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CENTRE DE CLUNY

HODNOCENÍ ŘEZIVOSTI VYBRANÝCH PROCESNÍCH KAPALIN V APLIKACI MQL

ON THE CUTTING PERFORMANCE OF SELECTED PROCESS FLUID IN THE MQL APPLICATION

DIPLOMOVÁ PRÁCE
MASTER´S THESIS

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v anglickém jazyce:

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ROZŠÍŘENÝ ABSTRAKT

1. Úvod

1.1 Úvod do problematiky

Chlazení v řezném procesu bylo poprvé použito F. W. Taylorem počátkem 20. století. Následně pokračovala éra užívání procesních kapalin ve velkém množství za účelem zlepšení řezného procesu. Tento trend pokračuje napříč celým 20. stoletím. Až ke konci století se začíná náhled na věc měnit. Používání procesních kapalin má sice pozitivní dopad na řezný proces, má ovšem i své negativní aspekty. Procesní kapaliny znečišťují životní prostředí a škodí zdraví pracovníků pohybujících se v jejich blízkosti. Nejčastějšími problémy jsou onemocnění kůže a dýchacích cest. Navíc recyklace těchto kapalin je náročná a nákladná. To nás přivádí ke druhému aspektu, což je ekonomická stránka věci. Náklady spojené s procesními kapalinami (kapaliny samotné, filtry, údržba atd.) se pohybují mezi 7-17% všech výrobních nákladů. Je tedy logické, že firmy se snaží tento podíl minimalizovat. Nejlevnější a nejekologičtější varianta je samozřejmě obrábění za sucha. Za sucha se běžně provádí některé soustružnické a frézovací operace. V případech, kdy je obrábění za sucha velmi komplikované až nemožné se používá metoda minimálního množství maziva, tzv. MQL (Minimum Quantity of Lubrication). Aplikované množství maziva je v řádu ml/h, zatímco při konvenčním chlazení počítáme s l/min. MQL tedy používá množství o 6 řádů menší, přičemž výsledky týkající se kvality obrobeného povrchu či řezných sil jsou mnohdy srovnatelné s konvečním užití kapalin. Navíc v porovnání s obráběním za sucha MQL dosahuje výsledků lepších.

1.2 Organizace práce

Cílem práce je porovnání řezivosti 4 různých olejů v aplikaci MQL. Základní charakteristiky olejů jsou sepsány v tab. 4.7, názvy olejů však z důvodu utajení zmiňovány nebudou. Obráběné materiály jsou korozivzdorná ocel AISI 316L a vytvrditelná hliníková slitina EN-AW 7020. Oba materiály jsou testovány při soustružení (ortogonálním řezu) a vrtání.

Práce je rozdělena na dva bloky; teoretická rešeršní část a část experimentální. Práce obsahuje 6 kapitol: Úvod, kapitola zaměřenou na procesní kapaliny a bibliografická rešerše, jejímž účelem je ucelit informace před prováděnými testy, patří do teoretického bloku práce. Experimentální část obsahuje také tři kapitoly, a to popis přípravy a průběhu experimentů, výsledkovou část a závěr.

2. Procesní kapaliny

2.1 MQL

MQL je způsob mazání za použití minimálního množství maziva. Jedná se o směs proudu vzduchu s miniaturními kapkami oleje, která je dopravována do místa řezu v podobě aerosolu či mlhy.

Jak už napovídá anglické slovo lubrication ze zkratky MQL, hlavní funkcí MQL je funkce mazací. Vedlejší funkce, vykonávány hlavně proudem vzduchu, jsou chlazení a odvod třísek.
Olej není po aplikaci MQL není recyklován, protože se prakticky všechen vypaří v důsledku tepla vznikajícího při obrábění.
Přívod MQL může být externí nebo interní (skrz nástroj mazacími kanálky) stejně jako klasické mazání či chlazení. Externí přívod bývá používán pro většinu vnějších operací (např. soustružení), interní mazání je důrazně doporučeno např. pro vrtání děr s poměrem l/D větším než 3. Jelikož interní přívod je nejčastěji uplatňován pro rotační nástroje, může zde vzniknout komplikace, že MQL směs je v důsledku odstředivé síly jaksi uvězněna v nástroji, držáku, či vřetenu a není ve správném množství dovedena do místa řezu.
Pro interní i externí přívod existují 2 systémy vedení: jednokanálový a dvoukanálový přívod. Jednokanálový přívod znamená, že vzduch a olej jsou přivedeny do místa řezu společně jedním kanálkem. Druhá varianta je jeden kanál pro vzduch a druhý vnitřní kanál pro mazivo. Tyto 2 kanálky se slučují těsně před tryskou. Dvoukanálový způsob je obecně lepší, protože mlha je tvořena až v místě, kde je potřeba. V případě jednokanálového systému je problém, že olej spíše teče po stěně hadičky a tvorba mlhy pomocí trysky může být problematická.
Nejdůležitější parametr MQL je objemový průtok oleje. Je udáván v ml/h, pohybuje se v rozmezí 5 – 80 ml/h a měl by být nastavitelný na každém čerpadle MQL. Druhým proměnným parametrem je tlak vzduchu. Udává se v barech a pohybuje se mezi 4 – 8 bary. V některých případech se může měnit i průtok vzduchu. Průtok vzduchu bývá poměrně vysoký (25-350 l/min), aby olej, co nejlépe prostupoval do místa řezu a aby byl zachován chladicí a čisticí účinek MQL.

2.2 Funkce procesních kapalin

Existují 2 základní funkce procesních kapalin, mazací a chladicí. Mazací funkce je zajišťována oleji a kapalinami na olejové bázi. Chladicí funkce je prováděna kapalinami na vodní bázi, nejčastěji tzv. emulze. Voda má vysokou měrnou tepelnou kapacitu, a proto má velmi dobrou ochlazovací schopnost. Mazání je obecně aplikováno při nižších řezných rychlostech, chlazení při vyšších, protože teplota roste s řeznou rychlostí.

Maziva snižují opotřebení nástroje, tření, částečně teplotu a udržují si svoje vlastnosti po dlouhou dobu. Jejich vlastnosti závisí na smáčivosti, viskozitě a schopnosti pronikat na rozhraní nástroj / tříska.
Obecně se tvrdí, že olej snižuje tření díky tenké vrstvě vytvořené v místě řezu. Pravdou však je, že hlavní důvod snižování tření spočívá ve zmenšení kontaktní délky mezi odcházející třískou a nástrojem na čele.
Nevýhodou používání maziv je vysoká cena, hořlavost a větší škodlivost pro lidské zdraví než kapalina na vodní bázi.

Chladicí řezné kapaliny působí na nástroj, třísku i obrobek. Vysoká teplota při řezu zkracuje životnost nástroje. Dále chlazení snižuje tepelnou roztažnost a tím přispívá k lepší rozměrové přesnosti obrobku. Kapalina navíc odvádí třísky pryč z pracovního prostoru. Stejně jako maziva chladicí kapalina snižuje kontaktní délku na rozhraní. Obecně nižší teplota zkracuje kontaktní délku nebo délka může být zkrácena chlazením třísky z vnější strany (ne mezi čelem a třískou), což třísku zkrucuje a tím minimalizuje kontakt třísky s čelem nástroje.

Procesní kapaliny můžeme rozdělit na několik kategorií:

2.2.1 Čisté oleje

Jedná se o nerozpustné oleje bez přísad. Aplikují se při nižších řezných rychlostech (v_c=30 m/min). Jejich původ může být minerální, rostlinný, živočišný nebo syntetický. Existují směsi jedlých a minerálních olejů, nebo mohou být přidávána aditiva zvyšující účinnost při vysokém tlaku. Aditiva jsou sirného, chlorového nebo fosforového původu.

2.2.2 Rozpustné oleje

Jedná o směs oleje a vody v určitém poměru, od 1/10 až po 1/50. Nejčastějším příkladem těchto kapalin jsou emulze. Emulze mají vysokou chladicí schopnost, nicméně díky přítomnosti oleje přispívají i k mazání.

2.2.3 Syntetické kapaliny (na vodní bázi)

Neobsahují žádný olej. Je to směs vody a anorganických chemických látek. Mají výbornou chladicí schopnost, ale kvůli absenci oleje velmi špatnou mazací. Výhodou je jejich průhledná barva, což umožňuje lepší viditelnost na obráběcí proces.

2.2.4 Polosyntetické kapaliny (na vodní bázi)

Obsahují 5-50% oleje. Kombinují výhody čistých olejů a syntetických řezných kapalin. Jsou méně škodlivé než minerální oleje a stejně jako syntetické kapaliny jsou průhledné.

2.2.5 Plyny

Chlazení plyny se běžně nepoužívá. Přesto nejtypičtějším plynem při obrábění je vzduch, který může být přiveden do místa řezu jako stlačený nebo můžeme s jistou mírou nadsázky říci, že vzduch při atmosférickém tlaku ochlazuje řezný proces při obrábění za sucha. Inertní plyny (Ar, He, N) se někdy využívají jako ochranná atmosféra proti korozi

2.2.6 Pevná maziva

Mohou být použity při závitování, vystružování nebo broušení nožů, obecně však jejich využití při obrábění je prakticky nulové. Využívají se spíše na údržbu strojů.

3. Bibliografická rešerše

Procesní kapaliny mohou být hodnoceny více způsoby. Základní rozdělení je na metody přímé a nepřímé. Příkladem přímých metod jsou hodnocení trvanlivosti nástroje, rozměrové přesnosti obrobku, kvality povrchu či spotřeby energie během obráběcího procesu. Nepřímé metody jsou většinou spojeny s řeznými silami, takže je nutné je měřit přímo při obrábění. Jsou to např. krouticí moment a posuvová síla při vrtání, jednotlivé složky řezných sil, studování vibrací, kontaktní délky na čele nástroje či součinitele pěchování třísky.

3.1 MQL

Podle literárních pramenů se objemový průtok oleje 5 ml/h se zdá být nedostatečný, řezné síly se hodně blíží silám naměřeným při chlazení stlačeným vzduchem. Naopak průtok 15 nebo 23 ml/h dosahuje vlastností blížícím se konvenčnímu chlazení.
Kvalita děr při vrtání oceli AISI 86400 je shodná při použití MQL a emulze.
Při obrábění hliníkových slitin je MQL účinnější při vysokých řezných rychlostech, méně materiálu přilíná na nástroj. MQL navíc dosahuje vyšší opakovatelnosti výsledků při měření drsnosti povrchu než konvenční chlazení.
Kontaktní délka na čele nástroje se snižuje se zvyšujícím se průtokem MQL, zajímavé je množství objemové průtoku MQL nemá vliv na trvanlivost nástroje při vrtání.
Obecně použití MQL sníží řezné síly o 1-37% oproti obrábění za sucha.

Kromě klasické technologie MQL existují i různá vylepšení. Jedním z nich je přidání různých plynů (O_2, Ar_2, N_2), přičemž kyslík zaznamenává nejlepší výkonnost. Druhá možnost je přidání mikrokapek vody do směsi olej – vzduch. Společným znakem těchto modifikací je zlepšení účinnosti MQL, hlavně z hlediska řezných sil.

3.2 Ortogonální řezání

Ortogonální řezání je experimentální metoda. Je třeba splnit 2 podmínky. Aby řezání bylo opravdu ortogonální, tak úhel nastavení hlavního ostří musí být κ_r=90° a úhel sklonu hlavního ostří λ_s= 0°. Ortogonálního řezu je možno dosáhnout při soustružení nebo při hoblování. Při soustružení existuje několik metod. Podélné soustružení trubky (celé stěny), příčné soustružení tenkého disku nebo místo disku může být použit válcový polotovar, který byl předobrobený tak, aby na něm byly 2 různé průměry – více disků na válci

(Fig. 3.3). Důležitým parametrem je šířka disku (či stěny trubky). V literatuře byly nalezeny hodnoty 1,2 mm a 2,5 mm, v protokolech z laboratoře 3 mm.

3.3 Vrtání

Pro testování výkonnosti řezných kapalin při vrtání se nejčastěji provádí test trvanlivosti a měření řezných sil. Test trvanlivosti vyžaduje větší množství času a opakovatelnost není příliš dobrá. Měření řezných sil je časově méně náročné a opakovatelnost je lepší.

Životnost nástroje je definována jako počet vrtaných děr (či vrtaná délka) do úplného zničení nástroje. Trvanlivost nástroje se zhoršuje s rostoucí teplotou, takže chlazení má pozitivní vliv. V některých případech však může mazivo paradoxně působit nepříznivě na trvanlivost nástroje tím, že odstraňuje nárůstek, který sice poškozuje geometrii břitu, zároveň ho však chrání.

Při vrtání potkáváme dva základní problémy: odvod třísek a teplota. Oboje se teoreticky zlepší aplikací kapaliny. Vrtání hlubokých děr je možné při aplikaci MQL s vnitřním přívodem.

Hliníkové slitiny jsou nejčastěji vrtání nástroji z rychlořezné oceli, nebo karbidy nepovlakovanými nebo povlakovanými DLC. Na karbidových nástrojích se většinou netvoří nárůstky jako na rychlořezné oceli. Řezné podmínky pro vrtání hliníkových slitin se pohybují okolo v_c=100 m/min pro nástroje z rychlořezné oceli a v řádu stovek m/min pro karbidové nástroje. Posuv na otáčku se nachází v rozmezí 0,1 – 0,25 mm pro oba obráběcí materiály.

Korozivzdorná ocel AISI 316L je obecně považována za hůře obrobitelný materiál díky nízké tepelné vodivosti, sklonu k velkému deformačnímu vytvrzení a tvorbě nárůstku. Tento materiál bývá téměř výhradně vrtán za pomoci konvenčního chlazení. Proto v dostupné literatuře nebyl nalezen žádný příklad vrtání této oceli za použití technologie MQL.

Stejně jako v případě hliníkových slitin, AISI 316L bývá obráběna vrtáky buď karbidovými (povlak TiAlN) nebo z rychlořezné oceli. Rychlořezná ocel může nepovlakovaná, povlakovaná TiN nebo s přídavkem kobaltu. Nalezené řezné podmínky pro nástroj z rychlořezné oceli jsou v_c = 15 – 40 m/min a f = 0,1 mm. V případě karbidového vrtáku se hodnoty pohybují okolo v_c = 40-80 m/min (výjimečně 100 m/min) a f = 0,04 – 0,2 mm. Všechny uvedené hodnoty jsou v situaci konvenčního chlazení.

