one due to contact friction between the needle surface with fabric and the other due to the contact friction between the inner edge of the needle's eye and the sewing thread.

In this model, the following assumptions are used:

- Needle, sewing thread and fabric are all at room temperature T_i initially before the sewing starts.
- The needle has uniform material properties throughout its length and can be assumed as a cylinder
- The thermal conductivity of needle material λ_n is much higher than the thermal conductivity of the sewing thread λ_y as well as than the thermal conductivity of the fabric λ_F. Here it is implicitly assumed that both the yarn and fabric can be assumed to have lumped thermal properties, i.e., each has uniform thermal conductivities, represented by single values.
- Since the total needle surface area is small, radiation heat loss is neglected.
- In this model, it is approximated that the friction heat is given as $\boldsymbol{Q = F.v}$ [1] where F is friction force and v is the relative velocity of the rubbing surfaces. The needle gains heat energy due to frictional rubbing with the fabric. The needle also gains heat due to frictional rubbing between the sewing thread and the needle eye.
- In case of the heat generated due to frictional rubbing between two materials, part of the generated heat will go to one and the rest will go to the other material. Here it is assumed that there is no other way of heat loss at the points of friction. A partition ratio, γ is considered to calculate the heat distribution between the rubbing

surfaces. In this study, the partition ratio is calculated using the Charron's relation [80] as

$$\boldsymbol{\gamma = \frac{1}{1+\xi_N}} \qquad (9.0)$$

Where $\xi_N = \frac{b_i}{b_N}$, N denotes the needle and i denotes the other rubbing material in contact, and b is the thermal absorptivity of the respective materials the calculated value given as $b = \sqrt{(\rho \times C \times \lambda)}$, where ρ is the density of the material, C is the specific heat of the material and λ is the thermal conductivity.

- The heat partition ratio between needle and fabric is γ_{FN} and between needle and sewing thread is γ_{YN}.

Heat is generated during the sewing process as a result of friction between the needle-fabric and needle-yarn. In this analysis, a steady-state condition is considered in which the amount of heat generated by friction exactly equals the amount of heat loss by the needle .The complex shape of needle is neglected, and it is treated as a uniform cylinder.

The heat generated due to rubbing between the surface of needle and the fabric can be expressed as

$$Q_{FN} = \gamma_{FN} \times \mu_{FN} \times F_{FN} \times v_{FN} \qquad (9.1)$$

The heat generated due to rubbing between the sewing yarn and the needle can be expressed as

$$Q_{YN} = \gamma_{YN} \times \mu_{YN} \times T_y \times \cos\theta \times v_{YN} \qquad \ldots (9.2)$$

Where

γ_{NY} = Partition ratio of heat gain between needle and yarn using Charron's relation

γ_{FN} = Partition ratio of heat gain between needle and fabric using Charron's relation

μ_{YN} = coefficient of friction between needle and sewing thread

μ_{FN}= coefficient of friction between fabric yarn and sewing thread

F_{FN}= needle penetration force with the fabric

T_y= maximum tension of sewing thread during sewing cycle

θ= the angle of sewing thread with needle

v_{FN}= velocity of needle with respect to fabric

Maximum needle speed is linear function of machine speed with multiplier constant C_{FN}=0.0008

v_{YN}= velocity of thread with the needle

The total heat gain by the needle is therefore,

$$Q_N = Q_{FN} + Q_{YN} \qquad \dots (9.3)$$

From 1st law of thermodynamics in a closed system,

$$Q = m \times C_N \times (T - T_i) \qquad \dots (9.4)$$

Where

m = Mass of needle

C_N = Specific heat of needle

T =Final temperature of needle

T_i =Initial temperature of needle

Using equations 1, 2, 3 and 4,

$$m \times c_N \times (T - T_i) = \gamma_{FN} \times \mu_{FN} \times F_{FN} \times v_{FN} + \gamma_{YN} \times \mu_{YN} \times T_y \times \cos\theta \times v_{YN} \quad \dots (9.5)$$

The above equation, for a more precise result, should be solved by evaluating it numerically over time as many of the variables present in equation (9.5) are complicated functions of time. However, in order to simplify the calculations, the maximum value of F_{FN} and T will be considered here for the prediction of maximum temperature of the needle. Similarly, the maximum relative speed between the sewing yarn and the needle will be used as v_{YN}. As a further approximation, both v_{FN} and v_{YN} can be expressed as proportional to the machine speed v_M. If C_{FN} and C_{YN} are the two coefficients of these proportionalities respectively, then it can be obtained from equation (9.5) that

$$T - T_i = B \times v_M \qquad \dots (9.6)$$

Where

$$B = \frac{1}{m \times c_N} \times \{\gamma_{FN} \times \mu_{FN} \times F_{FN} \times C_{FN} + \gamma_{YN} \times \mu_{YN} \times T \times \cos\theta \times C_{YN}\} \quad \dots (9.7)$$

Thus, equation (9.6) indicates that the maximum needle temperature is a linear function of machine speed. The prediction of maximum temperature of needle from the machine speed is possible if the parameter *B* can be evaluated using equation (9.7).

9.1 Material and methods

In order to verify the simplified model, an industrial sewing machine (Brother Company, DD7100-905 was used for experiments. The needle used in this machine was Groz-Becker 100/16 R- type (134x5). The sewing thread details are given in Table 18 and cotton denim fabric was used to stitch during the experiments and the denim fabric details are given in Table 2.

Table 18 Sewing thread used for the experiments

Thread type	Company name	Fineness (Tex)	Twist (t/m)	Twist direction (ply/single)	Coefficient of friction μ
Polyester–polyester core spun	AMANN-Saba C-35	40*2	534	Z/S	0.30

9.2 Needle temperature measurement

Experimental needle temperature measurement with inserted thermocouple method shows better repeatable and reproducible results. The thermocouple is located near the eye of the needle to measure the exact needle temperature at different sewing speeds. This method proved to be very efficient as it provides continuous changes in needle temperature with respect to sewing time and gives low standard deviation. The thermocouple remains inside the needle groove during the sewing process and measurements are recorded wirelessly on a computer through a wireless device.

9.3 Sewing thread velocity measurement

During the stitch formation the bobbin assembly pulls the sewing thread which makes higher speed of thread as compared to needle speed. The thread speed is measured experimentally by using a high speed camera (OLYMPUS *i-speed 3*) during the sewing process. The white thread was marked with red ink at every 5 cm of its length to see the movement of thread and distance travelled by the thread during high speed sewing (1000 r/min to 4700 r/min). Thread velocity is not constant within a stitch and is maximum when the bobbin assembly pulls the thread downwards for the loop formation. Figure 53 shows one frame of the stitch formation motion captured by high speed camera. Coloured marks on the sewing thread are made to follow the motion of thread and measure the thread velocity during stitch formation.

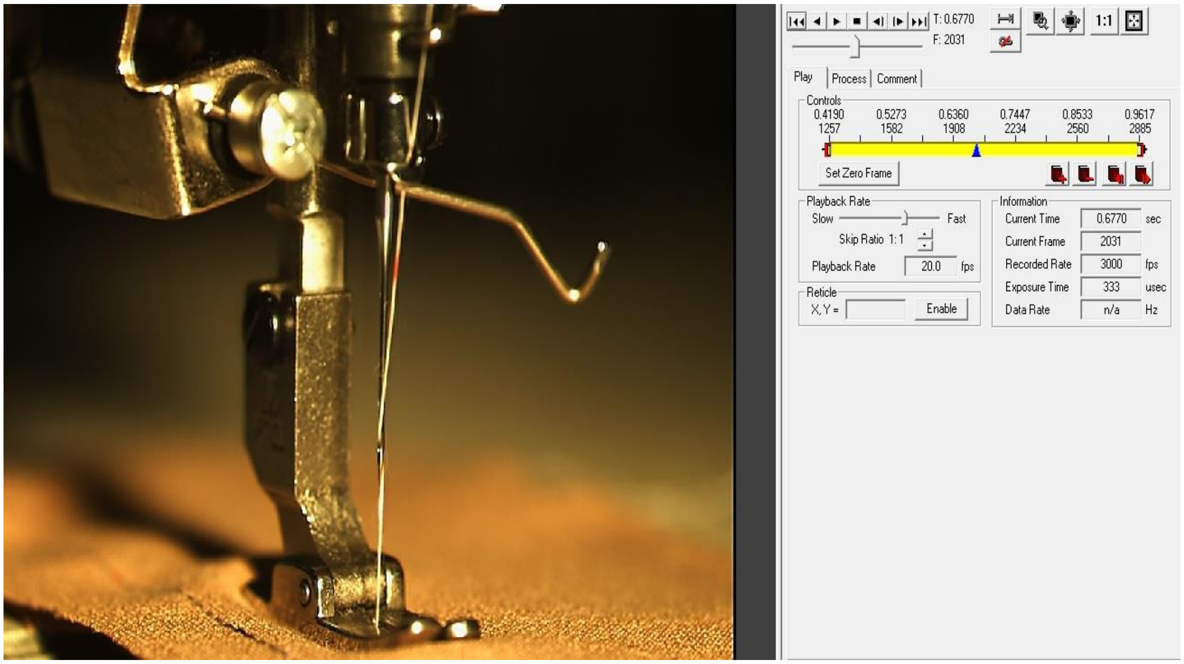

Figure 53 Analyzing the thread speed during sewing using software i-speed 3

9.4 Needle penetration force

Fabric and needle interaction is the second major cause of needle heating. To measure the friction forces it’s necessary to know the exact value of the normal force acting on the needle by fabric. The needle penetration force depends on different fabric properties like fabric thickness, weave style and yarn count etc. and can be measured experimentally. Some researchers [81,82] have used tensile tester with special attachments to experimentally measure the needle penetration force. Same technique was used in this research work to measure the penetration force. Measurement of needle penetration force is performed on a tensile tester (Testometric Company). In order to hold the fabric samples on the machine, a custom made metal frame with 3mm of hole for the needle passage was used on the lower jaw of the machine. The cyclic needle penetration was performed 20 times for two layers of denim fabrics, the needle insertion speed was adjusted at 460 mm/min .The machine setup for needle penetration force is schematically shown in Figure 54.