3.4 Měřící techniky

Měření teploty při vrtání slepých děr probíhá téměř výhradně termočlánky. Termočlánky bývají rozmístěny podél vrtané díry, mohou obklopovat díru z více stran. Každopádně je třeba předem vyvrtat do součásti díry pro vložení termočlánků. Důležité je zachovat vzdálenost mezi koncem termočlánku a stěnou budoucí díry, literaturou doporučená hodnota je 0,3 mm.

Kromě klasického termočlánku existuje i bezdrátový systém, který spolehlivě funguje až do rychlosti 20 000 min^{-1}. Je však třeba speciální vrták s drážkou

pro zavedení termočlánku podél šroubovice vrtáku od držáku až k ostří. Od držáku je signál rádiově přenášen do zesilovače a počítače.
U průchozích děr je možné měření teploty termokamerou v místě, kde vrták vystupuje z materiálu.

Měření teploty při ortogonálním řezání je jednodušší protože se jedná o vnější operaci. Lze tedy jednoduše použít termokameru, která s určitou frekvencí vyfotí obrázky ve stupních šedi. Tyto obrázky je možné například v MATLABu transformovat na barevné obrázky s odpovídající teplotní škálou. Existuje levnější varianta, tzv. CCD kamery, které částečně nahradí termokamery. Nevýhodou je, že fungují blízko infračervené oblasti, takže není možné jimi měřit nižší teploty, např. při obrábění hliníkových slitin.

Měření silového působení při obrábění probíhá bez ohledu na druh operace piezoelektrickými dynamometry. Signál je přenášen do zesilovače a dále zpracováván v počítači programem LabView nebo DasyLAB. U soustružení a frézování jsou měřeny síly ve 3 osách (či řezná, posuvová a pasivní složka). U vrtání se nejčastěji měří krouticí moment a posuvová síla. Síly při vrtání je možné měřit síly dvěma způsoby; buď statickým dynamometrem na součásti, nebo rotačním dynamometrem na nástroji.

4. Průběh experimentální části

4.1 Ortogonální řezání

Vybrána byla možnost obrábění disku. Disky jsou pro oba materiály shodné. Jsou vyrobeny z válcového polotovaru d=75 mm. Polotovary byly podélně osoustruženy na 70 mm. Do nich byla vyvrtána díra o d = 25 mm, následně byly upíchnuty disky o šířce 3 mm.
Pro tyto pokusy byl vyroben přípravek, který byl upnut do sklíčidla a umožňoval rotaci disku při obrábění.
Pokusy byly prováděny na CNC soustruhu SOMAB T400. Bylo měřeno silové působení a teplota. Řezná a posuvová složka síly byly měřeny za pomoci dynamometru KISTLER 9121 a softwaru DasyLAB. Teplota byla měřena kamerou s infračerveným filtrem, což znemožnilo měření teploty při obrábění hliníkové slitiny kvůli nízké teplotě. Získané obrázky ve stupních šedi byly zpracovány za pomoci programu MATLAB.
Mazivo ve formě MQL bylo vytvářeno přístrojem Lubrimat L60 od německého výrobce Steidle. Jedná se o externí dvoukanálový přívod.

Proměnné parametru pokusů jsou 4 oleje, 2 řezné rychlosti, 2 objemové průtoky oleje a 2 tlaky vzduchu. Také jsou 2 materiály, ale pro každý materiál je odlišný experimentální plán. Plán vychází z Taguchiho tabulky, kde pro tuto konfiguraci experimentu je tzv. kompletní plán 32 testů na materiál. Kompletní plán se však většinou omezí na tzv. optimální plán, který je v tomto případě 16 testů na materiál. Na každý pokus bylo použito nové ostří nástroje.

Na obrábění AISI 316L byly použity vyměnitelné břitové destičky povlakované TiAlN + TiN od firmy SECO. Na hliníkovou slitiny nepovlakované karbidové destičky taktéž od firmy SECO.

4.2 Vrtání

Součásti pro vrtací testy byly nejprve řezány pásovou pilou z poměrně velkých kvádrů, poté frézovány na konečné rozměry 73x40x45(50 pro EN-AW 7020). Jedna součást slouží pro vrtání 8 experimentálních děr průměru 12mm a hloubky 36 mm. Byly vyrobeny 4 součásti z každého materiálu, což poskytuje dostatečnou rezervu pro pokusy. Dále musely být vyvrtány díry pro vložení termočlánků. Tyto díry mají průměr 1mm a hloubku 4,7. Jedná se obtížnější operaci vzhledem malému průměru a velkému l/D poměru. Podél každé experimentální díry bylo vrtáno 6 děr pro termočlánky, což dohromady znamená 192 děr na materiál. Rozteč mezi jednotlivými dírami je 5 mm. Pro vrtání 1mm děr byly zvoleny nepovlakované karbidové vrtáky od firmy SECO. Jeden na předvrtání, který umožňuje vrtání do hloubky pouze 2mm a druhý, který vyvrtá díry do potřebné hloubky. Vrtání těchto děr probíhalo za intenzivního chlazení emulzí.

Pokusy jsou prováděny na 3-osé CNC frézce DMG DMC 65V. Zdrojem MQL je tentokrát numericky řízené čerpadlo od firmy SKF. Umožňuje interní jednokanálový přívod MQL. Je možné vybrat ze 16 přednastavených konfigurací MQL. Jednotlivé konfigurace se liší objemovým průtokem oleje a vzduchu, tlak vzduchu je fixní 6 barů.
Ze silového působení byly měřeny veličiny pro vrtání typicky, tzn. kroutící moment a posuvová síla pomocí rotačního dynamometru KISTLER 9123C a softwaru DasyLAB. Pro měření teploty byly využity termočlánky a taktéž software DasyLAB.

Experimentální plán se nezměnil co se týče velikosti oproti ortogonálnímu řezání, co se týče obsahu však ano. S přihlédnutím k výsledkům ortogonálního řezání bylo shledáno, že jediný opravdu vlivný parametr je řezná rychlost. Pro tentokrát byly pro každý materiál stanoveny fixní řezné podmínky. Zařízení SKF neumožňuje měnit nezávisle 2 parametry MQL, pouze celou konfiguraci. Proměnné parametry experimentálního plánu tedy jsou 4 oleje a 2 konfigurace MQL. Kompletní plán je 8 pokusů, tento plán bude opakován, čímž se dostáváme na počet 16 pro každý materiál.

Pro testy vrtání do hliníkové slitiny byly použity nepovlakované karbidové vrtáky od Sandvik Coromant. Na pokusy s každým olejem byl použit jeden nástroj, tzn. nástroj na 4 díry, přičemž po každé díry bylo případné opotřebení nástroje visuálně kontrolováno na optickém mikroskopu KEYENCE. Pro měření teploty však byly použity pouze 4 termočlánky proti původním šesti, protože bylo použito jiného příslušenství, které neumožňuje připojení 6 termočlánků.

Na vrtání korozivzdorné oceli byly vybrány povlakované karbidové vrtáky. Kvůli problémům při předběžných tzv. COM testech (pro určení optimálních řezných podmínek), kdy došlo ke zničení několika nástrojů, musela být zredukována řezná rychlost i hloubka vrtané díry na konečných 15mm. Pro tuto hloubku bylo účelné zapojit pouze 2 termočlánky. Každý nástroj byl použit na 2 díry, pokus a jeho opakování.

5. Výsledky a komentáře

Výsledky byly zpracovány rozptylovou analýzou. Rozptylová analýza určí, jestli faktor (proměnný parametr – olej, objemový průtok atd.) má podstatný nebo zanedbatelný vliv na konkrétní měřený parametr (řezné síly, teplota). Tabulky s těmito vlivy jsou umístěny v přílohách.

5.1 Ortogonální řezání

Výsledky ortogonálního řezání je možno rozdělit na 3 skupiny: řezné síly, teplota a drsnost povrchu. Způsob měření první dvou veličin je popsán výše, kvalita povrchu byla měřena dotykovým přístrojem Somicronic Surfascan. Každý disk byl měřen třikrát.

Ze silového působení byla měřena průměrná hodnota řezné a posuvové složky a také výchylka řezné složky. Síly jsou ovlivňovány prakticky jen řeznou rychlostí, přičemž při vyšší rychlosti jsou obecně síly menší, stejně tak výchylka F_c při obrábění AISI 316L.
Výsledky teploty byly zpracovány pouze pro AISI 316L, protože dostupné vybavení (kamera s infračerveným filtrem) neumožňuje měření teplot nižších než cca 450°C. Čili nebylo možné změřit teplotu při obrábění hliníkové slitiny.
Na teplotu má podle rozptylové analýzy vliv řezná rychlost a tlak vzduchu. Teplota roste s řeznou rychlostí, tlaku vzduchu sice mění teplotu, ale způsobem natolik nepravidelným, že jej nelze spolehlivě interpretovat.
Jako parametr popisující drsnost povrchu byl vybrán Rt. Vzhledem k povaze testů ortogonálního řezání, kde Rt není klasicky ovlivňováno hodnotou posuvu, je kvalita povrchu velmi dobrá. Pro hliníkovou slitinu jsou hodnoty Rt i odchylky mezi jednotlivými oleji natolik malé, že žádný rozdíl nemůže být konstatován. V případě korozivzdorné oceli jsou sice hodnoty i rozdíly vyšší, ale jejich charakter je příliš náhodný, což je potvrzeno i rozptylovou analýzou. Podle ní nemá na strukturu povrchu žádný faktor rozhodující vliv.

Závěr z testů ortogonálního obrábění je, že není patrný zásadní rozdíl ve výkonnosti jednotlivých olejů. V některých případech jsou dokonce výsledky testů za sucha lepší než při použití MQL. Celkově olej B (s nejvyšší viskozitou) dosahuje nejhorších výsledků, rozdíly jsou však natolik nepatrné, že se pohybujeme spíše v oblasti hypotéz. Vysvětlením těchto výsledků může být určitá nenáročnost operace ortogonálního řezání. Neboť se jedná o vnější operaci a pouze 2D řez, takže se účinky jednotlivých olejů nemohly plně rozvinout.

5.2 Vrtání

Při vrtacích pokusech byly měřeny stejné veličiny jako při ortogonálním řezání, drobný rozdíl je v měření silového působení, zde je měřen krouticí moment a posuvová síla. Kvalita povrchu se rovněž měří přístrojem SOMICRONIC Surfascan, přičemž povrch obvodové stěny každé díry je měřen třikrát. Všechny grafy obsahují výsledky pro 4 oleje a každý olej pro 2 objemové průtoky, což znamená 8 sloupců. Do vybraných grafů je pro ilustrační srovnání přidána hodnota dané veličiny při vrtání za sucha z předchozích testů.

Vrtací pokusy přinesly daleko zajímavější výsledky. Rozdíly mezi jednotlivými oleji jsou patrné, což je potvrzeno i rozptylovou analýzou. V oblasti řezných sil jsou rozdíly mnohem znatelnější na krouticím momentu než na posuvové síle. Výsledky krouticího momentu ukazují, že aplikace MQL snižuje silové působení oproti obrábění za sucha. Ze silových výsledků vychází jako jednoznačně nejlepší olej D, nejhorších výsledků dosahuje olej A.
Naměřené hodnoty teploty jsou těžko vysvětlitelné. Například olej A má nejmenší chladicí účinek pro AISI 316L a naopak největší při vrtání EN-AW 7020. Avšak rozdíly mezi jednotlivými teplotami nejsou markantní.
Výsledky drsnosti povrchu jsou velmi rozdílné pro oba materiály. V případě korozivzdorné oceli jsou výsledky všech olejů velmi podobné, ale mnohem lepší než při vrtání za sucha. U hliníkové slitiny zaznamenávají oleje A a C velmi dobré výsledky, naopak C a B velmi špatné (při použití oleje B je hodnota Rt dokonce vyšší než za sucha).
Celkově pomyslnou soutěž s přehledem vyhrál olej D, který dosahuje nejlepších výsledků ve většině parametrů. Olej D je na syntetické bázi. Výkonnost ostatních tří olejů je velmi vyrovnaná. Olej A byl sice nejhorší, co se týče snižování silového působení, nicméně předčil zbylé dva oleje v chladicím účinku a v drsnosti povrchu.

6. Závěr

Práce se zabývá poměrně komplexní problematikou, byť to není na první pohled zřejmé. Kromě obrábění je zde problematika řezných kapalin a systému MQL. Je důležité také pracovat s poměrně velkým počtem měřících systémů.

Testy vrtání ukázali mnohem více rozdílů v řezivosti olejů než ortogonální řezání. Díky vrtacím pokusům můžeme konstatovat, že pro studované parametry je nekvalitnější olej D. Pořadí dalších olejů je velmi obtížné určit. Poněkud překvapivé je zjištění, že objemový průtok nemá podle provedených testů prakticky žádný vliv na studované parametry ani při ortogonálním řezání ani při vrtání.

Zajímavým obohacením práce by byly testy trvanlivosti nástroje při vrtání, z časových důvodů bohužel však nemohly být uskutečněny v rámci této práce.
.
Na závěr bych rád přidal několik osobních doporučení vypozorovaných během experimentů. Vrtání korozivzdorné oceli AISI 316L při aplikaci MQL je komplikované a pravděpodobně i ekonomicky nevýhodné.
Při používání přívodu MQL středem nástroje, je vhodné mít k dispozici dvoukanálový systém, aby směs byla tvořena až těsně před vřetenem. Nicméně druhý problém s odstředivou silou bude i tak přetrvávat.
MQL je ekologická metoda z hlediska spotřeby kapaliny. Mlha, vznikající při MQL, je však zdraví škodlivá a dosti nepříjemná pro pracovníky obsluhy strojů. Odsávací systém by tedy měl být součásti každého stroje, na které je MQL používáno.

Klíčová slova: MQL, řezné oleje, ortogonální řezání, vrtání

ABSTRACT

This paper deals with the Minimal Quantity Lubrication (MQL) application. The aim is to compare experimentally the performance of 4 different cutting oils. The oils will be called A,B,C and D and their elementary characteristics are listed in the chapter Experimental part. Their commercial designations won´t be mentioned because of confidentiality reasons.
The performance of the oils will be tested at turning orthogonal cutting and drilling. Two workpiece materials are used for the both operations: stainless steel AISI 316L and aluminum alloy EN-AW 7020. Evaluated parameters for turning and drilling tests are the cutting forces, the maximum temperature and the surface roughness.
The experimental part is preceded by bibliographic research about cutting fluid, the MQL application in general, the machining operation (orthogonal cutting and drilling) with accent on the fluid application and the measurement of the temperature and cutting forces.

Keywords: MQL, cutting oils, orthogonal cutting, drilling

BIBLIOGRAFICKÁ CITACE

PAZDERA, L. *Hodnocení řezivosti vybraných procesních kapalin v aplikaci MQL.* Brno: Vysoké učení technické v Brně, Fakulta strojního inženýrství, 2013. 95 s., 4 přílohy, Vedoucí diplomové práce prof. Ing. Miroslav Píška, CSc..

Statement

I declare that the present diploma thesis with its name On the cutting performance of selected process fluids in the MQL application was carried out only by me with the help of literature and sources stated in the reference list which is a part of this diploma thesis.

Datum 24. 5. 2013

…………………………………….

Bc. Lukáš Pazdera

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CONTENT

1 INTRODUCTION

1.1 Background of the project

The cooling by water was used for the first time at the beginning of 20th century by F.W. Taylor and the result was the increased tool life. It started a large use of cutting fluids. [1] Machining of nowadays tends to decrease the amount of process fluids. There are several reasons for this: It is especially the economical and ecological motives, or there could be also technological reasons. The economic reason is paramount. Lubricants, including the equipments, accessories, recycling system and maintenance, represent 7-17% of the total production cost. Therefore the companies look for reducing these costs. The principle is simple, less fluids the company consumes, less it costs. Consequently, the techniques that avoid heavy watering develop. It is the dry machining and the near-dry machining (NDM) which uses the technology of minimum quantity lubrication (MQL). [1, 2, 3, 4, 5, 6, 8]

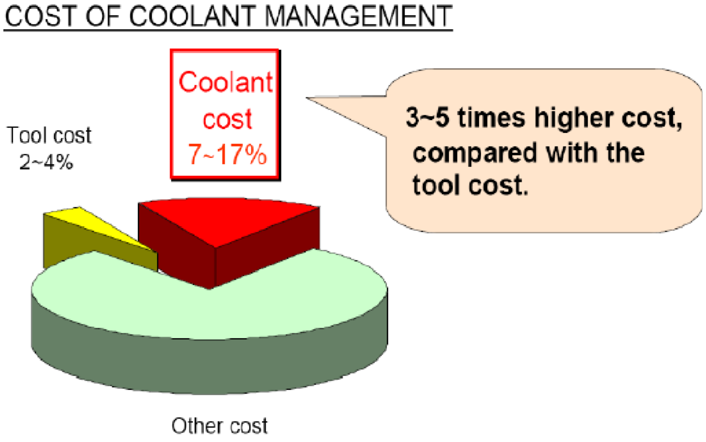

Fig 1.1 – Cost of coolants in manufacturing process [2]

The second aspect of the use of MQL is the ecology and the health protection. In our age, we must protect the nature and the environment. Even if the fluids are recycled, anyone cutting fluid is more or less harmful whatever it is, an emulsion or an oil. During the machining process, the fluids evaporate and they soil workspace of the machine at the same time. These effects are unfavourable to the global environment, but especially for operators who find themselves in daily contact with the fluids. Operators touch the fluid wetted parts and breathe the vapors containing fluids which can cause skin and lungs diseases. Moreover, many cutting fluids contain extreme pressure (EP) additives such as chlorinated paraffines, which have been identified as potentially carcinogenic substances. [3, 7]

That is why the state governments and international organizations try to motivate companies to make production more environmentally friendly. There are established a system of rules by means of laws and punishments in one side, but also some motivation by means of various certificates if the company fulfills certain conditions. A certificate of ecology can improve the company image in the market and can be used for advertising purposes. This links the economic and ecological aspect of using the MQL.

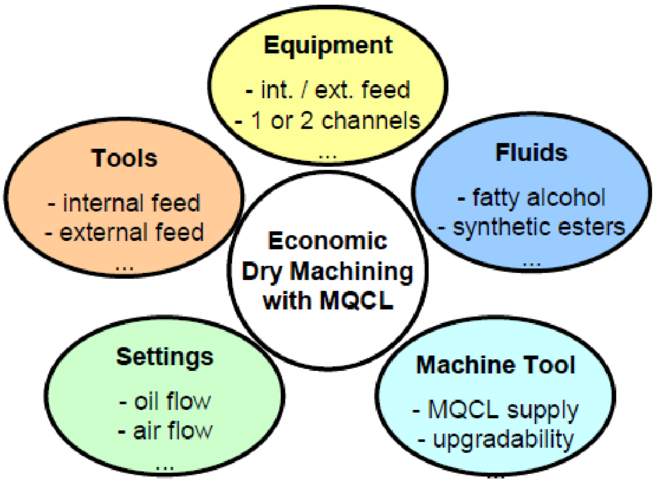

Fig 1.2 – Aspects of MQL [4]

The optimum is to achieve the completely dry machining, because there is of course no cost of lubrication, no maintenance required and the machine environment stays clean. The dry machining is already widely used for several applications, for example the turning of hard materials or the machining of aluminum or magnesium. [1]

Nevertheless dry machining is not feasible for all types of operations. Especially inside operations (such as drilling or tapping) require the use of fluid to remove chips from the hole and to reduce cutting forces. This brings us to the second option, the machine near-dry machining using the minimum amount of lubrication. Henceforth, we will call them by the abbreviations (NDM = Near Dry Machining and MQL = Minimal Quantity of Lubrication). The amount of lubricant used in MQL is counted in ml/h, meanwhile in the conventional watering in liters per minute. That makes the difference of flow by order of 10^6. It is the coefficient of one million. [9] However, the results of cutting forces and surface condition using MQL are often comparable or even better in some cases compared to conventional cooling. Moreover, the MQL achieved clearly better results in the mentioned criteria relative to the dry machining. This is the purpose of the MQL. [10]

1.2 Organization of the work

The work is divided into the theoretical and experimental part and it contains overall 6 chapters and the appendices.

1.2.1 Theoretical part

The introduction mentions the ecological and economical aspects of using the MQL and the organization of the work.
The second chapter of this work is focused on the issues of cutting fluids. The objective of this review is to deepen the knowledge about the cutting fluids, their division. The MQL application is also explained in this chapter.
The third chapter summarizes the bibliographic research done about all main topic of this project. The first part of this the theoretical review concerns the orthogonal cutting. About that there are not many useful publications on the internet. On the other side, several orthogonal cutting tests were carried out during the previous years in the laboratory of Cluny. Therefore, internal laboratory documents, reports written by former students, were studied. I would like to compare different ways of orthogonal cutting and choose the one most suitable. At the same time, the experimental plan of the tests is based on the Taguchi table. [11]
The portion after is directed to the other test run of the project, that is to say the drilling. It is necessary to find how the drilling tests are routinely done. Information on several things were searched: the hole diameter, the drilled depth, the coating of machining material and cutting conditions. What is strongly related to drilling tests, it is the tool life tests, which are included in the theoretical review.
In parallel, some information is gathered about the acquisitions and forces and temperature measurement. The force and temperature measurement temperature is common for all tests, but the measurement way is different for orthogonal cutting and drilling.

1.2.2 Experimental part

The 4th chapter describes the samples preparation and the experimental setup of the both provided tests, the orthogonal cutting and the drilling.
This chapter is logically succeeded by results and commentaries. The work is terminated by the conclusion and practical recommendations.

2 PROCESS FLUIDS

2.1 Description of the MQL

2.1.1 Principle of MQL

The MQL lubrication is composed of oil and compressed air. These two components form an aerosol mixture, which is applied to the cutting area. The oil is introduced at a determined rate, the amount of air is regulated by the inlet pressure. Once the oil and the air are mixed, a mist forms and lubricate the cutting area. Because the amount of the oil is very minimal (order of ml/h), the heat generated during machining evaporates practically the integrity of the oil. So, the workpiece is got out dry and clean, which present a significant advantage over the conventional lubrication, because neither degreasing nor cleaning of the workpiece is necessary. [1, 3]

Oil is the main component because it provides the lubrication of the cutting area. The primary function of the air is to blow and transport the oil into the application area. The secondary functions are to help to evacuate the chips (e.i. drilling) and also cool, but this capacity is not important.

2.1.2 MQL application

We distinguish two types of MQL application: external and internal supply. The external supply sprays the aerosol on the cutting edge via external nozzles. This method can be used for the operations where the fluid accessibility on the cutting edge is not very limited, such as milling, turning, sawing or drilling with l/D ratio < 3. The internal application is used for tapping, reaming and deep hole drilling. For both types of MQL, there is the one-channel supply and two-channel (dual) supply system. The one-channel supply means that the MQL mixture is formed outside the spindle and there is only one channel which brings the aerosol towards to the tool. The two-channel supply feeds the oil and the air separately, and the mixture is produced just in front of the tool. [2, 4]

A disadvantage of internal system is that the mist could be easily dissipated in the toolholder or in the tool and the effect is limited. [12]

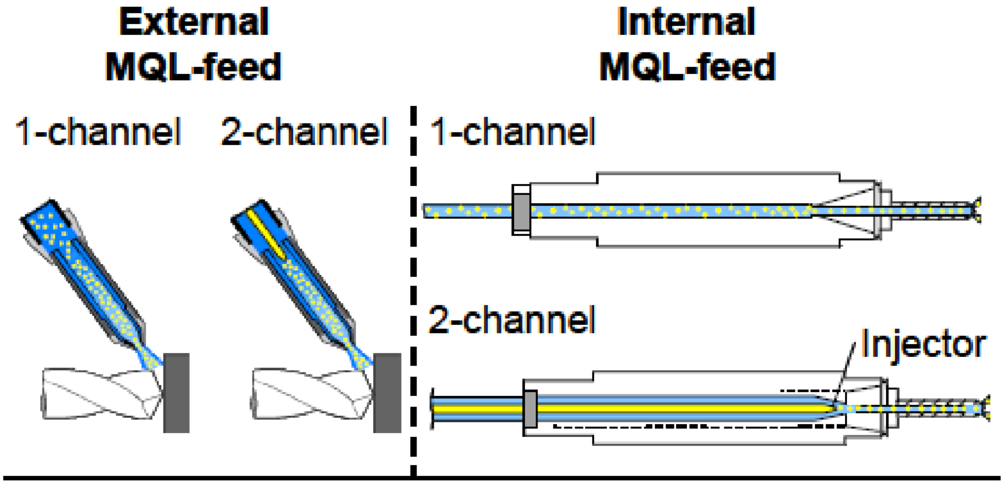

Fig 2.1 – MQL supply systems [4]

2.1.3 Adjustable parameters of the MQL

The practical information on adjustable parameters of the MQL must be analyzed to be able to perform the tests. This information is contained in the vast majority of articles. This is the oil rate, the air pressure and some publications specify also the air rate. The oil rate usually varies between 10 (exceptionally 5 ml/h) and 100 ml/h, but usually the oil rate does not exceed 80 ml/h. The air pressure is expressed in units of bars, the most common value is 6 bars, the current range is from 4 to 8 bars. The magnitude of the air rate is about hundreds of liters per minute. [1, 5, 13, 14, 15, 16, 17, 18, 19]

2.2 Cutting fluid action

The aim of cutting fluids is to improve the efficiency of machining operations in terms of tool life, surface finish, dimensional tolerances, cutting forces, vibrations and energy consumption. Another function is to flush away the chips and protect the workpiece from corrosion. But their effect depends not only on the fluid properties but also on the workpiece material, tool material and geometry and cutting conditions. [1, 20, 21]

There are two basic types of cutting fluid action. It is the lubrication and the cooling. The lubrication ensured by oil-based fluids, is effective at lower cutting speeds and prevents the formation of the BUE.
At higher cutting speeds, the cooling capacity of fluid becomes more needful, therefore the water-based solutions are applied. [1]

The ensemble of cutting media can be divided according to the physic state onto liquid, semi-solid (colloidal), solid and gaseous. The liquid category is the most common and it includes mineral, vegetable and animal, synthetic oils and generally all coolants. Some fatty lubricants, emulsions and parrafines are classed into the semi-solid (colloidal) group. Solid lubricants are lamellar, polymeric, soft metals, oxides and powders. The compressed air or the air at the atmospheric pressure (simply the case of the dry machining) can be considered as a gaseous coolant. [20, 22]

2.2.1 Lubricating action

Some of general functions of a lubricant are the reduction of the tool wear, the friction decreasing, cleaning of contact surfaces, the cooling effect and maintaining its properties for a long term. [22]

The lubrication efficiency depends on the fluid wettability, viscosity, layer resistance and the ability of penetrating on the chip-tool interface. [1]

Classical theories say that the oil creates a soft film at the chip-tool interface and reduces the friction coefficient. But the main goal of the lubrication is the restriction of the contact area and contact length on the interface. This implies the chip speed increasing and the reduction of vibrations, BUE formation, chip temperature, chip compression ratio (thinner chip), cutting forces and energy consumption. This causes a lower load on the rake face, better fluid accessibility and reduced chip adhesion. The decrease of the contact length improves the surface finish quality especially at low cutting speeds. The tool rake face or the clearance face can be lubricated. [21, 23, 24, 25, 26, 28]
Disadvantages of using oils are high cost, fire risks, smoke formation and higher risk to the human health comparing to the water-based cutting fluids. [1]

2.2.2 Cooling action

The energy consumed during machining process is almost completely transformed on the heat. This heat is dissipated into the chip, the workpiece and the tool. [28]

$$Q_{\Sigma} = Q_{ch} + Q_{W} + Q_{ct} \quad [28] \tag{2.1}$$

The coolants act on tool, part, machine tool and swarf. The cutting temperature has a negative influence on the tool wear, here is the first aim of the coolants. The cooling capacity decreases with the increase of cutting speed and depth of cut [1]
Then, the cooling process contributes to keep the dimensions within the tolerances by lowering the thermal dilatation of the tool. [14, 21]
The carry the chips away is also one of important functions of a coolant [23]
One big problem when machining aluminum alloys or stainless steel is the BUE formation. The use of coolant shifts the range of BUE formation towards to higher cutting speeds. [21]