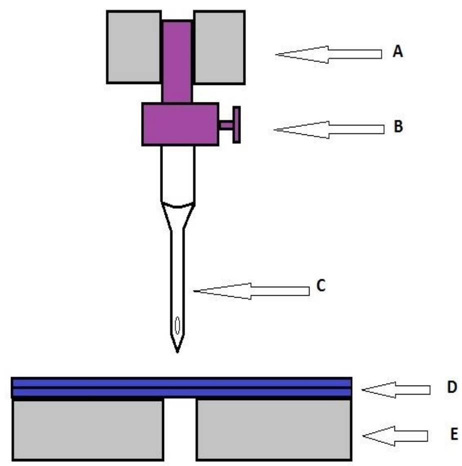

Figure 54 Schematic diagram of needle penetration force measurement

Where A-Needle holder in upper jaw ,B-Needle holder,C-Needle ,D-Fabric layers and E-fabric holder with hole at lower Jaw

9.5 Friction measurement

To theoretically analyse the sewing needle temperature, it's necessary to know the coefficient of friction between needle and thread for sewing. Thread to metal coefficient of friction is measured with instrument CTT-LH401 (Lawson-Hemphill) according to standard ASTM D-310 [91].

9.6 Results and discussions

The maximum thread velocity with respect to needle is measured using high speed camera and shows a linear relation between sewing speed and maximum thread velocity as shown in figure 55. It can be observed from the figure 55 that maximum velocity of sewing yarn is a linear function of machine speed with multiplier constant $C_{YN} = 0.0246$.

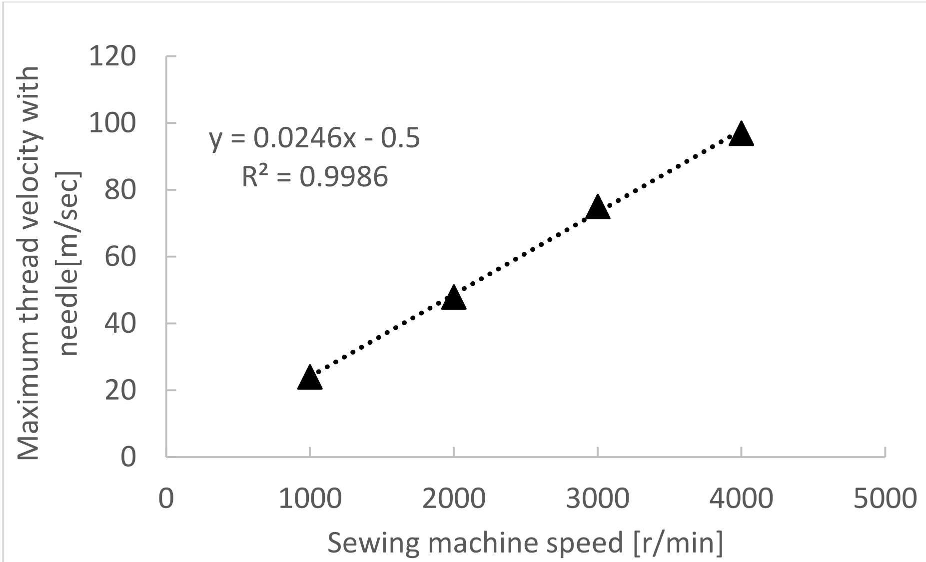

Figure 55 variation of maximum thread speed with different machine speeds

The Needle penetration force is measured by many researchers [83-90] using the special attachments to the tensile tester. The needle is inserted in to the fabric and penetration force is experimentally calculated. Figure 56 shows the needle penetration force in fabric, the experiment is repeated at 5 different places of fabric. The peak in the graph is the needle penetration force and the height of the flat plateau between two peaks shows the force acting on the needle after the fabric is punctured and needle moves across the fabric. This needle penetration force measurement technique is also used by some researchers [81,82]and the same technique is followed here as the penetration force may depend on needle dimensions and fabric weave structure, so it is necessary to know the exact penetration force with the sewing needle and fabric that was used in this study.

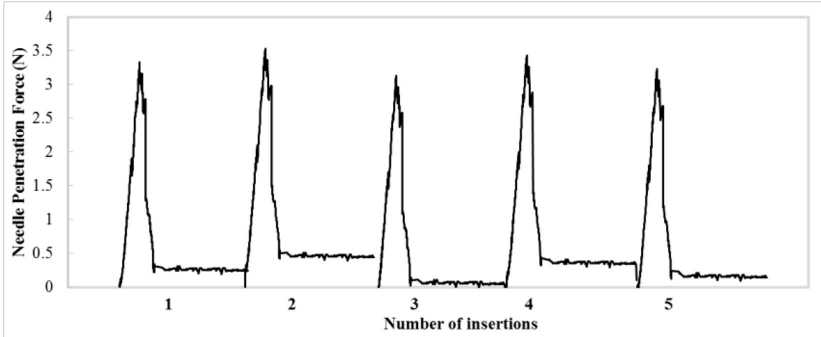

Figure 56 Variation of force on the needle during needle insertion

The Sewing needle temperature after 30 seconds of continuous sewing as measured by the thermocouple is shown in Table 19. It can be seen that the heat generated by the rubbing of the sewing thread and the needle eye contributes significantly to the needle temperature.

Table 19 Experimental results of needle temperature measurement

machine speed [r/min]	Without thread [°C]*(standard deviation)*	With thread [°C] *(standard deviation)*
1000	50*(0.57)*	79*(1.15)*
2000	67*(1.1)*	143(*1.55*)
3000	78*(1.77)*	213(*1.75*)
4000	92*(2.7)*	255(*2.83*)
4700	112*(3.4)*	290(*2.89*)

9.7 Comparison of experimental and theoretical model

The needle temperature was calculated using equations (9.6) and (9.7). Table 20 summarizes the values used for the various parameters for this calculation.

Table 20 Values of various parameters used for the theoretical prediction

Property	Symbol	Value	Unit
Heat partition ratio(fabric & needle) [80]	γ_{NF}	0.979871	-
Heat partition ratio (Yarn & needle)[80]	γ_{NY}	0.969961	-
density thread [94,95]	ρ_y	1400	Kg/m^3
specific heat of thread[93]	C_y	750	J/KgK
thermal conductivity of thread [93]	λ_y	0.15	W/mK
density fabric yarn [98]	ρ_f	1540	Kg/m^3
specific heat fabric yarn [93]	C_f	750	J/kgK
thermal conductivity of fabric yarn[93]	λ_f	0.06	W/mK
density needle [92]	ρ_n	7850	kg/m^3
specific heat needle [92]	C_n	523	J/kgK
Thermal conductivity of needle[92]	λ_n	40	W/mK
Friction coefficient needle and thread [experimental value]	μ_{YN}	0.3	-
Friction coefficient needle and fabric yarn [experimental value]	μ_{FN}	0.45	-
Tension thread max [96,97]	T_y	1.1	N
Needle velocity [experimental value]	v_N	2.3	m/sec
Machine speed	V_m	1000-4700	r/min
Needle and thread angle of contact [4]	θ	60	^{o}
Frictional normal penetration force to needle from fabric [experimental value]	F_{FN}	3.3	N

As can be seen from Figure 57 the simple theoretical model gives reasonably close values with respect to the experiment in both the cases when a sewing thread is and is not used. The calculated values seem slightly lower than actual values and such error could be expected since a number of approximations have been made to simplify the model and some of the values used for the calculation were not measured but obtained from literature. Nevertheless, the simple theoretical model is able to indicate the fact that the presence of sewing thread contributes to the needle heating which has been ignored by some previous literature and it also gives a linear relationship between the machine speed and needle temperature as observed by experiments. This simple approach may be more useful for shop floor compared to the complicated numerical methods.