The cooling of the chip backsurface results in increase of chip curl which reduces the contact length without requiring the fluid access to the interface. The reduction of contact area can be due to overall lower temperature. [21, 23, 25, 26]

2.3 Mist systems

It is a mixture of oil with the air. This technology is also used for MQL. A small jet disperses a process fluid as very fine droplets which form a kind of mist. The air pressure is 69-552 kPa. Since the oil is applied as little droplets, it evaporates and rapidly removes heat by vaporization. A mist system reaches a better tool life than the dry machining, but there are other advantages. This system is able to apply the fluid to otherwise inaccessible areas, gives better visibility during cutting than a flood system and the fluid velocity in the cutting zone is greater. Unlike the cooling capacity is limited. [2, 20]

2.4 Cutting fluids categories

2.4.1 Neat oils

They are called also as straight oils or insoluble oils. Straight oils contain no water, which explains their lower cooling capacity. Their main function is the lubrication. They are applied at relatively low cutting speeds ($v_c < 30$ m/min), on difficult-to-machine materials, more difficult operations and to reach better surface finish. The oils have generally a long life and require less maintenance than coolant [2, 20, 27]

2.4.1.1 Straight mineral oils

Their advantage is lower cost, a corrosion protection and chemical stability, but the lubrication capacity is weaker. [20]

2.4.1.2 Fatty oils

This type of oils is extracted from the lard or the colza and is used mainly as additives. They can be divided on the vegetable and animal ones. Their lubricating properties are very good, but their direct use is impossible due to the high cost and quick deterioration. [1, 27]

However, they are used as additives to in mineral oils to increase lubricating properties. [1, 20]

2.4.1.3 Compound cutting oils

It is a mineral oil with polar additives which improve cutting capacity by penetrating to the chip-tool interface. [20]

2.4.1.4 Fatty mineral oils

It is a mixture of fatty and straight mineral oils. [20]

2.4.1.5 Extreme pressure (EP) additives

This type of oils is used in machining operations such as tapping or broaching where the cutting forces are important. They dispose of antiweld properties and minimize the BUE formation. EP additives such as sulfur, chlorine or phosphorus improve the oils wettability. [2, 20]

2.4.1.6 Active cutting oils

These oils are suitable for using at high pressure applications, they have antiweld properties and increase the tool life at high temperatures. The additives commonly used are the sulfur, the chlorine and the phosphorus. [20]

2.4.2 Water-miscible (water-soluble) fluids

It is a concentrated mixture with the water. The ratio concentrate/water is generally from 1/20 to 1/30 for machining operations and 1/40, 1/50 for grinding, but it can vary from 1/10 to 1/100. The water disposes of the high specific heat, high thermal conductivity and high heat of evaporation, which makes the water one of the best cooling fluids. Therefore the water miscible fluids have great cooling capacities, reduce the abrasive wear at high temperature and their application is for higher cutting speeds. [2, 20]

2.4.2.1 Emulsifiable oils (soluble oils, emulsions)

Soluble oils contain additives (emulsifiers) which form soap. The emulsions dispose of lubricating and rust-protection properties of oil and at the same time they contain cooling properties of water. An example of anticorrosive additives is the sodium nitrite. Biocides are also contained to avoid bacteria growing. They are commonly used in several machining and all grinding operations. [20]

2.4.2.2 Other type of water soluble oils

It can be distinguished as general-purpose soluble oils. It is a milky fluid with droplets of 0,005-0,2 mm. Then clear type (or translucent) soluble oils consist of more emulsifier and less oil. It exists also fatty and extreme pressure soluble oils. [20]

2.4.3 Chemical (synthetic) fluids

It consists of inorganic substances dissolved in water with no mineral oils. A quick heat dissipation, a good workpiece size control, a rust resistance, a long life and keeping clean the machine area are advantages. “These solutions are transparent, which causes a good visibility in the machining process. [1]” An insufficient lubrication capacity is a weak point. [1, 2, 20]

2.4.3.1 True-solution fluids

This type of synthetic fluids is called also chemical solution or chemical grinding fluids. It contain rust inhibitors and therefore it is added into emulsion to enhance their corrosion resistance [20]

2.4.3.2 Surface active chemical fluids

It is extremely fine colloidal solutions. There are both organic and inorganic materials dissolved in water. A good heat dissipation, antirust and antifoaming action are some advantages. The ratio oil/water varies from 1/10 to 1/40. This type of flood exists also as extreme pressure (EP) option for tougher machining operations. [20]

2.4.4 Semichemical (semisythetic) fluids, (microemulsions)

The content of mineral oils is 5-50%, the remainder is formed by additives and chemical composites. They combine the qualities of chemical fluids and soluble oils. Comparing to classic chemical fluids, the semichemical ones are cleaner and have better lubrication properties. There is a larger amount of emulsifiers than there is in soluble oils which causes a transparency of the fluid. They are less harmful than the soluble oils. „Their application is at higher speed and feed operations [2]." [1, 20]

2.4.5 Gases

The most common gas coolant is obviously the air. Using the air under athmospheric conditions is simply the dry machining. The air is also present when a fluid is used. The air cooling is really applied by stream directed to the cutting zone. The pressurized air blows the chips away as its auxiliary function.

Inert gases as the argon (Ar), the helium (He) or the nitrogen (N) are used to prevent oxidation. They conserve even good cooling abilities and clear view during machining process. They increase the tool life and do not contaminate the workpiece. [20]

2.4.6 Paste and solid lubricants

Their use in machining is not very ordinary. Their value can be found at hand tapping and reaming, knife grinding or other special operations. They are widely used for the maintaining lubrication of machines. [20]

3 BIBLIOGRAPHIC RESEARCH

3.1 Effect of the process fluids and the MQL applications

We can find a large number of publications concerning the problem of MQL. But often they treat a subject quite concrete that is not necessarily related to this topic. On the other side, there are many studies containing very useful comparison of process fluids, unfortunately they deal with flooding, not with MQL. However, they show the basic properties of tested fluids.

The articles often focus on the comparisons: In most cases, we can find comparisons of the MQL method with the dry machining. Another example, these are some studies of effectiveness of MQL oils compared to conventional emulsion flooding. [18]
The comparisons should be applied to compare the fluids belonging to the same category. [7]
There are publications that report about the modeling of cutting forces in MQL. The effectiveness of MQL depends on several factors which are detailed in a studied article [29].
Besides the classic MQL, there are also some special technologies which are generally more effective. A common point of most of the publications and at the same time a very important issue to exploit, it is information on the MQL conditions, such as the oil rate and the air pressure. Since this is the machining, we must also consider the material of the workpiece, the machining material and cutting conditions.

3.1.1 Cutting fluid evaluation

3.1.1.1 Test approaches

There are three main types of cutting fluid evaluation tests: The facing temperature test for investigating the cooling properties, the restricted contact tool testing which assesses the lubrication capacity of oils, the last one is the short time wear test to evaluate the combine effect of cooling and lubrications. It takes approximately 5 minutes and a good repeatability is affirmed. [24]

There are two approaches how to study the friction at the interface chip/tool/workpiece. The macroscopic approach measures cutting forces and torque, the other approach examines the microstructure of the chip and the tool wear. [9]
Then we can divide the cutting fluids evaluation onto direct one and indirect one. The direct measurement is oriented on the results which are detectable after finishing the operation. It is the tool life, the product quality and the power consumption. Indirect parameters must be obligatorily measured during the cutting operations. Their examples are: the chip compression test, the contact

length test, the drill penetration test, the drill torque test, the temperature test or the vibration test. [23, 25]

3.1.1.2 Parameters influencing the MQL

The quality of MQL is influenced by several parameters:
A constant oil rate should be kept to avoid losses which requires a constant pipe section. Secondly, it is advantageous to have the oil droplets sufficiently small in the MQL applications. The optimal size is between 1 and 10 microns. If the size exceeds 10 microns, the particles will adhere to the walls of the channel which will reduce the effectiveness of MQL. At the internal lubrication (which is our case of drilling tests), a very high rotation speed must not be reached, because the centrifugal and aerodynamic force deviate the flow. If necessary, it must be compensated by sufficiently high pressure. More the inlet pressure increases, more the jet is directed and closer it is to the cutting edge. [29]

We can see comparisons between different lubrication modes very often: the conventional flooding, the MQL and the dry machining. The order in which the methods were listed corresponds generally to the quality given. However, the MQL is more efficient than conventional watering in some cases. For example, the life of a diamond coated carbide tool may be the longest with MQL. [9, 17]

3.2 Review on the MQL application

3.2.1 Effects of the MQL application

A comparison of the emulsion cooling, the air flow and three configurations of MQL (5, 15, 23 ml/h) shows some surprising results. The tool wear is most important when using the emulsion followed by air and MQL. The MQL rate of 5ml/h and cooled air have similar properties. The greatest force is observed using air, lower one with emulsion. The worst surface quality appears when cooling by air. [18]
Sales et al. confirm when drilling of steel AISI 8640, the MQL 10 ml/h reach similar results concerning the roundness, cylindricity, diameter accuracy and surface roughness as flooding by soluble oil. At high speed turning of steel 1045, the MQL did not reach better results than dry machining. [1]
The MQL systems are more efficient in higher cutting speeds and higher feed rates, meanwhile the conventional flooding in small ones. [9, 14, 20]
Less chip adhesion on the tool is observed at the cutting speed 5000 m/min than at 2000 m/min when machining of a cast aluminum alloy A356.
One example of grinding of quenched and tempered ABNT 4340 steel by Al_2O_3 and CBN wheels shows, that MQL reduces the tangential force more than the cooling, but the residual compression stress is more important than when using the cooling. [19]

It is observed during drilling of aluminum alloy 5080, that the flooding and MQL significantly reduces the torque comparing to cooling airflow and dry machining. The MQL shows the smaller difference of the surface roughness in repeated experiments (inferior to 15%), while the deviation with conventional watering is up to 75%. Conversely, the MQL cannot provide a sufficient alternative concerning the cooling performance of the emulsion. The hole diameters obtained using the conventional cooling method are included within the tolerance, but the MQL does not prevent entirely the thermal dilatation of the drill due to the previous hole drilling, which results in diameter slightly above tolerance. [14]

As mentioned above, one function of a cutting fluid is also to reduce the contact length on the cutting interface. [26] This length is the shortest using conventional flooding. With MQL, the contact length decreases with increasing rate (70 ml/h has less contact than 24 ml/h). It can be concluded that more fluid is present on the interface, less contact there is [16].
Nevertheless, „the MQL rate does not influence the tool life of drill, which is quite interesting [13]."
The dry friction coefficient is strongly dependent on the sliding speed at the interface. MQL decreases the friction coefficient, but does not influence the sliding speed. [9]

A study compares the performances of various oils among them, at drilling but using conventional lubrication: The tool life is extended by 177% and the thrust is reduced by 7% with vegetable oils relative to a commercial mineral oil (in the best of cases). In addition, vegetable oils come from renewable sources, which is advantageous from the environmental point of view. [30],[31].
The great performance of vegetable based fluids (also at conventional flooding) is confirmed by another testing which compares some straight oils among them (mineral oil, ester oil and two mixtures vegetable/ester) and some water based fluids independently (vegetable, synthetic and mineral). The evaluated criteria are the tool life and cutting forces in turning, drilling, reaming and tapping of the austenitic stainless steel 316L. Vegetable oils and esters have the best results in all operations both in the straight oils group and in the water-based one. [6]
The implication of the MQL reduces the cutting forces in general from 1 to 37% relative to the dry machining [8].

3.2.2 Advanced techniques of the MQL

There are some advanced versions of MQL system. This is the addition of gas and water droplets in the MQL fluid or by using ultrasonic vibrations. All these special techniques bring improvement in general. The classic MQL remarks relatively the worst results. Then MQL + O_2 is the best and is followed by MQL + Ar_2 and MQL + N_2 (the efforts are reduced by one third). Besides, there is a system of adding water microdroplets which is abbreviated as WMD - Water Micro Droplet. This technique also reduces thrust forces in drilling by one third.

Moreover the WMD can reduce the coefficient of friction. However the use of these techniques is quite difficult and in the context of this project, it is not practically feasible. It provides just a theoretical example. [5, 15]

3.2.3 MQL application on aluminum alloys

In the literature, we can find most frequently the application of the MQL system when machining the aluminum alloys. Aluminum alloys are known as materials quite easy to machine, but we can still encounter difficulties. The aluminum swarfs have a strong tendency to adhere to the tool. That is why there are three generalized properties which fluids used on aluminum alloys should have. The fluid must not react during cutting and not form the aluminum oxide which is hard and wears the tool. Then, these fluids must contain lubricant and extreme pressure (EP) additives against the BUE (due to silicon contains in the alloy). Thirdly, the fluid is supposed to dissipate heat quickly in order to limit the thermal expansion of the part. [14]

The machining of the aluminum alloys is often carried out with uncoated carbide tools. The optimal performance of such tools is recognized just with MQL. [17] The MQL reduces significantly the adhesion of the aluminum on the high speed steel (HSS) tool, whereas uncoated carbides improvement (in terms of adhesion) is not recognized because this material has a lot of antisticking abilities against the aluminum even at dry cutting. [9]

3.3 Orthogonal cutting

The orthogonal cutting is a method purposed mainly for experimental needs, because it facilitates the measurement of various components of cutting forces. It is usable at the turning or planing. The basic rules of the orthogonal cutting are: The entering angle κ_r is 90° and the chisel edge angle λ_s is equal to 0°. [53] It is possible to use four different assemblies. The first one has already been mentioned, it is the planing (fig. 3.1), three others are used in turning. The most common option is a disc (fig. 3.2) which is mounted on a prepared cylinder hold in the chuck. In this case, the tool cuts the disc in the radial direction. The second option of the radial cutting is a cylinder with pre-machined shaped slots (Fig. 3.3). [32, 33, 34, 35]

Each slot functions as a disc and the spaces between the slots are used to make place to the cutting tool when penetrating into the disc. The advantage of this arrangement is that it avoids changing discs after each cut. The disadvantage is the need is the same as the disc width.

The last type of assembly is a tube. (Fig. 3.4) Orthogonal cutting of a tube is carried out in the axial direction to use the tailstock if a long sample is machined. This presents a disadvantage. The tailstock takes up a lot of space and thus prevents the installation of the thermal camera, if required. The tube wall width is the same as the disc´s one. This type also presents some difficulties. After each cut, the tube must be cut off to retrieve the samples and the clamping pressure of the chuck must be adjusted to avoid breaking of the tube. Another possibility for the axial, it is frontal grooves on a cylinder. This technique saves the material, but the cut is made in several different diameters that influence thermally the experiment.

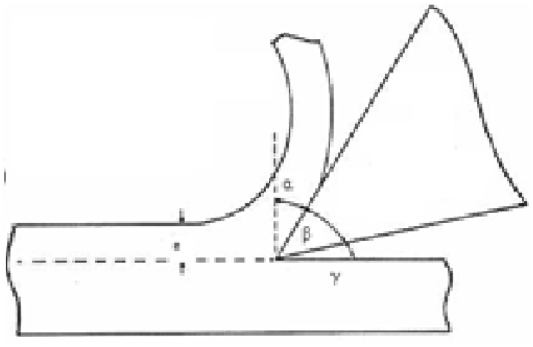

Fig. 3.1 – Orthogonal cutting in planning [32]

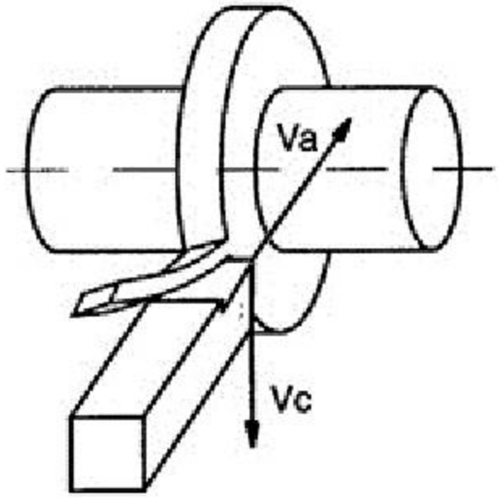

Fig. 3.2 – Orthogonal cutting of a disc [33]

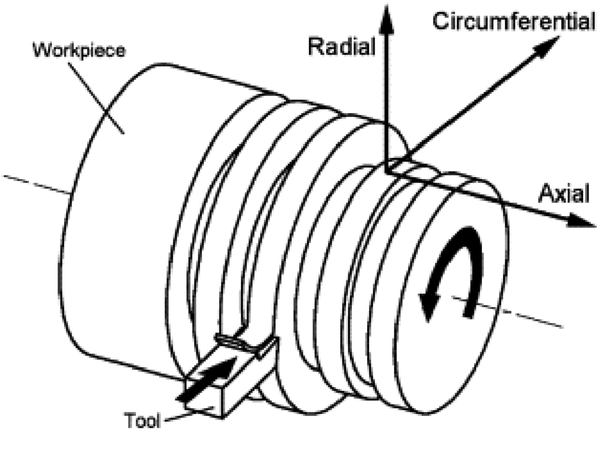

Fig. 3.3 – Orthogonal cutting of a slot [34]

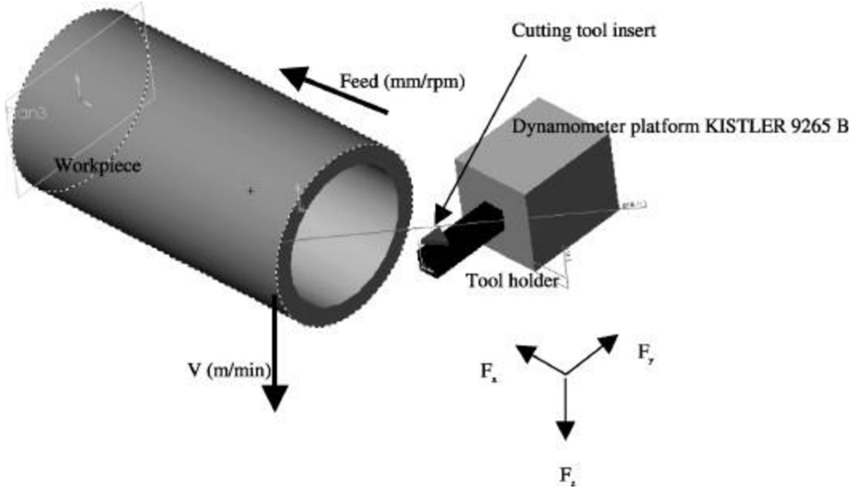

Fig. 3.4 – Orthogonal cutting of a tube [35]

The orthogonal cutting is always treated by a theoretical model. The best known model is the Merchant´s one. This model considers the primary shear zone as infinitely thin and works with the rake angle equal to zero ($\gamma = 0$ °). The material is considered as perfectly plastic. That means that there is no strain hardening, and no influence of temperature and deformation rate. [36]

For the experimental part, we look for the dimensions (especially the width) of used discs or tubes. The diameter of the disc is not really limited. Only if it is too small, the cut will be too short, if it is too high, it may cause the instability of cutting. This may appear as if a long tube is used because there no is no support on the other extremity.
The most commonly used width of the elements is 3 mm, eventually 4 mm according to the laboratory reports. In the literature, we can find smaller width, such as 1,2mm and 2,5mm. [5, 16]

Suitable cutting conditions especially for stainless steel to prevent vibration are discoverable in laboratory reports. They contain the COM analysis (COM = Couple Outil-Matière). COM is a graphic representation of the specific cutting force in function of the cutting speed or in function of feed rate. It is determined for each workpiece and tool material. In our case, it is 316L stainless steel and carbide tool [37, 38]

The use of the lubrication in the orthogonal cutting of medium carbon steel reduces the contact length factor (formula 3.1), that means that a higher feed can be used. [24]

$$n = \frac{L_0}{f}$$

[24] (3.1)

3.4 Drilling

Drilling is an inside operation. There are two main issues: The first is the chip removal. The cutting fluid improves the chip evacuation. The second challenge is the temperature generated in the hole which is quite different from that of orthogonal cutting. [1, 14]
MQL medium also provides a partial cooling function due to airflow. [39]
The performance criteria generally evaluated in drilling are the tool life and the cutting forces. [25]
The tool life test require a long time and are generally quite poor repeatability, the cutting force test are characterized by shorter time and better repeatability. [40]

3.4.1 Tool life

The tool life of a drill is not only a characteristic of the drill itself, but also a performance characteristic of the process fluid, which is used. The tool life is strongly affected by the temperature generated during machining, the tool life is generally increased by cooling effect. On the other side, the lubrication could eventually decrease the tool life. The explanation of this phenomenon is that, one of lubricating effect is the BUE removal, knowing that the BUE protects the cutting edge (beside other negative effects). The behavior of a process fluid cannot be predicted, so the tool wear test is quite important. That is why, the tool life test is a very common method to evaluate and compare the fluid performance.
A drill life is determined as the number of holes to total failure of the tool tip or it can be expressed as a drilled length (depth). The tool wear, especially the flank wear is evaluated after drilling a determined number of holes (or determined drilled length). [23, 24]

3.4.2 Drilling of aluminum alloys

Considering the example of aluminum which is extremely sticky, we can easily imagine that once, the flute of the drill is blocked, chip evacuation is no longer guaranteed and the tool breaks. Therefore the dry machining of aluminum is really difficult. [1, 14]

The application of MQL is possible even in deep drilling (depth/diameter ratio is important) and becomes increasingly attractive to industry. [39]
An experiment testing the wear of a DLC coated carbide tool (DLC = Diamond Like Carbon) in the aluminum alloy AC8A (according to JIS - Japanese Industrial Standard) by drilling holes of diameter 6mm and 50mm deep (more than 8xD what is deep drilling) demonstrates this point. Cutting conditions are v_c= 94 or 132 m/min and f= 0,1 mm, the catastrophic tool wear is not observed after 100 holes. [5].

During a drilling test an aluminum alloy A390 with a HSS tool using conventional flooding (cutting conditions v_c = 150 m/min and f = 0,05/0,1 mm, depth = 30 mm) the flank wear of 0,5-1 mm is observed after 300 drilled holes. The flank wear is measured on two different points a and b after each 100 holes. The machining time necessary to reach a wear VBa = 0,6mm varies in function of used fluids between 22 and 58 minutes, for VBb = 0,8mm from 13 to 30 minutes. The cutting forces are measured from the hole number 10 to 19. [30]

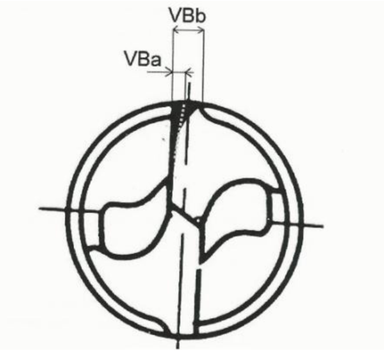

Fig. 3.5 – Flank wear measurement used in [30]

Tests on aluminum alloys are carried out with the HSS tools, DLC coated carbide or non-coated carbide tools. Overall, the use of the HSS is not very suitable for the machining of aluminum alloys because aluminum adheres strongly to the tool. Such a tool has been destroyed after 49 holes in the aluminum alloy A319 (v_c = 50 m/min, f = 0,25 mm, diameter = 6,35 mm, depth= 19mm, lubrication MQL 30 ml/h). [10].
However, the same type of HSS but DLC coated has drilled all 150 planned holes at the same cutting conditions. A slight torque increase between the first (1,68 Nm) and the 150th (1,75 Nm) hole is noticed, which proves that the tool wear is not catastrophic. [10]
The DLC coating is usually the most suitable material to machine the aluminum thanks to its tribological properties and because it prevents the BUE formation. [9, 10]

Another experiment conducted with uncoated carbide drill in an aluminum alloy A356 shows that this type of tool is also suitable for aluminum alloys. After drilling 612 holes (which is equal to 20 meters of length), the flank wear is only 0,05 mm. It should be noted that the cut is made using a MQL coolant with flow rate 10 ml/h and the cutting conditions are the following: v_c=300m/min, f=0,1-0,2 mm, diameter = 10 mm, depth = 33 mm. The MQL rate is such small because the authors of this experiment proceed from previous studies which shows that the flow rate (10, 30 or 60 ml/h) has no influence on the tool wear. [13]

The range of cutting speeds used for drilling of aluminum alloys is below 100 m/min with HSS tools and cutting speeds are about hundreds of meters per minute using carbide tools. Feed values vary between 0,1 and 0,25 mm per revolution for machining of both materials. [5, 10, 13, 14, 39]

3.4.3 Drilling of stainless steels

The stainless steel 316L is often treated in the literature in several applications, including drilling. Nevertheless, it is practically impossible to find the intersection of drilling of 316L on one side and the using of MQL on the other one.

Nevertheless, we can synthesize articles that contain either information only. In general, stainless steels are considered a material that is difficult to machine. The challenges are in their low thermal conductivity which generates the quite high temperature in the cutting area. The material has a tendency to adhere to the tool as well as aluminum and therefore form the BUE. The BUEs cause a irregular tool wear. [41]

A test is performed to compare various flooding modes, including MQL in drilling carbon steel C42 and C46. During the tool wear tests, 272 are drilled holes for each fluid, catastrophic wear of the tool is not observed. Forces are measured in the first hole, after the 105th and 272nd one. The purpose of such measurement is to evaluate the evolution of the tool wear. [18]

In another tool life test of a HSS tool drills the stainless steel 316L under conventional flooding (cutting condition v_c = 25 m/min and f = 0.1 mm, depth=33 mm), the tool wear is checked after every 30 holes. Cutting forces are measured between the holes number 10 and 19. [30]

Le Chiffre [42] compares in one experiment different cutting fluid at drilling using the conventional flooding. It can be observed that a neat oil reach lower torque, but higher thrust force than an emulsion and a chemical coolant (v_c = 40 m/min). During the tool life test, the torque increases approximately by 20 percent, the thrust force by 30 percent shortly before failure [42].

According to the literature, it can be noticed that the stainless steel tools are drilled by either HSS or carbide tools. A HSS tool can be uncoated or coated TiN or often with the addition of cobalt. A suitable domain of cutting speeds for the HSS are included between 15 and 40 m/min. The value of the feed is around 0,1 mm. [30, 31, 43]

If a carbide tool is used, it is a mostly coated carbide, the coating TiAlN concretely. In this case, cutting conditions vary around v_c = 40-80 m/min (exceptionally 100 m/min) and f = 0,04 to 0,2 mm. [44, 45]
It can be noticed that the cutting conditions are recommended for conventional cooling.