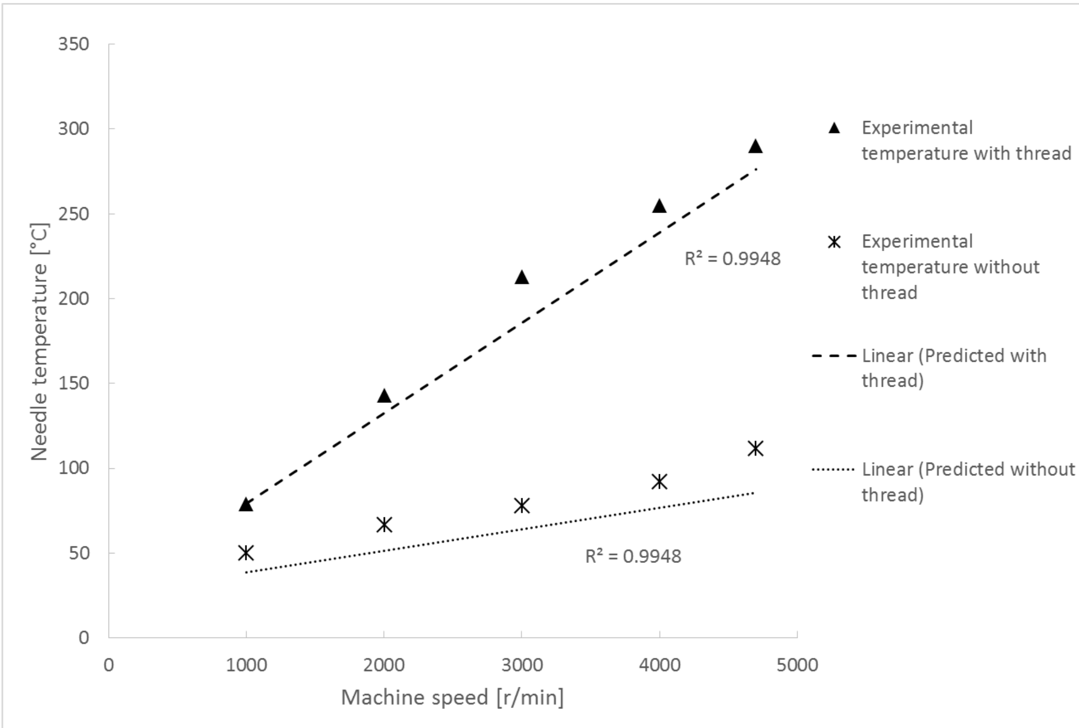

Figure 57 Comparison between theoretical prediction and experimental observation for needle temperature against machine speed

Table 21 shows the comparison of sewing needle temperature (without thread) by other researchers and the present analytical model. Most of the researchers have predicted needle temperature at low speed of sewing and without thread due to complexity in predicting the effect of sewing thread in needle heating. The needle penetration force is required for the presented model, which is obtained from literature [81, 82] according to the fabric used by the researchers.

Table 21 Needle temperature comparison with previous researcher's results

Machine speed [r/min]	Experimental Results [1,8] [°C]	sliding contact model[1] [°C]	Lumped variable model[1] [°C]	FEA [4] [°C]	**Present Analytical model [°C]**
500	77	109	110	87	69
1000	117	145	140	127	112
2000	170	197	195	180	198

9.8 Summary

Friction between needle and sewing thread is one of the major sources of needle heating. In general the needle heating is a complicated heat transfer problem. In this work a simple analytical model was developed to calculate the needle temperature at steady state from a set of parameters including friction coefficients, friction forces, thread tension and a simple linear equation was obtained with machine speed as the independent variable. Suitable experiments were carried out to measure the needle temperature using thermocouples. Some of the other process parameters used in the model were also measured to finally calculate the predicted needle temperature at a given machine speed. It was found that the model could predict the maximum needle temperature which needle can attain during a continuous sewing process of more than 10 seconds with reasonable accuracy. The important role of the sewing thread in contributing towards the needle temperature was also established both theoretically and experimentally.

The presented analytical model does not require extensive computation. As a result, it can be used to estimate the needle temperature at sewing floor and provide valuable information for optimizing the industrial sewing operation.

Conclusion

Needle heating is a serious issue for sewing industries and understanding the causes of heating and applying this knowledge for reducing needle temperature during high speed sewing can bring greater corporate benefits. It can be concluded from the present research that:

- Needle temperature can be precisely measured with inserted thermocouple method which shows minimum standard deviation and higher repeatability as compared to thermal camera or Thermocouple touch method. The thermal camera works on emissivity, and a needle with low emissivity and thread with high emissivity are too close to be differentiated by the thermal camera. All three methods of needle temperature measurement showed that the needle temperature was higher when sewing with thread as compared to dry sewing (without thread).
- Multiple factors were considered in this research to determine their impact on sewing needle temperature. It was observed that the sewing speed, the thread count, the sewing time and the fabric thickness had significant impact on sewing needle temperature. On the other hand, ambient humidity, ambient temperature, stitch density and needle parameters played a minor role in heating of the sewing needle.
- Air cooling (Vortex) is an effective way of decreasing needle temperature, and the continuous cooling method decreases the needle temperature significantly. At high speed sewing, the contact time between the thread and needle is very low, but as the machine comes to a complete stop, the contact time of the thread and needle is relatively higher, which causes the major damage to the sewing thread. The results reflect this that cooling at the time of machine stoppage and continuous cooling show the same results in terms of thread tensile properties. Cooling only at the time of machine stoppage can save 60-80% on energy consumption. Industrial sewing machine producers must operate the air cooling device with the machine speed pedal, which operates at 3000r/min and higher, and at the time of machine deceleration.
- The effect of lubricant amount on tensile properties of thread should always be considered for sewing process. It is advised to use the lubricant when sewing speed is 2500r/min and higher. The higher amount of lubricant decreases the needle

temperature and thread tenacity. To obtain highest tensile properties and maximum sewing speed it is recommended to use 2-4% of lubricant amount, but if it's necessary to achieve lower needle temperature due to synthetic fabrics then lubricant amount of more than 3% can be used.

- This research shows that needle temperature has a dominant influence on the strength of sewing thread. Seam thread was considered as the thread with the weakest tensile properties as compared to the parent thread but the research shows that the hot needle also damages the thread when the machine stops after sewing and needle is in direct contact with the thread. This needle-heat damaged thread eventually becomes part of the next seam and causes loss in seam strength. It is recommended to waste 20 cm of the thread after one complete sewing, so that the thread damaged at the needle eye after machine stoppage should not be part of the next seam. As thread moves from cone to the seam, it undergoes various stresses, there is a marginal decrease in tensile strength for thread at 1000 and 2000 r/m of machine, whereas loss of tensile strength of thread is much significant from 3000 r/m of machine and higher. Bobbin thread interaction and needle heat are the two main causes of reduction of tensile strength, breaking elongation and initial modulus of thread. In this section the loss of tensile strength is mainly due to bobbin thread interaction and friction of guides and tension devices on machine, but due to high speed of machine the contact time between thread and needle is much less to impact. That is why the thread at seam shows higher tensile properties as compared to section of thread that stay in the hot needle after machine stoppage.
- It's possible to cover the needle with DLC coating but the complex shape of the needle eye makes it impossible to determine if the coating is evenly applied at the inside part of the needle's eye. DLC-coated needles along length shows better roughness property as compared to normal needles by AFM measurement. Diamond polish is also important step in bringing better surface properties of martial but the needle eye could not be diamond polished due to the complex shape of the needle eye. There was a small improvement noted in terms of tensile properties and needle temperature for DLC coated needles.

- In this work a simple analytical model was developed to calculate the needle temperature at steady state from a set of parameters including friction coefficients, friction forces, thread tension and a linear equation was obtained for the temperature of the needle related to the machine speed as an independent variable. It was found that the model could predict the maximum needle temperature that can be attained during a continuous sewing process of more than 10 seconds with a reasonable accuracy. The important role of the sewing thread in contributing towards the needle temperature was also established both theoretically and experimentally. The presented analytical model does not require extensive computation. As a result, it can be used to estimate the needle temperature at sewing floor and provide valuable information for optimizing the industrial sewing operation.

Future Work

The inserted thermocouple method can be further tested for different sewing conditions in different industries such as sewing of car seat covers, airbags and smart textiles; where quality and durability is of key importance. The technical conductive sewing threads with steel and carbon fibres could be used in future to see the effect of conductance on sewing needle temperature. Polishing the needle eye of DLC coated needle may decrease the needle temperature.

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APPENDIX I

(REFEREED RESEARCH)

EXPERIMENTAL TECHNIQUES FOR MEASURING SEWING NEEDLE TEMPERATURE

DİKİŞ İĞNESİ SICAKLIĞININ ÖLÇÜMÜ İÇİN DENEYSEL TEKNİKLER

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ABSTRACT

In this article, three different methods (thermal camera, attached thermocouple and inserted thermocouple) are used to measure sewing needle temperatures on a lockstitch machine. The experiments were conducted at machine speeds from 16 stitches/sec to 66 stitches/sec and for a maximum time of 60 seconds. This research is useful for predicting the real temperature of needles at different sewing speeds and for comparing methods of measurement. The inserted thermocouple method showed the lowest standard deviation and highly reproducible results. The results for all the measurement techniques are compared at different sewing speeds and will be beneficial for researchers who have made theoretical models for sewing needle temperatures and need to verify them using experimental results. The information in this article will also be useful for thread lubricant producers who use thermal cameras for needle temperature measurement. All of our experiments indicate that the needle temperature is always higher when thread is used, which is contradictory to the results of some researchers, who have found that needle temperature is lower when thread is used.

Key Words: Sewing needle, needle temperature, needle heat measurement.

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1. INTRODUCTION

Industrial sewing is one of the most common manufacturing operations. Its application can be found in the manufacturing of garments, shoes, furniture and automobiles. Every day, millions of products ranging from shirts to automotive airbags are sewn. Hence, even small improvements may result in significant corporate benefits. Heavy industrial sewing, such as that used in the manufacture of automobile seat cushions, backs and airbags, requires not only high production but also high sewing quality (i.e. good appearance and long-lasting stitches). Typically, the material being sewn includes single and multiple plies of synthetic fabric or leather, sometimes backed with plastics, and needle heat-up is a major problem on the sewing floor. In recent years, in order to increase production, high-speed sewing has been extensively used. Currently, sewing speeds range from 10~100 stitches/sec. In heavy industrial sewing, typical sewing speeds range from 16~50 stitches/sec.