3.5 Measuring techniques

3.5.1 Temperature measuring at drilling

The temperature measuring in drilling blind holes is made almost exclusively by the thermocouples. The workpiece must be equipped by narrow holes to insert the thermocouples along the future hole. [14, 39]

The most commonly used thermocouples are those type K. The spacing and number of thermocouples depends on the depth of the hole and the available accessories to connect the thermocouples. In examples for a hole depth of 30mm, 4 thermocouples and the spacing of 6 mm are used. For a very deep hole 250mm, 21 thermocouples are introduced, their spacing is not specified, but it is possible to estimate it on 10-12mm. [14,39]

What is more important, that is the distance between the tip of the thermocouple and the drill, or else the thickness of the wall between the end of the thermocouple hole and lateral surface of the hole. This distance must be small enough because of the large temperature gradient that puts down the temperature quite quickly. In addition, the distance must be the constant everywhere, otherwise the heat dissipated to the thermocouple is not the same everywhere and the temperature measuring is no longer correct. The value recommended by literature is 0,3 mm. [14, 46, 47]

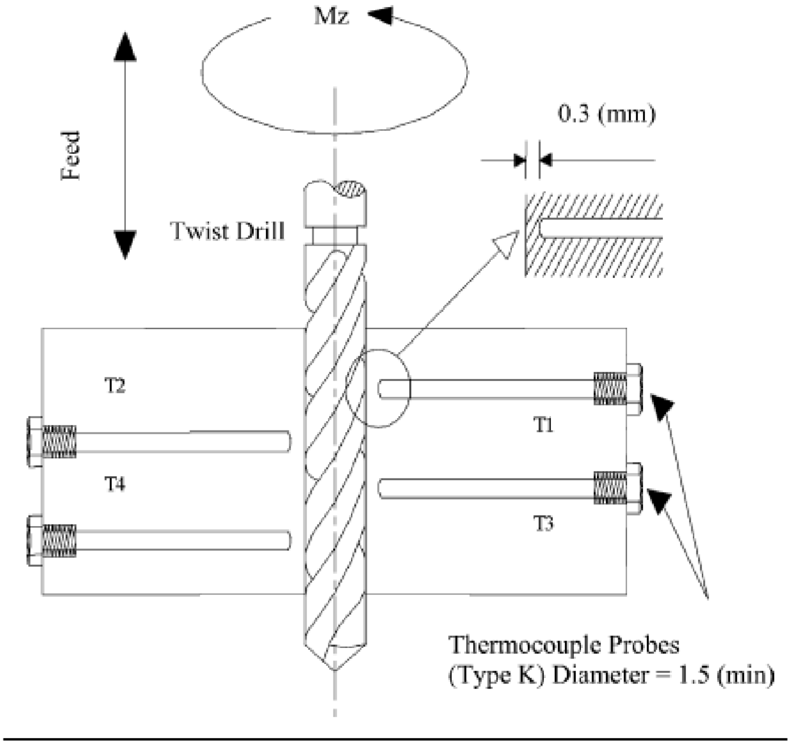

Fig. 3.6 – Instrumentation of the workpiece for temperature measuring [14]

Beside conventional thermocouples, there is also wireless thermocouple systems. The thermocouple is inserted into the tool and transmits the signal through the tool holder from where it is sent by radio towards to the amplifier and the computer. This technique is well reliable for high rotational speeds up to 20 000 rev/min, but it needs a special drill with groove to introduce the thermocouple. [46]

The temperature can be measured during drilling by several ways: an infrared pyrometer with optical fiber inserted through the piece can measure the temperature in the cutting edge. However, the emissivity of the material must be known and the application of this technique is limited in dry conditions. [46, 47] The thermal camera can only be used for through holes, where the temperature is measured at the moment the drill gets out of the workpiece. [46]

The temperature when drilling depends not only on cutting conditions, the hole depth and materials, but also on the thickness of the material with respect to the depth drilled, which is not obvious. More material remains below the hole, lower the temperature is, because the heat can be better dissipated into the part. The highest temperature is generated by drilling through holes (comparing at the same working condition). [48]

3.5.2 Temperature measuring at the orthogonal cutting

The orthogonal cutting being an external operation allows to measuring the temperature by camera. A CCD camera (Charged Coupled Device) is often used. This solution is less expensive than conventional thermal camera, but results are comparable. The CCD camera operates close to the infrared range (wavelength 400 to 1100 nm). An infrared filter is mounted on the camera. The camera can measure the temperatures superior to 450-500°C, which means unfortunately some limitations. In particular, the temperature of the aluminum machining is not measurable. The temperature is recorded using the MATLAB software in form of photos in grayscale. The white color corresponds to the level of 255 and means the maximum temperature. The frequency of obtaining the images is adjustable in MATLAB. A MATLAB program is also able to convert photos from the grayscale to colored images. By introducing a calibration curve, a certain temperature corresponding to the colored scale is obtained. [38, 47]

3.5.3 Cutting forces measuring

The forces are measured by the dynamometers in whatever type of operation. A very common mark of piezoelectric dynamometers is a swiss company KISTLER. The signals captured by the dynamometer are transferred through an amplifier to a software for processing and directly draw graphics. Such software may be DASYLab and LabView.

In case of turning or milling, the three values of forces are measured: the cutting force, the feed force and the penetration force. In drilling, there are 2 possibilities how to measure forces, either on the part with a static dynamometer or on the tool with a rotary dynamometer. For both ways, the feed (or thrust) force and torque are measured. [14, 38]

4 EXPERIMENTAL PART

4.1 Work materials

4.1.1 Stainless steel AISI 316L (1.4404)

It is austenitic non-magnetic steel with low carbon grade. It has a low thermal conductivity, high strain hardening and high ductility. The chips are usually difficult to fragment. These factors make this material hard to machine. [3]

AISI is the American Iron and Steel Institute numbering system. The European designation of this alloy is 1.4404. Its chemical composition is marked in the table 4.1 and the physical and mechanical properties respectively in tables number 4.2 and 4.3 [20]

Tab. 4.1 – Chemical composition [20, 49].

Chemical element	Fe	C	Cr	Ni	Mo	Mn	Si	P	S
Amount in %	base	0,03	16-18	10-14	2-3	2,0	1,0	0,045	0,03

Tab. 4.2 - Physical properties [49].

Density	8 g.cm^{-3}
Melting point	1400 °C
Thermal expansion	15,9.10^{6} m.m^{-1}K^{-1}
Modulus of elasticity	193 GPa
Thermal conductivity	16,3 W.m^{-1}.K^{-1}
Electrical resistivity	0,074.10^{-6} Ω.m

Tab. 4.3 - Mechanical properties [49].

Yield stress	220 MPa
Ultimate tensile stress	520 – 680 MPa
Elongation	40%

4.1.2 Aluminum alloy EN-AW 7020

The designation of this alloy according to the European standard is EN-AW 7020 or AlZn4,5Mg1. Its previous AFNOR designation is AZ5G and according to the UNS (Unified Numbering System) is A97020. [50]

The alloys of range 7000 contain 1-8% of zinc (Zn), can be alloyed by copper (Cu) and are widely used in the aircraft industry. This alloy has quite high strength, but limited resistance to the corrosion cracking. The properties are very similar to a more known alloy 7075. [20, 50]

Its chemical composition, physical and mechanical properties in T6 condition (solution treated, quenched and naturally aged) are shown in three tables below.

Tab. 4.4 – Chemical composition [50].

Chemical element	Al	Zn	Mg	Mn	Cr	Zr
Amount in %	base	4,5	1,2	0,25	0,22	0,14

Tab. 4.5 - Physical properties [50].

Density	2,78 $g.cm^{-3}$
Mean specific heat	0,875 $J.g^{-1}.K^{-1}$
Thermal expansion	$23{,}1.10^{6}$ $m.m^{-1}.K^{-1}$
Thermal conductivity	137 $W.m^{-1}.K^{-1}$
Electrical resistivity	$0{,}0493.10^{-6}$ Ω.m

Tab. 4.6 - Mechanical properties [50].

0,2% Yield stress	280 MPa
Ultimate tensile stress	350 MPa
Elongation	10%

4.2 Objective

The objective of the experimental is to evaluate the performance of four straight oils in MQL. Their basic characteristics are summarized in the tab. 4.7. As mentioned in the table, each of oils has a different base. The cutting operations chosen to evaluate these process fluids are the turning (more exactly the orthogonal cutting) and the drilling of blind holes.

Tab. 4.7 – Oils´ characteristics.

Oil designation	Oil base	Density (15 °C)	Cinematic viscosity (40 °C)
A	Fatty alcohol	844,3 $kg.m^{-3}$	27,39 $mm^{2}.s^{-1}$
B	Vegetable (Colza)	913,7 $kg.m^{-3}$	45,06 $mm^{2}.s^{-1}$
C	Biodegradable (EP sulfur additives)	911,9 $kg.m^{-3}$	26,34 $mm^{2}.s^{-1}$
D	Synthetic and ester polymer	848,4 $kg.m^{-3}$	35,20 $mm^{2}.s^{-1}$

4.3 Orthogonal cutting

4.3.1 Sample preparation

As mentioned, there are several strategies of the orthogonal cutting. Turning strategies of the orthogonal cutting seem simpler and more reliable to provide at the beginning, which excludes the method of planing. Finally, the option with the discs is chosen from three possible strategies of turning. The discs are fabricated from cylinder rods of diameter 75 mm. The rods are machined on the diameter 70 mm and a hole of diameter 20 mm is machined. Then the discs of width 3 mm were cut off. This preparation mode is used for the both materials. A special piece is produced to be able to hold the discs during the tests (Fig. 4.1).

Fig. 4.1 – Special disc holder

4.3.2 Experimental setup

The lathe SOMAB T400 (Fig. 4.2) is equipped by accessories to measure the cutting forces and the temperature. The cutting forces are measured by piezoelectric dynamometer KISTLER 9121 and DasyLAB software. The temperature measuring is performed by camera Kappa with infrared filter. The images taken by camera are treated in MATLAB. The principle is described more in detail in the chapter 3.5.2. That implicates the temperature measuring using this method is possible only for the stainless steel. The camera is mounted into the lathe using a special support (Fig. 4.3). Cutting edge radius of the tool must be ground in order to obtain a flat surface (Fig. 4.4) which is necessary to be able to take right photos by camera. The oil in the mist form is provided by pomp of Steidle company (Fig. 4.5). This machine provides a dual-channel external supply of MQL. The air pressure, the frequency of impulsion and the oil quantity per impulsion are adjustable. The oil rate is defined by the frequency and quantity per impulsion. One nozzle is used and the tool rake face is lubricated.