Depending on the sewing conditions, maximum needle temperatures range from 100°C~300°C (1). This high temperature weakens the thread, since thread tensile strength is a function of temperature (1), resulting in decreased production (2). In addition, the final stitched thread has 30–40% less strength than the parent thread (3). Various methods for measuring needle temperature, such as infrared pyrometer, thermocouple and temperature sensitive waxes, have been used. Because the needle is moving extremely fast during the sewing process, it is quite difficult to measure the exact temperature (4). There are few theoretical models available to predict sewing needle temperature (4, 5), but experimental verification has been done by thermal cameras, which is influenced by emissivity issues (7). Sondhelm (10) used a lacquer painted in the needle groove to observe a change of colour with temperature. Laughlin (11) tried to measure needle temperature through infrared measurement from the needle using a lead-sulphide photocell. Another technique using thermocouples was later developed by Dorkin and Chamberlain (12). As a result of improved understanding of the causes of sewing damage, many technical developments, such as improved needle design (13,15), fabric finishes (16,17,18), thread lubrication and needle coolers (13,14,15), have taken place over the years.

In this research, three different methods (thermal camera, attached thermocouple and inserted thermocouple) are used to measure the sewing needle temperature of a lockstitch machine at different machine speeds. The results are compared to see which method provides the highest accuracy and the most repeatable results. This research will be beneficial for comparing needle temperatures at different machine speeds and can also be used to verify theoretical model predictions. This research will be useful for thread lubricant producers like TEXTILCHEMIE DR. PETRY from Germany, which uses thermal cameras to measure needle temperature to test the effect of lubricants on sewing needle heat (8).

2. MATERIAL AND METHOD

For this research, three different methods (thermal camera, attached thermocouple and inserted thermocouple) are used to measure the sewing needle temperature on an industrial lockstitch machine (BROTHER Industries). Conditions for all experiments were kept constant at 26oC and 65% RH. The devices used for the experiments are listed below:

- Lockstitch machine (Brother Company, DD7100-905).
- Thermal camera (P60) from the FLIR Company, and TS60 from the Fluke Company.
- Thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) for the inserted method.
- Thermocouple by Omega (TJ36-CAIN-010U-6) for the touch method.
- Thermocouple by Omega -wireless device and receiver (MWTC-D-K-868).
- Needles (Groz-Becker 100/16) R- type.
- Sewing thread properties are shown in Table 1.
- Fabric properties are shown in Table 2.

All methods were tested 20 times each and the results are shown with standard deviations. Maximum sewing time was 60 seconds for all techniques. The stitch length was kept constant at 5 stitches/cm and the sewing process was done both with and without thread to determine the temperature difference caused by the sewing thread. All three methods, along with their results, are presented in the next section.

2.1. Thermal camera Method

The Fluke TS60 is a manual thermal camera that measure temperature as triggered by the operator, whereas the FLIR P60, as shown in Figure 1, is a continuous filming camera. All thermal cameras work on the principal of emissivity of the object. For this test, the emissivity of the needle was calculated by ASTM standard E 1933 – 99a and determined to be 0.08 for a chromium polished needle at 37oC, as shown in Figure 2. As the needle is thin and shiny, it is complicated to determine the exact emissivity, and most researchers adopt the emissivity of the needle as that for polished chromium, which is 0.06 (9). Even with knowing the emissivity of the needle, measurement is extremely difficult, as the sewing process is fast and the needle moves at a rate of 30~90 stitches per second. Another problem is that the emission of the needle changes during the sewing process, as the surface characteristics change (9). Therefore, the Fluke TS60 was used for the emissivity measurement for the sewing process, and the FLIR P60 was used for measuring the needle temperature during the sewing process. The first experiment was conducted without thread at speeds of 16–50 stitches/sec; the standard deviation increased sharply at 50 stitches/sec. It is not possible to use the camera at speeds higher than that as the needle is moving more than 60 stitches per second, which makes it impossible to focus the camera on the needle. When the experiment was performed with thread even at 2,000 rpm, it was difficult to measure the needle temperature, as the thread, which has an emissivity of nearly 0.9, significantly affects the needle measurement, which has an emissivity of 0.08, as shown in Figure 3.

Table 1. Properties of the sewing thread

Thread type	Company name	Yarn count (tex)	Twist (t/m)	Twist direction (ply/single)	Coefficient of friction μ
Polyester–polyester core spun	AMANN-Saba C-80	22*2	660	Z/S	0.14

Table 2. Properties of the fabric

Fabric type	Weave	Weight (g/m2)	Ends/cm	Picks/cm	Thickness(mm)
100%cotton Denim	2/1 Twill	257	25	20	0.35

Figure 1. Thermal camera FLIR P60 with Lockstitch machine

Figure 2 shows a needle with a portion painted with OMEGA paint with of an emissivity 0.96. Figure 3 shows the thermal camera picture of a sewing needle with thread at 50 stitches/sec. Due to the higher emissivity of the thread, it is almost impossible to measure the needle temperature because focusing only on the needle is difficult on machines running at 50 stitches/sec.

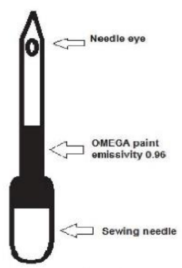

Figure 2. Needle emissivity measurement

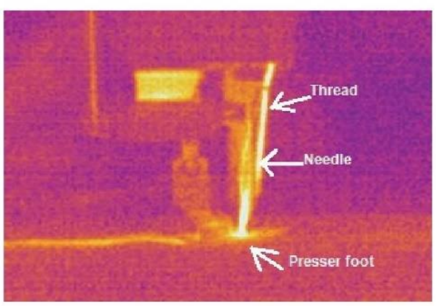

Figure 3. Needle eye temperature measured by camera

Figure 4 shows the increase in the needle temperature (without thread) with an increase of sewing speed, measured by the thermal camera. The maximum machine speed used was 50 stitches/sec, as after this speed, it was not possible to focus on the needle. Even at 50 stitches/sec the standard deviation was much higher than at slower speeds. It can be seen that after 15 seconds of sewing, there was not much difference in the needle temperature as the process stabilizes with the surroundings.

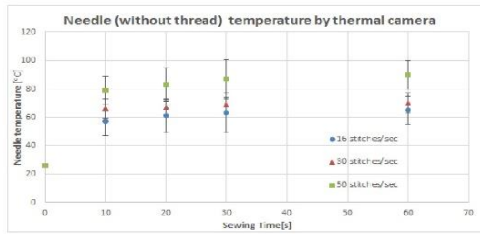

Figure 4. Needle (without thread) temperature measured by thermal camera

Figure 5 shows the increase in needle temperature (with thread) with the increase of sewing speed. The needle temperature (with thread) was higher as compared to the needle temperature without thread. The mean needle temperature reached 135°C at speed of 50 stitches/sec after 60 seconds of sewing.

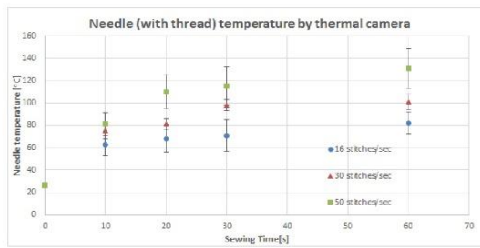

Figure 5. Needle (with thread) temperature measured by thermal camera

The thermal camera was placed at position B, as shown in Figure 6. Even changing the position from A or C caused a significant change in the needle temperature recording; this might be because of surrounding energy sources, which receive reflection from the shiny needle. These energy sources are almost impossible to omit, and performing the sewing process under an enclosed black box is not suitable for determining the exact needle temperature as the surrounding conditions will not be same as those on the sewing floor.

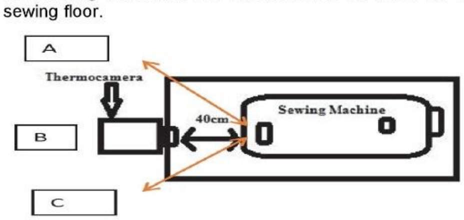

Figure 6. Placement of thermal camera

The needle (without thread) temperature can be measured by thermal camera, but the emissivity of the needle and the external energy sources reflecting off the needle make it difficult to determine the exact temperature.

2.2. Thermocouple touch method

In this method, a thermocouple by Omega (TJ36-CAIN-010U-6) was used to measure the sewing needle temperature. The sewing process was done for 10-, 20-, 30- and 60-second time periods, and the thermocouple was manually touched to the eye of the needle to measure the temperature. This method involved a degree of human error, as the thermocouple was applied to the needle just after the sewing process finished. Being quick when applying the thermocouple and taking multiple observations for each time period reduces the percentage of error, however, the needle temperature results were still much lower when compared with the other methods, as the needle dropped heat very quickly. Figure 7 shows the thermocouple and the placement of the thermocouple after each sewing process interval.

Figure 8 shows the needle (without thread) temperature at the different sewing speeds; the maximum machine speed was 66 stitches/sec, which shows a mean temperature of 98^{o}C after 60 seconds of sewing. The recorded temperature was much lower than with the other methods of measurement, which might be due to delay in obtaining the measurement, as the temperature is measured manually after each sewing interval.

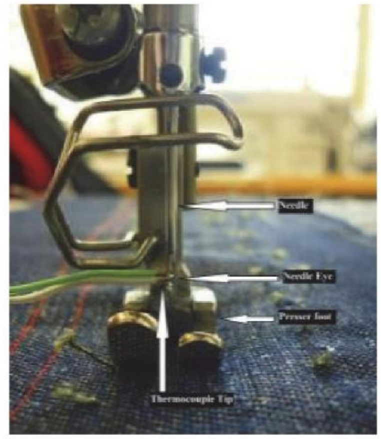

Figure 7. Needle temperature measured by the thermocouple touch method (6)

Figure 9 shows the needle (with thread) temperature measured by the thermocouple touch method. At a machine speed of 66 stitches/sec, the needle temperature reached 122^{o}C, which is much higher when compared to the needle temperature without thread.

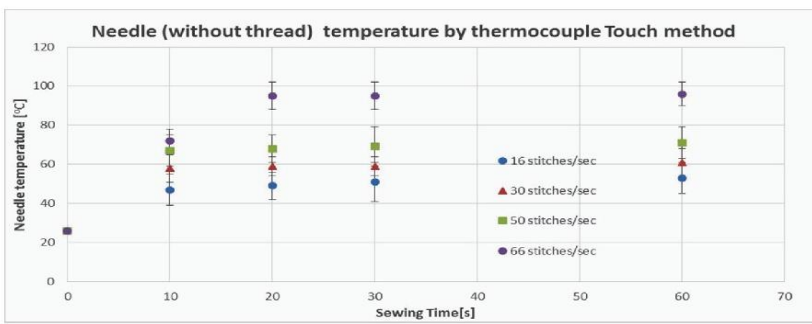

Figure 8. Needle (without thread) temperature measured by the thermocouple touch method

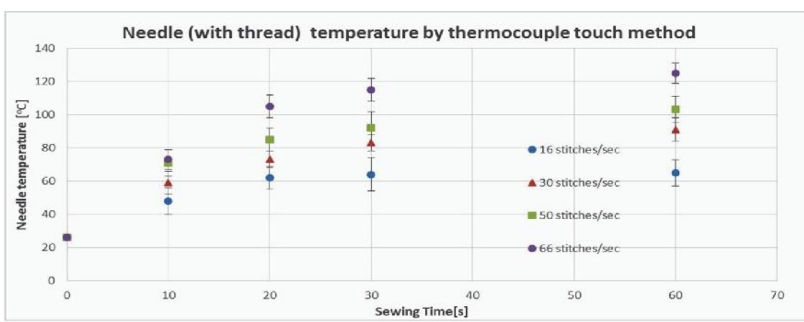

Figure 9. Needle (with thread) temperature measured by the thermocouple touch method

2.3. Inserted thermocouple method

In this unique method for measuring sewing needle temperature, a thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) was inserted into the groove of the sewing needle and soldered. The thermocouple was located near the eye of the needle to measure the exact needle temperature, and the temperature was measured at different sewing speeds. This method proved to be very efficient as it provided continuous changes in needle temperature every second and it had a low standard deviation. Figures 10 and 11 show the placement of the thermocouple inside the needle groove. The thermocouple remained inside the needle groove during the sewing process and measurements were recorded wirelessly on a computer through a wireless end device (MWTC-D-K-868).

Figure 10. Inserted thermocouple

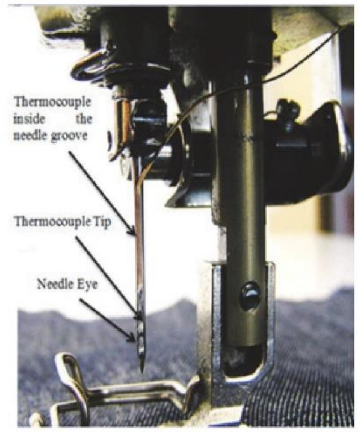

Figure 11. Placement of the thermocouple

Figure 12 shows the needle temperature measured by the inserted thermocouple method without thread. At a sewing machine speed of 66 stitches/sec, the needle temperature reached 110°C, which is almost 20°C higher than the temperature measured by the touch method. This method proved to be efficient for the different machine speeds and had a lower standard deviation as compared to the other methods of measurement.

Figure 13 shows the needle (with thread) temperature measured by the inserted thermocouple method at the different machine speeds. At 66 stitches/sec, the needle reached an average temperature of 202°C after 60 seconds of sewing, which is almost twice the needle temperature recorded in the trial without thread.

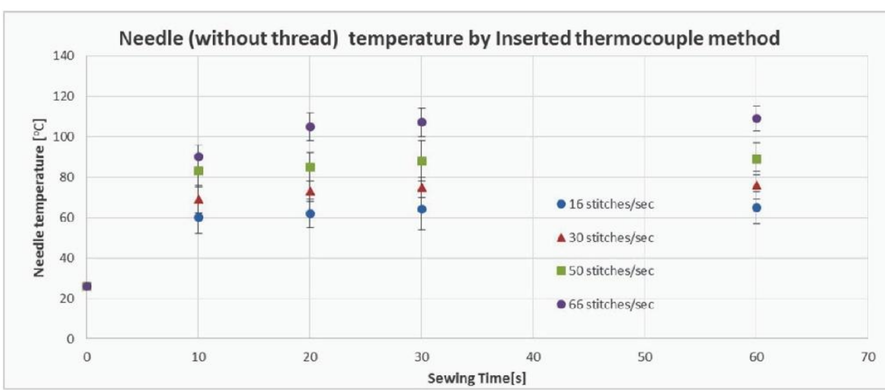

Figure 12. Needle (without thread) temperature measured by the inserted thermocouple method

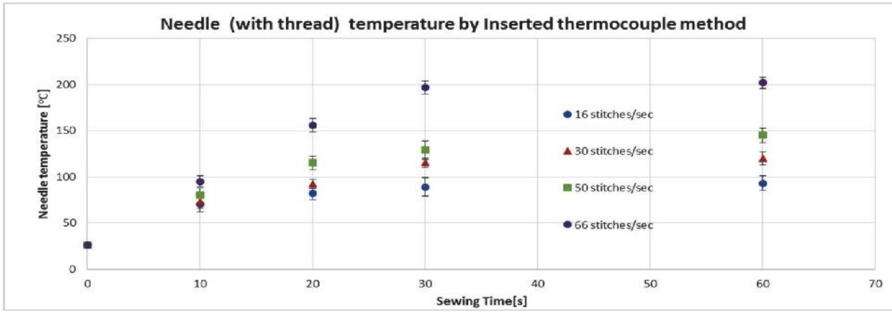

Figure 13. Needle (with thread) temperature measured by the inserted thermocouple method

3. RESULTS AND DISCUSSION

Figure 14 shows the needle (without thread) temperature comparison for the different methods of measurement at a machine speed of 50 stitches/sec. The inserted thermocouple method and the thermal camera show nearly the same average needle temperature after 60 seconds of sewing, but the standard deviation is much higher for the thermal camera measurements. The thermocouple touch method shows an almost 20°C lower temperature as compared to the other methods of measurement.

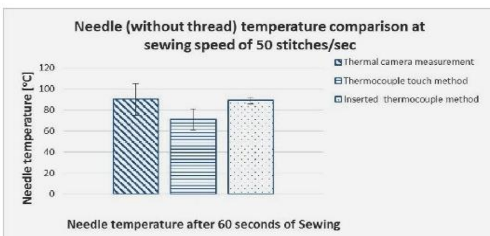

Figure 14. Comparison of the needle (without thread) temperature measurement methods

Figure 15 shows the needle temperature (with thread) comparison for the different methods of measurement at a machine speed of 50 stitches/sec. The inserted thermocouple method shows the highest needle temperature after 60 seconds of sewing with the lowest standard deviation, followed by the thermal camera measurement, which had the highest standard deviation. The thermocouple touch method shows the lowest temperature of the three methods of measurement.

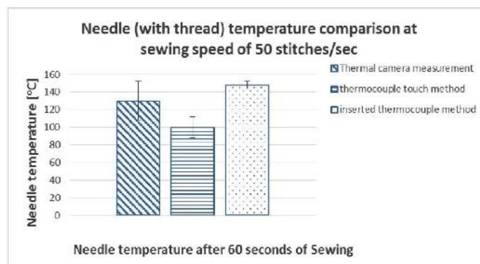

Figure 15. Comparison of the needle (with thread) temperature measurement methods

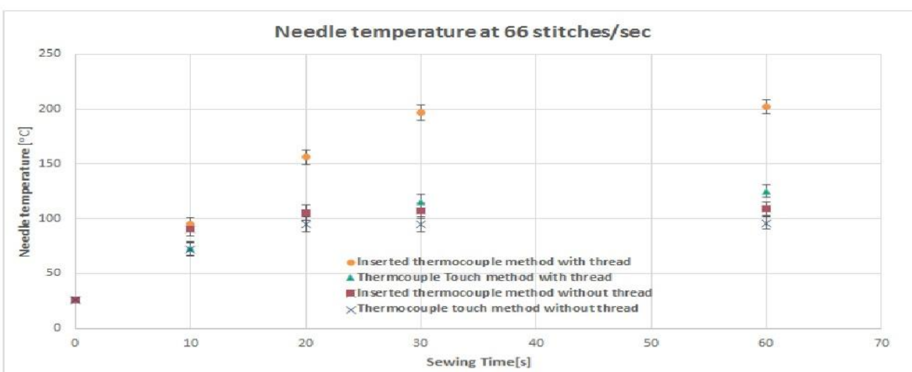

Figure 16. Needle temperature comparison of the thermocouple touch method and the inserted thermocouple method, with and without thread, at a sewing speed of 66 stitches/sec

It was impossible to measure the needle temperature with the thermal camera at speeds higher than 50 stitches/sec; therefore, the thermocouple touch method and the inserted thermocouple method were used to measure needle temperatures at sewing speeds of 66 stitches/sec, both with and without thread. The inserted thermocouple method shows significant temperature differences between the tests performed with and without thread. Each experiment was repeated 30 times.