Fig. 4.2 – Lathe SOMAB T400

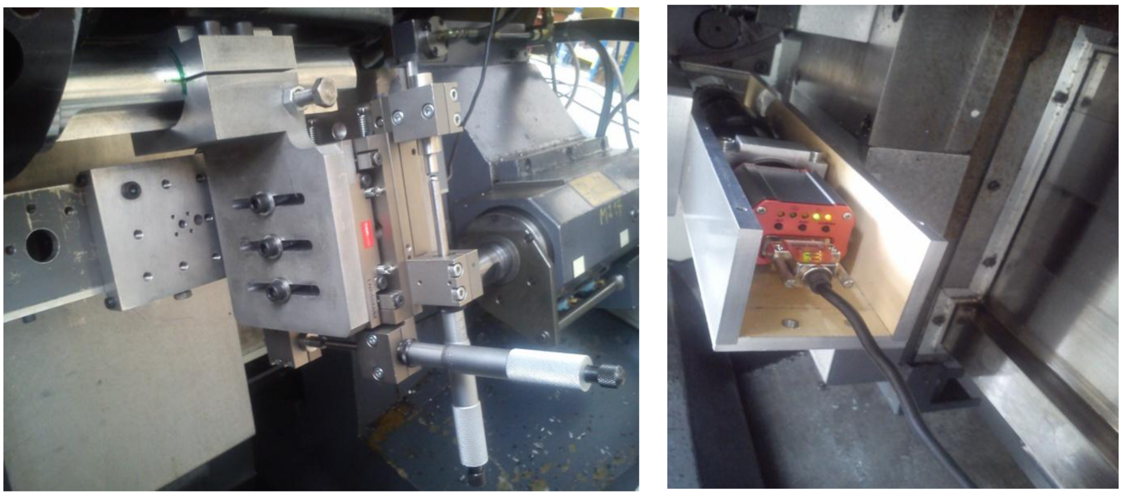

Fig. 4.3 – Camera support and camera box

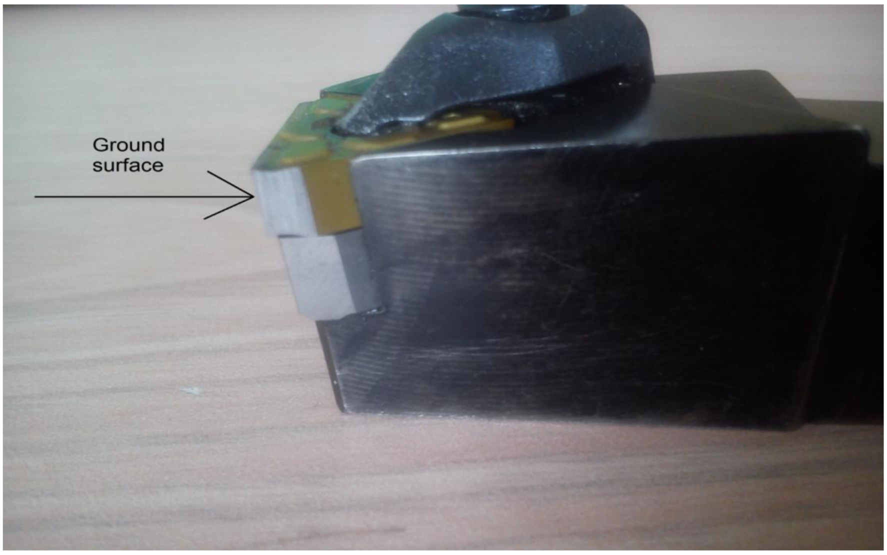

Fig. 4.4 – Ground insert radius in order to obtain a flat surface

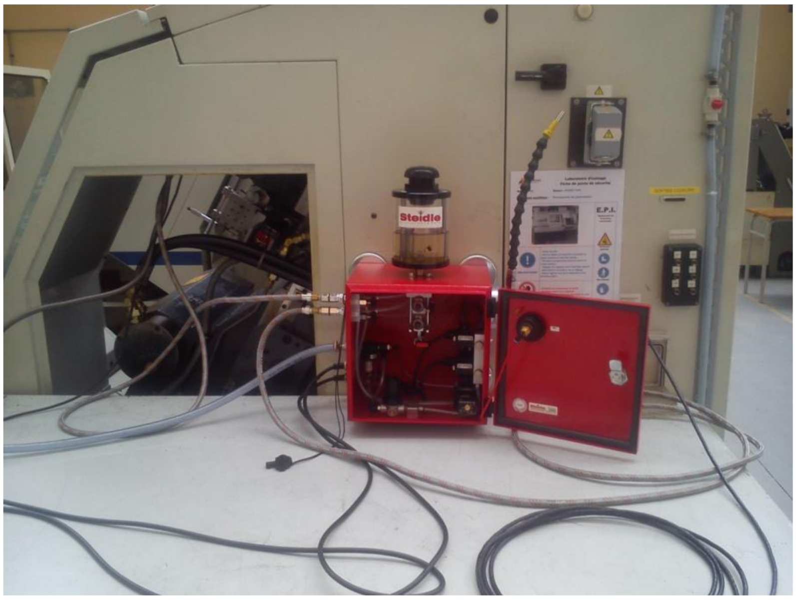

Fig. 4.5 – Steidle machine with the MQL external supply

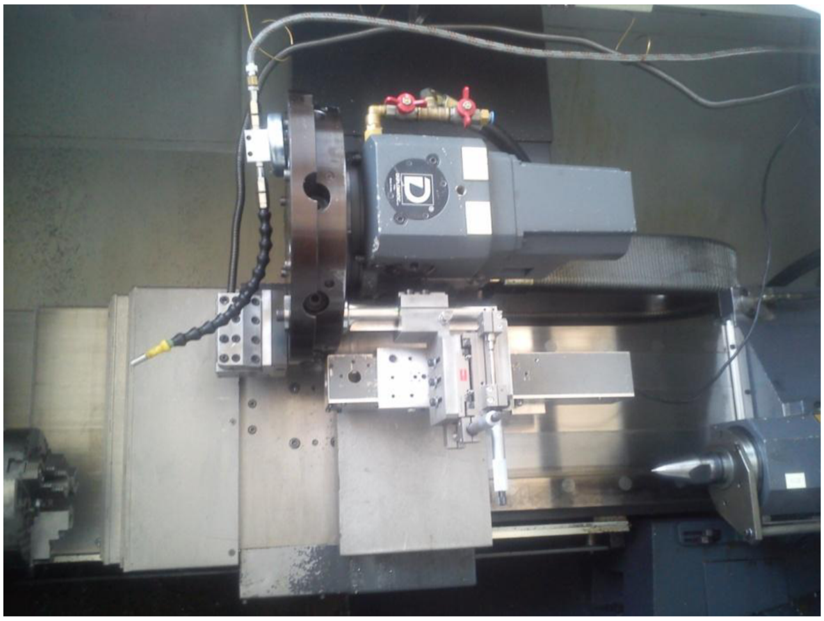

Fig. 4.6 – Complete accessories mounted in the lathe

Fig. 4.7 – Global view on the working post

During the orthogonal cutting tests, the discs are machined from the initial diameter 70 mm to the final diameter 50 mm (Fig. 4.8). The variable parameters are 4 oils, 2 oil rates, 2 air pressures and 2 cutting speeds for each material. The measured parameters are the average value and the amplitude of cutting forces, the surface roughness and the temperature during machining of the stainless steel. The complete experiment plan consists of 32 tests, but according to [11], the experiment plan is reduced to 16 tests per material. It should be specified that experimental plan are independent for each material in all cases of this work. The details of the experiment plans including cutting conditions are shown in the tables (4.9 and 4.11). Some additional tests (mainly dry cutting tests) are carried out except this experimental plan. A new cutting edge is used to machine each disc. The obtained results are investigated by the algorithm of the variance analysis (described in 5.1). This method determines which variable parameters are significant for the measured parameters.

a) b) c)

Fig. 4.8 – a) Initial aluminum disc ; b) Aluminum disc after machining ; c) Comparison of the both disc with scale

4.3.3 Stainless steel AISI 316L

Tab. 4.8 – Cutting tool characteristics for AISI 316L [51].

Tool holder	DTFNR2020K16-M
Insert designation	TNMG 160408-MF4 CP500
Rake angle γ	-6°
Clearance angle α	6°
Coating	SECO CP500 = TiAlN + TiN

*Coating CP500 is destined for finishing and light roughing of stainless steels and can be used as an alternative for aluminum alloys. [51]

Fig. 4.9 – Cutting tool for AISI 316L

Tab. 4.9 – Experimental plan of AISI 316L.

Test number	**Oil**	**Cutting edge number**	**oil rate**	**air pressure**	**v_c**	**f**	**a_p**
			ml/h	bar	m/min	mm	mm
1	A	1	30	4,5	180	0,1	3
2	A	2	30	7	240	0,1	3
3	A	3	70	4,5	240	0,1	3
4	A	4	70	7	180	0,1	3
5	B	5	30	4,5	240	0,1	3
6	B	6	30	7	180	0,1	3
7	B	7	70	4,5	180	0,1	3
8	B	8	70	7	240	0,1	3
9	C	9	30	4,5	240	0,1	3
10	C	10	30	7	180	0,1	3
11	C	11	70	4,5	180	0,1	3
12	C	12	70	7	240	0,1	3
13	D	13	30	4,5	180	0,1	3
14	D	14	30	7	240	0,1	3
15	D	15	70	4,5	240	0,1	3
16	D	16	70	7	180	0,1	3

4.3.4 Aluminum alloy EN-AW 7020

Tab. 4.10 – Cutting tool characteristics for EN-AW 7020 [51].

Tool holder	STFCR2020K16
Insert designation	TCGT 16T308F-AL KX
Rake angle γ	0°
Clearance angle α	7°
Coating	SECO KX = uncoated

*Coating KX means an uncoated insert and is destined for aluminum alloys and other non-ferrous metals [51]

Fig. 4.10 – Cutting tool for EN-AW 7020

Tab. 4.11 – Experimental plan of EN-AW 7020.

Test number	**Oil**	**Cutting edge number**	**oil rate**	**air pressure**	**v_c**	**f**	**a_p**
			ml/h	bar	m/min	mm	mm
1	A	1	30	4,5	300	0,3	3
2	A	2	30	7	500	0,3	3
3	A	3	70	4,5	500	0,3	3
4	A	4	70	7	300	0,3	3
5	B	5	30	4,5	500	0,3	3
6	B	6	30	7	300	0,3	3
7	B	7	70	4,5	300	0,3	3
8	B	8	70	7	500	0,3	3
9	C	9	30	4,5	500	0,3	3
10	C	10	30	7	300	0,3	3
11	C	11	70	4,5	300	0,3	3
12	C	12	70	7	500	0,3	3
13	D	13	30	4,5	300	0,3	3
14	D	14	30	7	500	0,3	3
15	D	15	70	4,5	500	0,3	3
16	D	16	70	7	300	0,3	3

4.4 Drilling

4.4.1 Sample preparation

The size and number of samples for drilling tests are determined by the number of holes to be drilled. The size of experimental plan is unchanged, 16 holes per material will be drilled. However some parameters of experimental plan are modified, but it is described below in chapter 4.4.2
The final dimensions of the workpiece are 73x40x40 for AISI 316L and 73x40x45 for EN-AW 7020. The difference in the third dimension (the height) has not any functional reasons, the blanks of aluminum alloys were simply higher than the steel blank. The hole diameter will be 12 mm and the drill depth 3xD, that means 36 mm. So the part height of the stainless steel block is sufficient. 8 holes can be drilled into each workpiece.

The workpieces are obtained by band sawing a big blank (Fig. 4.11) onto small pieces of approximate dimensions 80x45x45/50 mm. Then all faces are end milled with respecting the perpendicularity constraints onto final dimensions.

Fig. 4.11 – Band sawing of an aluminum alloy blank

After, the hole to introduce the thermocouples must be drilled. The diameter of these holes is 1 mm and their depth is 4,7 mm. Because of an important l/D ratio, this drilling operation is quite difficult. Moreover, 6 thermocouples will be introduced a long one hole of diameter 12 mm. A sample part dispose of 8 future holes and four parts of each material are produced to have a sufficient reserve. That means 192 holes of 1mm by material have to be drilled.

Fig. 4.12 – Workpiece for the drilling test

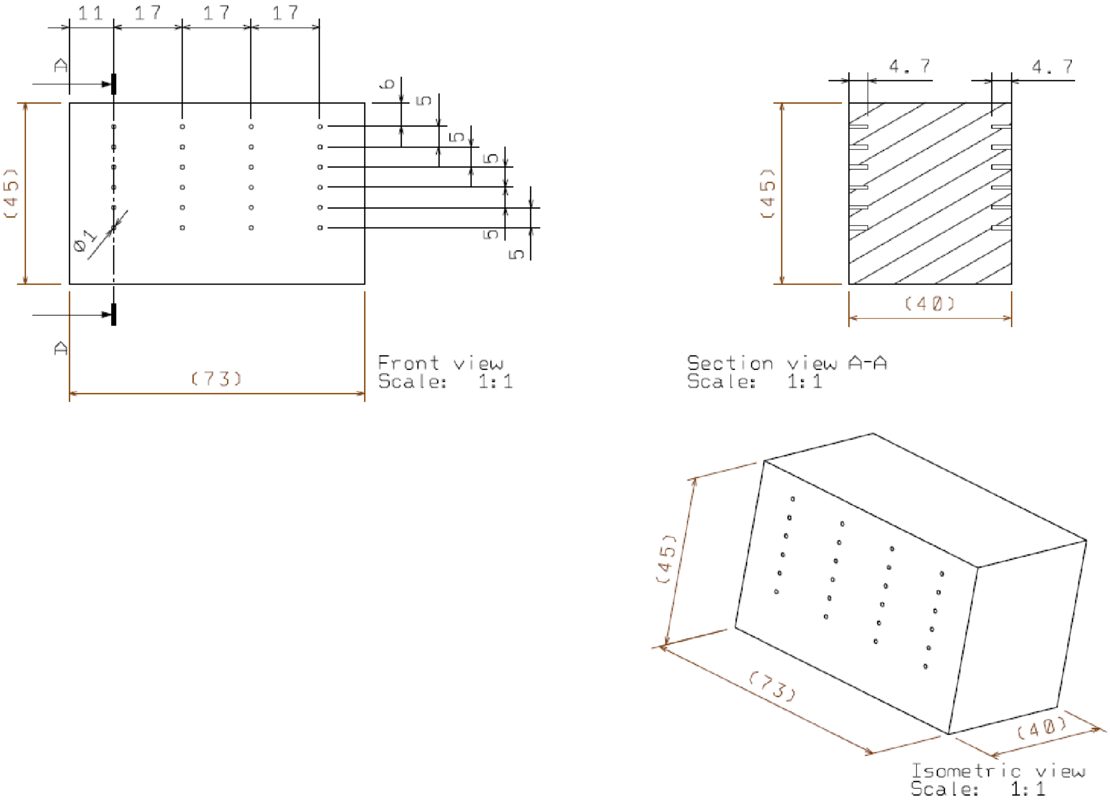

Fig. 4.13 – Drawing of the workpiece by CATIA V5R20

Two types of uncoated carbide drills by SECO are used for that drilling operation. The first one (SD22-1.00-2.00-3R1) is stiffer, but can drill only 2 mm of depth, the other one (SD26-1.00-6.50-3R1) is able to drill up to 6,5 mm. In fact, two drilling cycle are used. The drill SD22-1.00-2.00-3R1forms the base of the holes in 1mm of depth and the reminder of hole is drilled by SD26-1.00-6.50-3R1.

The same drills are used for the both materials. The cutting process is cooled by emulsion externally, although the machine DMC 65V (Fig. 4.15) is equipped for internal cooling and even the drill SD26-1.00-6.50-3R1 dispose of internal channel. It is not managed to start the internal cooling with this drill probably because of insufficient pressure. The cutting conditions are chosen according to the SECO catalog [51] and are listed in the table 4.12.


a) b)

Fig. 4.14 – Drills for the thermocouple holes;
a) SD22-1.00-2.00-3R1, b) SD26-1.00-6.50-3R1

Tab. 4.12 – Cutting conditions for drilling 1mm holes [51].

Material	v_c (m/min)	f (mm)
AISI 316L	10	0,006
EN-AW 7020	80	0,013

4.4.2 Experimental setup

The drilling tests are carried out with the CNC milling machine DMG DMC 65V (Fig. 4.15). 16 holes per material are drilled, that means 4 holes per oil per material. From this point of view, the experimental plan stays the same as for the orthogonal cutting test. But according to the results of the orthogonal cutting tests (next chapter 5.2), it has been decided to use fixed cutting conditions for all 16 holes by material.

Fig. 4.15 - CNC 3-axis milling machine DMG DMC 65V.

For drilling the hole of l/D ratio = 3, an external MQL supply is not effective. A numerically controlled machine by SKF (fig. 4.16) is used. This machine permits the internal one-channel supply. The numeric control presents some advantages, but there is less of parameters variability. There are 16 unchangeable programs, which vary the oil rate and air rate at the same time. The air pressure is constantly 6 bars for all programs. Consequently the air rate and oil rate cannot be varied independently.

Fig. 4.16 - Numerically controlled MQL generator by SKF

The cutting forces are measured by a rotary piezoelectric dynamometer KISTLER 9123C. As typically, the thrust force and the torque are acquired. They are treated by DasyLAB software as in the case of the orthogonal cutting. The temperature measuring is insured by thermocouples. The holes for thermocouples type K and diameter 1mm are designed in order to obtain the distance between the extremity of the thermocouple and the peripheric surface of the future hole equal to 0,3 mm as recommended in [14].

Fig. 4.17 - Rotary piezoelectric dynamometer KISTLER 9123C

The cutting conditions are chosen thanks to preliminary COM tests. The tests are based on the range of cutting speeds and feeds recommended by SANDVIK [45]. But these cutting conditions are determined when using the conventional flooding and consequently they are not adapted to the MQL. So the COM tests have to be carried out for the lower cutting speeds and feed rates also. In the case of the aluminum alloy, the lowest recommended values can be applied without problem due to its good machinability. Some problems are observed during COM tests of the stainless steel. The drill is broken in the recommended cutting speed. After decreasing onto v_c= 10-25 m/min, the drill breaks also. It is impossible to use a packing cycle due to temperature measuring. A continuous cutting cycle is necessary, and the depth of 36 mm is too important to drill the stainless steel because of difficult chip removal. Consequently the depth of the hole has to be reduces. The cutting conditions and the holes depth are summarized in tab. 4.13.

Tab. 4.13 – Cutting conditions for drilling tests.

Material	v_c (m/min)	f (mm)	Depth (mm)
AISI 316L	15	0,1	15
EN-AW 7020	120	0,3	36

Although the samples dispose of 6 holes for thermocouple by hole, only two thermocouples for the stainless steel and four ones for aluminum alloys are inserted. The reason of reduction of thermocouples used for drilling of AISI 316L is evident. It is the depth reduction 15mm and the samples have been already finished, so only two first thermocouple holes are useful. Finally, a different acquisition card with 4 plug contacts is used (instead of 6 plug contacts initially supposed). The thermocouples are plugged in the 2nd, 4th, 5th and 6th hole. This corresponds to the depths of 11; 21; 26 and 31 mm. This configuration permits also to observe the temperature evolution along the hole.