The thermal camera was not the best method for sewing needle temperature measurement. The emissivity of the needle posed a major problem and changed the surface properties (7); during the normal sewing process, surrounding energy sources reflected off the needle surface. Keeping the same emissivity caused a large standard deviation in the needle temperature measurement—and it was even higher when sewing was done with thread. The thermal camera works on emissivity, and a needle with low emissivity and thread with high emissivity might have caused this result for some researchers (8, 9). In our results, the needle temperature always increased when sewing thread was used.

The thermocouple touch method resulted in the lowest needle temperature, which was most likely due to measurement time delays. Some researchers (12) have proposed this method; however, the time it takes to touch the needle with the thermocouple always causes a lower temperature reading.

The inserted thermocouple appeared to be a unique method of measurement. Wireless data transfer makes it possible to record needle temperatures each second at all sewing speeds.

4. CONCLUSION

- Thermal camera is not the most effective method for measuring sewing needle temperature because the emissivity of the needle and external energy sources reflecting from the needle surface causes problems in measurement.
- Needle temperature is always higher when thread is used, difference is much higher at higher speeds of sewing machine.
- The thermocouple touch method shows lowest needle temperatures as compared to the other methods, which is due to delay in measurement time. This method is quick and easy for estimating the temperature, but actual needle temperatures are always much higher. The thermocouple touch method shows an almost 20°C lower temperature as compared to the other methods of measurement.
- The inserted thermocouple method and the thermal camera method show nearly the same average needle temperature after 60 seconds of sewing for sewing speed of 50 stitches/sec, but the standard deviation is much higher for the thermal camera measurements.
- For sewing speed of 30 stitches /second and after 60 seconds of sewing, inserted thermocouple method shows almost 17% increase of needle temperature as compared to needle (without thread) temperature. Thermal camera shows 14% increase followed by touch thermocouple method showing 12% increase of needle temperature as compared to needle (without thread) temperature.
- The inserted thermocouple method shows the highest needle temperature after 60 seconds of sewing with the lowest standard deviation, followed by the thermal camera measurement, which had the highest standard deviation for machine speed of 50 stitches/sec. The thermocouple touch method shows the lowest temperature of the three methods of measurement.
- For sewing speed of 66 stitches /second and after 60 seconds of sewing, thermocouple touch method shows 15% increase in temperature of needle (with thread) as compared to needle (without thread) temperature. Whereas inserted thermocouple method shows almost 60% increase of needle (with thread) temperature.
- Experimental results from the inserted thermocouple method can be used to predict the exact sewing needle temperature.

ACKNOWLEDGEMENTS

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APPENDIX II

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Influence of Needle Heat during Sewing Process on Tensile Properties of Sewing Thread

Vpliv segrevanja šivalne igle med procesom šivanja na natezne lastnosti sukanca

Preliminary Report/*Predhodna objava*
Received/*Prispelo* 11-2013 • Accepted/*Sprejeto* 12-2013

Abstract

In this work, the tensile properties of a sewing thread, i.e. tenacity, breaking elongation and initial modulus of two common industrial sewing polyester-polyester core spun threads, were studied at four sewing stages. Firstly, the needle heat was measured at different speeds from 1000 rpm to 4700 rpm of an industrial lockstitch sewing machine with the inserted thermocouple method. Secondly, the tensile properties of a thread were compared at different predefined sections of the sewing thread in the sewing process. The results show that the needle heat and bobbin thread interaction has a great impact on the sewing thread tensile strength, while the tensile strength is minimal at the point when the machine stops and the thread is in direct contact with the hot needle. Tenacity, breaking elongation and initial modulus decrease substantially with a higher speed of the machine as the needle temperature increases. At 4000 rpm of the sewing speed, the sewing thread loses 50% of its tenacity as the needle temperature reaches nearly 250 °C, the impact being higher for higher count (linear densities) threads.
Keywords: sewing needle, sewing thread strength, needle heat, thermocouple method

Izvleček

V članku je predstavljena raziskava nateznih lastnosti sukanca, kot so trdnost, pretržni raztezek ter začetni modul dveh v industriji pogosto uporabljenih poliestrskih sukancev iz oplaščenene preje, in sicer v štirih fazah šivanja. Na začetku smo izmerili temperaturo igle pri različnih hitrostih, in sicer od 1000 do 4700 vrtljajev na minuto na industrijskem šivalnem stroju s pomočjo metode vstavljenega termočlena. Natezne lastnosti sukanca smo nato primerjali pri različnih vnaprej določenih delih šivalne niti med samim procesom šivanja. Izsledki raziskave so pokazali, da ima interakcija med segrevanjem igle in sukancem na navitku velik vpliv na natezno trdnost sukanca, medtem ko je natezna trdnost najmanjša na točki, ko se stroj ustavi in je sukanec v neposrednem stiku z vročo iglo. Trdnost, pretržni raztezek in začetni modul se znatno zmanjšajo pri večji hitrosti stroja, ko se poviša tudi temperatura igle. Pri hitrosti 4000 vrtljajev na minuto izgubi sukanec 50 % trdnosti, saj se temperatura igle povzpne na skoraj 250 °C. Vpliv je večji pri sukancih z višjo linearno gostoto.
Ključne besede: šivalna igla, trdnost sukanca, segrevanje igle, metoda s termočlenom

1 Introduction

During high speed sewing, the sewing thread is subjected to friction, heat, pressure, torsion and bending. These forces act on the thread repeatedly, and its tensile properties decrease substantially [1]. The thread has to pass through the needle eye, fabric and bobbin case mechanism 50–80 times before becoming a part of the seam [2]. Local abrasion and cutting of the needle thread can occur due to the

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rubbing at the top of the needle eye [3]. In an early research work, Crow and Chamberlain [4] reported that there is a reduction of up to 60% in the thread strength after the sewing. Later, a number of researchers observed that there could be a 30–40% strength reduction in the cotton thread after the sewing and various reasons assigned included structural damage, dynamic and thermal loading [5–9]. In a recent study on the tensile properties of mercerized cotton threads, around 30% in strength reduction, about 20% loss in both breaking elongation and initial modulus, and 45% loss in breaking energy was reported [10]. Furthermore, a closer estimation of the seam strength was also possible after considering the loss in thread strength [11, 12]. The damage is mostly concentrated at the interlocking portion of the needle thread in the stitch, where maximum tension, bending and thread-thread abrasion take place [5, 8]. A number of researchers also studied the thread tensions during the sewing process and it is well known that the highest thread tension force occurs at the moment of stitch tightening [13–16].
Nevertheless, earlier studies are based on the effect of mechanical abrasion [17] as a cause of the thread tensile loss. In this work, we measured needle heat at different speeds of the sewing process and made sections of the sewing thread from the cone to the seam to measure the tensile properties of the sewing thread. We used two most common polyester core spun threads and measured the tenacity, initial modulus and breaking elongation of the thread at different stages of the thread, including the impact of needle heat.

For our research, we used the inserted thermocouple method invention by Hes [18] to measure the needle heat from 1000–4700 rpm of the machine. In this method, a thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) is inserted inside the needle groove and the sewing is done while the thermocouple is inside the needle groove. The needle temperature values can be obtained through a wireless device on a computer.

2 Methodology

2.1 Sewing thread and material properties

The details of the sewing thread and textile material used for the experiment are listed below.

- Thread polyester-polyester core spun (for details cf. Table 1)
- Denim fabric, two layers (for details cf. Table 2)

2.2 Sewing machine and needle temperature measurement

The devices used for the experiments are listed below:

- lockstitch machine (Brother Company, DD7100-905),
- thermocouple by Omega (K type 5SC-TT-(K)-36-(36)) for the inserted method,
- Omega – wireless device and receiver (MWTC-D-K-868) and
- needles (Groz-Beckert 100/16) R- type.

The needle temperature was measured using the inserted thermocouple method and the sewing process

Table 1: Physical properties of sewing threads

Thread type	Producer/ product name	Fineness [tex]	Twist [t/m]	Twist direction [ply/ single]	Tenacity [cN/tex]	Elon-gation at break [%]	Initial modulus [N/tex]	Coeffi-cient of friction [–]
Poly-poly core spun	AMANN/ Saba C-35	40 × 2	534	Z/S	50	18	4.4	0.16
Poly-poly core spun	AMANN/ Saba C-80	22.2 × 2	660	Z/S	45	21	3.26	0.14

Table 2: Fabric used for experiments

Fabric type	Weave	Mass/Unit area [g/m²]	Warp density [ends/cm]	Weft density [picks/cm]	Fabric thickness [cm]
100% cotton denim	2/1 twill	257	25	20	0.035

was performed at 1000–4700 rpm. The total of 150 observations was taken for each thread. The maximum time of sewing was 30 seconds for all speeds of the machine from 1000 rpm to 4700 rpm. The needle thread tension was adjusted to 140 cN to obtain a balanced stitch. The stitch length was kept constant at 5 stitches/cm. The conditions for all experiments were kept constant at 26 °C and 65% RH. Figure 1 shows the placement of the thermocouple for measuring the needle temperature at different speeds of sewing.

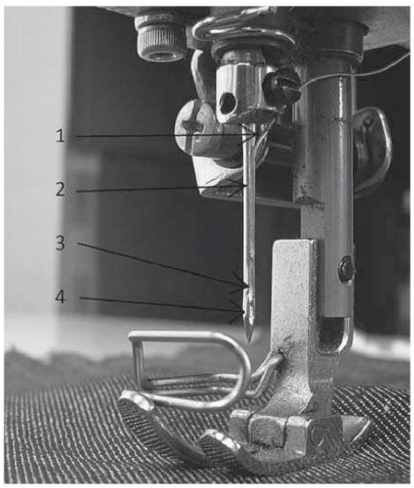

Figure 1: Sewing needle with inserted thermocouple
Legend: 1 – thermocouple wire, 2 – needle groove, 3 – thermocouple measuring point, 4 – needle eye

2.3 Stages of sewing thread for tensile properties measurement

The sewing thread was divided into four sections as shown in Figure 2. For the tensile testing of the sewing thread, an Instron tensile tester as per ASTM standard D2256 was used. The tensile testing of the parent thread corresponds to that of the section S1. For the tensile testing of the thread in the section S2, 250 mm length of thread from mark A towards G2 was mounted in the jaws. For the tensile testing of the thread in the section S3, a length of 250 mm from mark A towards point B was mounted in the jaws. A sufficient length of the thread was removed from the seam for gripping in the lower jaw, whereas the section S4 thread was pulled out precisely from the seam by cutting the bobbin thread. 30 samples of each section (S1, S2, S3, S4) were tested for tensile properties at each speed of the machine.

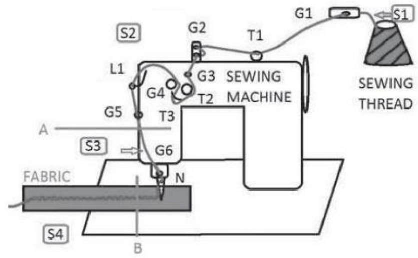

Figure 2: Passage of sewing thread through sewing machine
Legend: S1 – same as parent thread, G1 to G6 – guides for thread, T1 to T3 – tension devices, S2 – section of thread from A towards point G1, S3 – section of thread from point A towards point B, point A – 12 cm from needle eye, point B – 22 cm from needle eye in the seam, S4 – thread in the seam (pulled out precisely by cutting bobbin thread), L – take-up lever, N – needle eye

The change (%) in tensile properties at different stages is calculated with the following equation:

$$Change\ (\%) = \frac{T_n - T1}{T1} \cdot 100 \qquad (1),$$

where Tn is the tensile property at different sewing stages, with n = 2, 3 and 4, corresponding to the sewing stage S2, S3 and S4, respectively. T1 is the tensile property of the parent thread at the sewing stage S1. A negative (–) change (%) indicates the loss in tensile property.

3 Results and discussion

3.1 Influence of sewing thread on needle temperature

Needle temperature is higher when a higher count thread is used as shown in Figures 4 and 5. At 4700 rpm of the sewing speed, the thread Saba C-35 showed the maximum temperature of 305 °C as compared to 285 °C for the thread Saba C-80; this might be a consequence of the increase in friction between a thicker thread and the needle eye. Figure 3 shows the needle temperature without the thread at a different speed of sewing, where the needle reached 112 °C at the maximum speed of 4700 rpm of the machine and for all speeds, the needle temperature stabilized after 15 seconds of continuous sewing. After 15 seconds, the rise in temperature was minor.

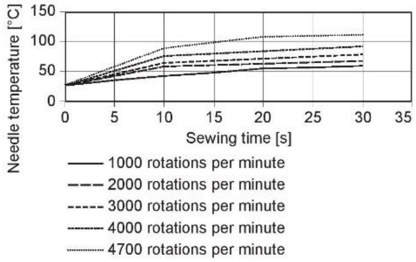

Figure 3: Needle (without thread) temperature

Figure 4 shows the needle temperature with the thread Saba C-80, which increased the needle temperature much more as compared to the needle temperature without the thread – at 4700 rpm of the machine after 30 seconds of sewing, the needle reached the maximum temperature of 285 °C. Nevertheless, the thread did not break or fuse as the thread was continuously moving and the needle heat was not fully conducted to the thread (a comparison of tensile strength at different speeds is discussed in continuation, cf. Figures 6–11).

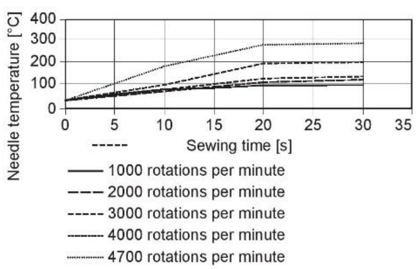

Figure 4: Needle temperature (with thread Saba C-80)

Figure 5 shows the needle temperature with the thread Saba C-35 (40 × 2 tex). The needle temperature rose to 305 °C at 4700 rpm of the machine. The temperature of the needle despite being higher than the melting temperature of polyester did not break the thread as the contact time of the thread with the needle was short.

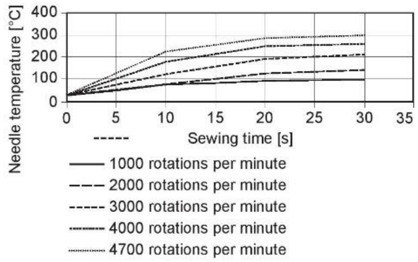

Figure 5: Needle temperature with thread Saba C-35

3.2 Effect of sewing speed on tenacity of threads

For 1000–2000 rpm of the machine, the minimum tenacity was noted for the section S4, which shows that the thread underwent mechanical abrasion especially from the bobbin mechanism and friction between the fabric and thread, whereas for 3000–4000 rpm of the machine, the minimum tenacity was observed at the section S3, which was due to the high temperature of the needle (the needle temperature at different speeds is shown in Figures 4 and 5). The effect was smaller for the section S4, as the machine was running at high speed and the contact time between the thread and needle was much shorter, whereas when the machine stopped, the thread was

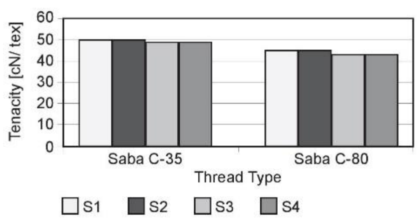

Figure 6: Tenacity of thread at 1000 rpm of machine

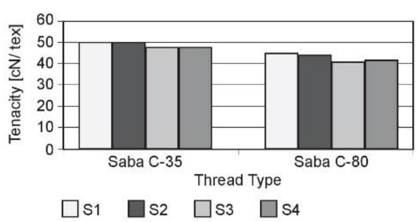

Figure 7: Tenacity of thread at 2000 rpm of machine

in direct contact with the needle eye and caused minimum tenacity at the section S3. This effect has always been neglected by other researchers, since for the tensile strength of the thread only the seam thread strength has been evaluated, which is not correct as the thread from the section S3 finally becomes part of the next seam and causes a weaker seam.

The tenacity of the thread was measured at different sections of the thread (S1, S2, S3 and S4). Figures 6 and 7, representing the machine speed of 1000 and 2000 rpm, demonstrate that the needle temperature was lower than 100 °C. The latter shows that the minimum tenacity of the thread was at the section S4, which underwent all abrasion and mechanical forces, yet the needle heat impact was not dominant.

It can be seen in Figures 8 and 9, displaying the speed of 3000 rpm and 4000 rpm, respectively, and the needle temperature rising to nearly 200 °C (needle temperature is shown in Figures 4 and 5), that the tenacity of the sewing thread started to play the dominant role in decreasing the strength of the sewing thread. It is to be noted that S3 had less tenacity than the section S4, which was due to the S4 thread being a part of the seam when the machine was running at high speed whereas the section S3 suffered more damage after the sewing finished and the thread remained on the hot needle eye.

Figure 11 shows the tenacity of threads at 4700 rpm of the machine where the needle reached 305 °C for the Saba C-35 thread and 286 °C for Saba C-80. The section S3 got the maximum damage and in the case of Saba C-35, the thread tenacity decreased by 70%, showing that the thread did not receive all the needle heat during high speed sewing.

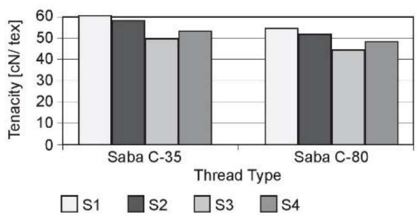

Figure 8: Tenacity of thread at 3000 rpm of machine

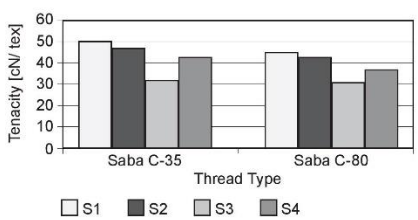

Figure 9: Tenacity of thread at 4000 rpm of machine

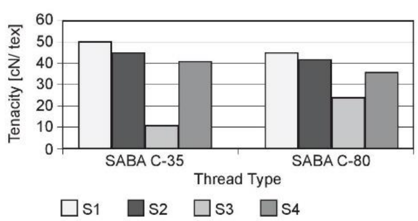

Figure 10: Tenacity of thread at 4700 rpm of machine

3.3 Effect of needle temperature at section S3

The section S3 thread underwent maximum needle heat after the machine stoppage as the thread was in direct contact with the hot needle. The tenacity of

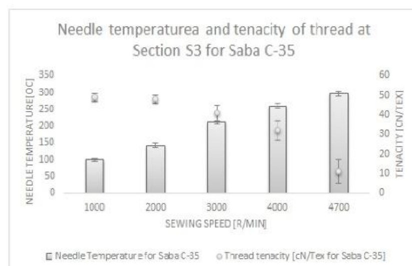

Figure 11: Needle temperatures and tenacity of thread at section S3 for thread Saba C-35

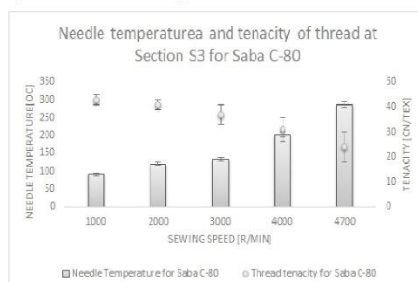

Figure 12: Needle temperatures and tenacity of thread at section S3 for thread Saba C-80

the thread was more affected at a higher count thread (Saba C-80) as the needle temperature was higher with higher count threads. Figures 11 and 12 show the needle temperature and the tenacity of the thread at the section S3 for different speeds of sewing. It can be observed that the needle temperature caused a great damage to the sewing thread tensile property. For Saba C-35, the thread tenacity decreased by 78%, followed by Saba C-80, which shows a 46% decrease in tenacity at 4700 rpm of the sewing speed. Saba C-35 is a higher count thread and showed higher needle temperature which might be a consequence of greater friction between the needle eye and the thread. The graph shows the needle temperature on the primary left axis, while the secondary axis on the right side of the graph shows the tenacity of both threads at different speeds of sewing.

3.4 Effect of sewing speed on thread tensile properties

Table 3 shows tenacity, initial modulus and breaking elongation for both threads, Saba C-35 and Saba C-80, at different speeds of the sewing machine and different sections of the sewing thread (S1, S2, S3 and S4). The change (%) is calculated according to Equation 1, and as Table 3 shows, the maximum loss in the tensile property was at the section S3, where the thread tenacity for Saba C-80 decreased to 46.7% and for Saba C-35, it decreased by 78% at 4700 rpm of the machine. The thread at the section S3 incurred the maximum needle heat after the machine stoppage, which resulted in the biggest change in the thread tensile properties.

The breaking elongation [%] property decreased more for Saba C-35 as compared to Saba C-80, but

Table 3: Mean values of mechanical properties of sewing threads

		Saba C-35 (80 tex)					Saba C-80 (44 tex)				
		Speed of machine					Speed of machine				
		1000 rpm	2000 rpm	3000 rpm	4000 rpm	4700 rpm	1000 rpm	2000 rpm	3000 rpm	4000 rpm	4700 rpm
Tenacity [cN/tex]	S1	50	50	50	50	50	45	45	45	45	45
	S2	50	50	48	47	45	45	44	43	43	42
	Change with respect to S1 (%)	0	0	−4	−6	−10	0.0	−2.2	−4.4	−4.4	−6.7
	S3	49	48	41	32	11	43	41	37	31	24
	Change with respect to S1 (%)	−2	−4	−18	−36	−78	−4.4	−8.9	−17.8	−31.1	−46.7
	S4	49	48	44	43	41	43	42	40	37	36
	Change with respect to S1 (%)	−2	−4	−12	−14	−18	−4.4	−6.7	−11.1	−17.8	−20.0
Breaking elongation [%]	S1	18	18	18	18	18	21	21	21	21	21
	S2	18	17.9	17.6	17.2	17	20.8	20.4	20.1	19.2	19
	Change with respect to S1 (%)	0.0	−0.6	−2.2	−4.4	−5.6	−1.0	−2.9	−4.3	−8.6	−9.5
	S3	17.5	17.2	13.6	12.2	5	20	19.5	17.4	14.5	12.4
	Change with respect to S1 (%)	−2.8	−4.4	−24.4	−32.2	−72.2	−4.8	−7.1	−17.1	−31.0	−41.0
	S4	17.6	16.2	16	15.7	14.3	19.6	19	18.2	17.3	16.8
	Change with respect to S1(%)	−2.2	−10.0	−11.1	−12.8	−20.6	−6.7	−9.5	−13.3	−17.6	−20.0
Initial modulus [N/tex]	S1	4.5	4.5	4.5	4.5	4.5	3.2	3.2	3.2	3.2	3.2
	S2	4.5	4.45	4.4	4.5	4.35	3.2	3.15	3.183	3.1	3
	Change with respect to S1 (%)	0.0	−1.1	−2.2	0.0	−3.3	0.0	−1.6	−0.5	−3.1	−6.3
	S3	4.4	4.3	4	3.1	2.7	3.1	3.1	2.85	1.8	1.4
	Change with respect to S1 (%)	−2.2	−4.4	−11.1	−31.1	−40.0	−3.1	−3.1	−10.9	−43.8	−56.3
	S4	4.4	4.4	4.2	3.6	3.3	3.1	3.1	3	2.2	2.1
	Change with respect to S1 (%)	−2.2	−2.2	−6.7	−20.0	−26.7	−3.1	−3.1	−6.3	−31.3	−34.4

again the impact was maximal at the section S3 where breaking elongation showed a 72% decrease for Saba C-35 and 41% for Saba C-80 at 4700 rpm of the machine.

The initial modulus of Saba C-80 decreased by 51% as compared to the 40% of Saba C-35 at the section S3 for 4700 rpm of the machine.

3.5 Relation between sewing speed, needle temperature and tenacity of sewing thread

Figure 13 shows that there is a strong linear relation between the needle temperature and the speed of the machine, whereas the experimental result shows a strong negative linear relationship between the speed of the machine and the tenacity of the sewing thread; at 4700 rpm of the machine, the sewing thread exhibited a nearly 70% decrease in tenacity.

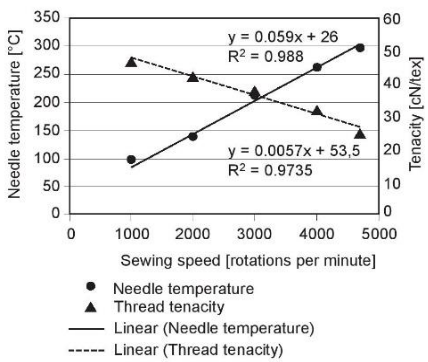

Figure 13: Needle temperature and tenacity of sewing thread

4 Conclusions

This research shows that the needle temperature has a dominant influence on the strength of the sewing thread. The hot needle mainly damages the thread when the machine stops after the sewing and when the needle is in direct contact with the thread. This needle-heat damaged thread eventually becomes a part of the next seam and leads to the loss in the seam strength. It is recommended to waste 20 cm of the thread after complete sewing in order for the thread damaged at the needle eye after the machine stoppage not to become a part of the next seam.

As thread moves from the cone to the seam, it undergoes various stresses and strain such as dynamic stress at the section S2. There is a marginal decrease in the tensile strength for the thread at 1000 and 2000 rpm of the machine, whereas the loss in the tensile strength of the thread is much more significant at 3000 rpm of the machine and higher.

The bobbin thread interaction and the needle heat are the two main causes for the reduction in the tensile strength, breaking elongation and initial modulus of the thread. The loss was greater for Saba C-35 (80 tex) polyester core spun thread, followed by Saba C-80 (44 tex) thread (cf. Table 3). The latter can be a consequence of higher friction between the needle and thicker thread, causing the needle temperature to increase. The needle temperature was by nearly 20 °C higher for Saba C-35 for all observations as compared to Saba C-80.

The thread at the section S3 underwent maximum needle heat after the machine stoppage, leading to the biggest change in the thread tensile properties. Therefore, this section thread exhibited the maximum loss in tensile property. For Saba C-80 thread, tenacity decreased to 46.7% and for Saba C-35, tenacity decreased by 78% at 4700 rpm of the machine. Breaking elongation decreased more for Saba C-35 as compared to Saba C-80, but again the impact was maximal at the section S3, where breaking elongation showed a 72% decrease for Saba C-35 and 41% for Saba C-80 at 4700 rpm of the machine.

The initial modulus of Saba C-80 decreased by 51% as compared to the 40% of Saba C-35 at the section S3 for 4700 rpm of the machine.

The section S4 thread is the seam thread pulled out precisely by cutting the bobbin thread. In this section, the loss of tensile strength was mainly due to the bobbin thread interaction and the friction of guides and tension devices on the machine; however, due to the high speed of the machine, the contact time between the thread and needle had a much smaller impact. Hence, the thread at the section S4 showed better tensile properties as compared to the section S3.

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