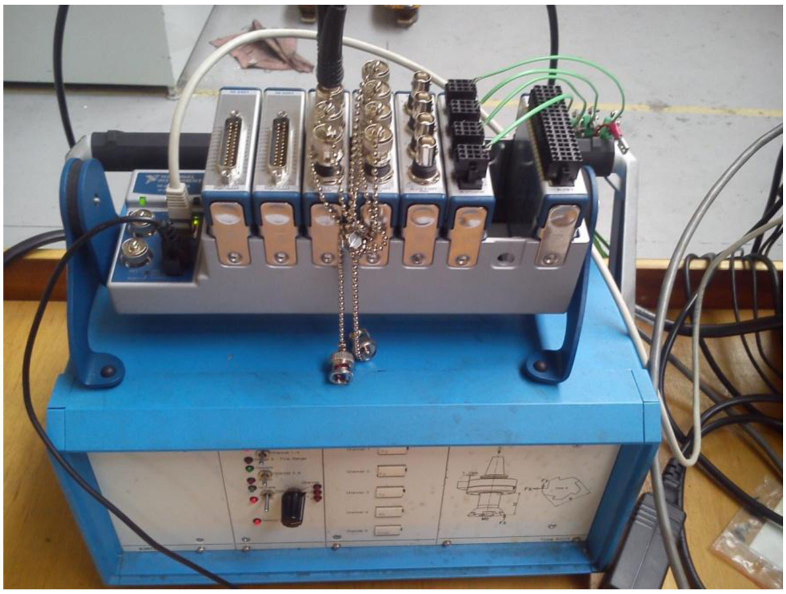

Fig. 4.18 – Acquisition card for thermocouples and amplifier for the rotary dynamometer

Fig. 4.19 – View on the prepared space in the interior of the machine

4.4.3 Stainless steel AISI 316L

The stainless steel is drilled by coated carbide twist drill R846-1200-30-A1A produced by Sandvik Coromant. The geometry of the drill is adapted to machine the stainless steels. It contains the inner cooling canals, which permit to use the internal MQL supply by SKF Machine.

Fig. 4.20 – Twist drill R846-1200-30-A1A

As mentioned above, only the oil type and MQL configuration vary during the drilling tests. The experimental plan consists of 8 tests two times repeated. For example test number 1.2 is the repetition of the first test. One test including its repetition is carried out with one tool. Before the repetition the tool is checked on an optical microscope KEYENCE VHX-S50. The tool is not worn in general, only a little BUE is always present (Fig. 4.22). But the conditions can be considered as identical for all the repetitions.

Tab. 4.14 – Experimental plan of drilling test of AISI 316L.

Test number	**Oil type**	**Cutting tool number**	**Oil rate**	**Air rate**	**Air pressure**
			ml/h	l/min	bar
1.1	A	1	20	85-110	6
1.2	A	1	20	85-110	6
2.1	A	2	60	220-235	6
2.2	A	2	60	220-235	6
3.1	B	3	20	85-110	6
3.2	B	3	20	85-110	6
4.1	B	4	60	220-235	6
4.2	B	4	60	220-235	6
5.1	C	5	20	85-110	6
5.2	C	5	20	85-110	6
6.1	C	6	60	220-235	6
6.2	C	6	60	220-235	6
7.1	D	7	20	85-110	6
7.2	D	7	20	85-110	6
8.1	D	8	60	220-235	6
8.2	D	8	60	220-235	6

Fig. 4.21 – Working post with microscope KEYENCE VHX-S50

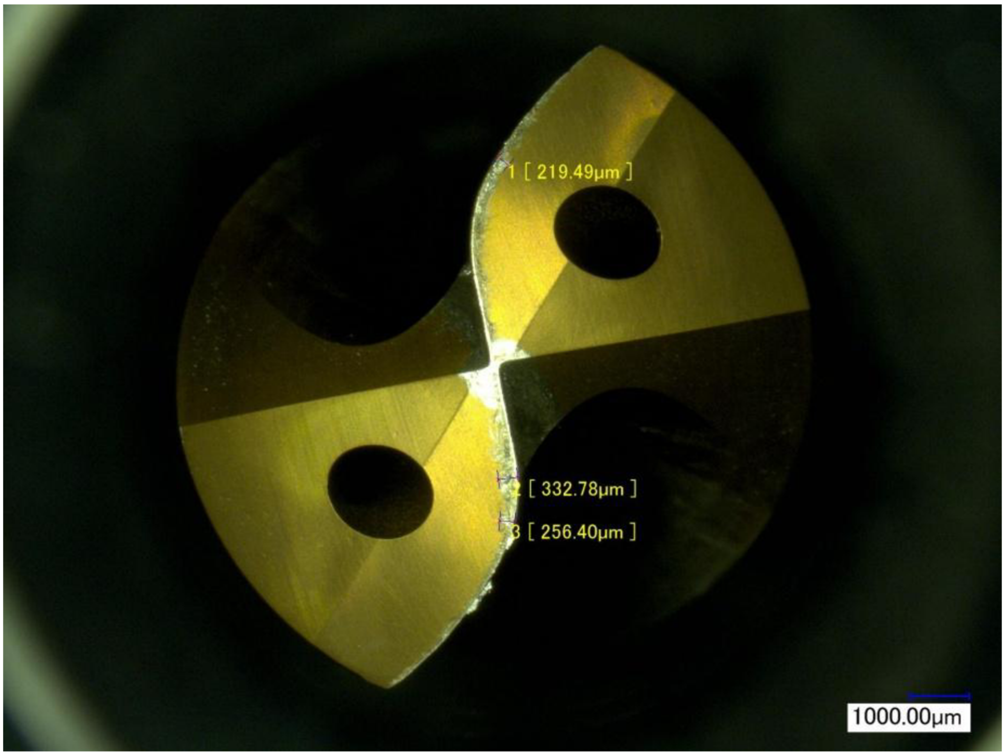

Fig. 4.22 – Exemplary photo by KEYENCE after test number 6.1

4.4.4 Aluminum alloy EN-AW 7020

The aluminum alloy is drilled by uncoated carbide tool Corodrill 860-1200-30-A1A by Sandvik Coromant with special geometry for Al alloys. It has also the option of internal flooding by canals.

Fig. 4.23 - Corodrill 860-1200-30-A1A

The test process is very similar to the stainless steel one. There are the same variable parameters, the same test number and repetition logic. There is only one difference. One drill is used for a complete test range of one oil, that means for four holes. Obviously, the machining of this aluminum alloys do not wear as much as the stainless steeel. During the regular control on KEYENCE microscope, but neither the tool wear, nor the BUE is observed (Fig. 4.24).

Tab. 4.15 – Experimental plan of drilling test of EN-AW 7020.

Test number	**Oil**	**Cutting tool number**	**Oil rate**	**Air rate**	**Air pressure**
			ml/h	l/min	bar
1.1	A	1	20	85-110	6
1.2	A	1	20	85-110	6
2.1	A	1	60	220-235	6
2.2	A	1	60	220-235	6
3.1	B	2	20	85-110	6
3.2	B	2	20	85-110	6
4.1	B	2	60	220-235	6
4.2	B	2	60	220-235	6
5.1	C	3	20	85-110	6
5.2	C	3	20	85-110	6
6.1	C	3	60	220-235	6
6.2	C	3	60	220-235	6
7.1	D	4	20	85-110	6
7.2	D	4	20	85-110	6
8.1	D	4	60	220-235	6
8.2	D	4	60	220-235	6

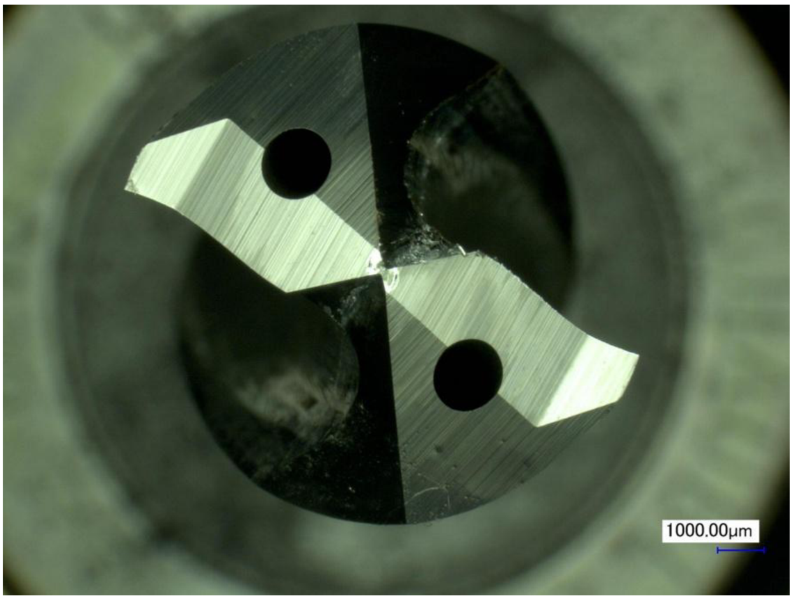

Fig. 4.24 – Exemplary photo by KEYENCE after have drilled 4 holes with oil A

5 RESULTS AND DISCUSSION

5.1 Variance analysis

The variance analysis is a statistical tool to evaluate the influence of adjustable parameters on the observed parameters of the experiment. The objective is to distinguish if a factor has a significant effect or not. There is an algorithm which is briefly explained below. The treatment of the orthogonal cutting results serves as an example. The variance analysis of the drilling tests results is leaded by the same way and is not shown in this work.

At the beginning, we have our experimental plan with some factors (parameters) and each factor has a certain number of levels.

Tab. 5.1 – Factors and levels for orthogonal cutting [52].

Factor	Oil type	Oil rate	Air pressure	Cutting speed - v_c
Levels	4	2	2	2

Then the experimental plan tables (Tab. 4.9 and 4.11) are transformed. The values of 2-level factor become -1 and 1, and for oils, it is -1;1;2;3. This table is a trial matrix called X. We consider that there are no interactions between the parameters, so the mathematic model is Cte + aA + bB + cC + dD, where a, b, c, d are coefficients. [52]

Tab. 5.2 – Trial matrix X [52].

	Factors			
Test number	A	B	C	D
1	-1	-1	-1	-1
2	-1	-1	1	1
3	-1	1	-1	1
4	-1	1	1	-1
5	1	-1	-1	1
6	1	-1	1	-1
7	1	1	-1	-1
8	1	1	1	1
9	2	-1	-1	1
10	2	-1	1	-1
11	2	1	-1	-1
12	2	1	1	1
13	3	-1	-1	-1
14	3	-1	1	1
15	3	1	-1	1
16	3	1	1	-1

The measured values of the observed parameters (cutting force, temperature, surface roughness etc.) are added into the next columns of the table. These values are called responses and one response column (one parameter), which will be used for the following calculations, becomes the matrix R. The matrix X is treated by following formula (5.1) to obtain the matrix of coefficients A, which obtains values Cte;a;b;c;d. [52]

$$A = ((X^T.X)^{-1}.X^T).R \text{ [52]} \tag{5.1}$$

The matrix A is multiplied by each line of the matrix X in order to obtain the theoretic responses. The differences between the measured and theoretical responses make the residual deviations.

Then the effects of factors are calculated. It is the average of one level of the studied factor divided by the average of the whole factor (value taken from the matrix X). The effects of the first factor (oil type) are noted $E_{A\text{-}1} – E_{A3}$. [52]

The main part of analysis of variance is summarized in the table 5.3

Tab. 5.3 – Analysis of variance factor A (oil type) and one measured parameters [52].

	Suma of squares	DoF	Variance	F_{cal}	$F_{theoretic}$
A	$\frac{N}{n_A}.\sum_{i}^{n_A} {E_{Ai}}^2$	$n_A - 1$	$V_A = \frac{\frac{N}{n_A}.\sum_i^{n_A} {E_{Ai}}^2}{n_A - 1}$	$=\frac{V_A}{V_R}$	Table Snedecor-Fischer
Residues	$\sum_{i}^{N} {e_i}^2$	N-DoF (of model)	$V_R = \frac{\sum_i^N {e_i}^2}{N-1}$		

If $F_{cal}>F_{theoretical}$, the influence the studied factor on the measured parameters is considered as significant, in the opposite case as insignificant.
The calculation of the influence of the other factors (B, C and D) on this parameter is provided by adding the lines with indexes b, c and d.
To calculate the influence of these factors on another measured parameter, the same table is re-used with taking the corresponding responses (matrix R). [52]

The aim of analysis of variance is to show if and how much a factor influences a measured parameter. This statistical tool is used mainly during complex tests when the factor effect is not apparent by the first view.

5.2 Orthogonal cutting

5.2.1 Results exploration

Cutting forces, the maximal temperature and surface roughness are evaluated. The cutting forces are measured by KISTLER piezoelectric dynamometer and the results are taken from DasyLAB files.

The temperature is measured by camera and acquired images treated by MATLAB. An example of obtained photo in the grayscale is shown in Fig. 5.1 and a treated image with temperature scale is in Fig. 5.2

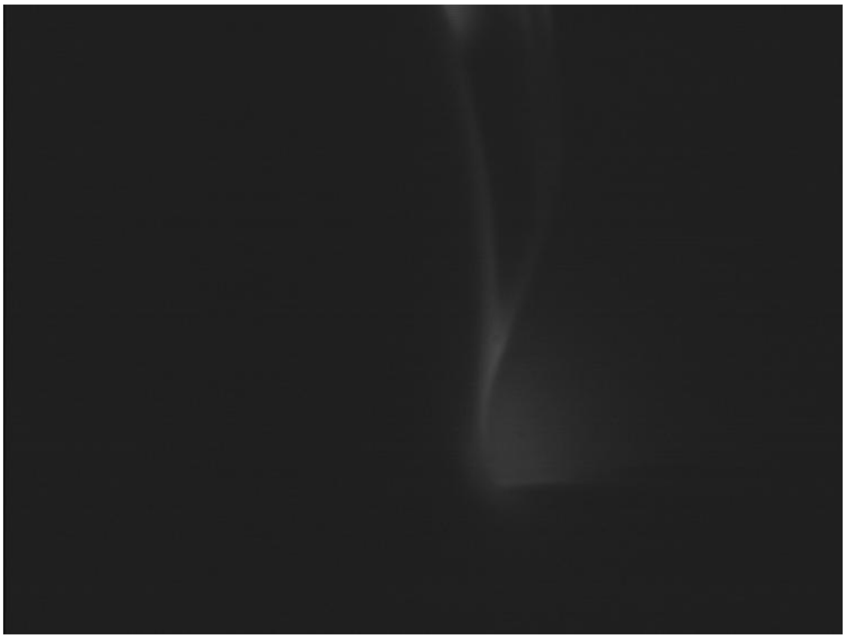

Fig. 5.1 – Photo taken by the thermal camera

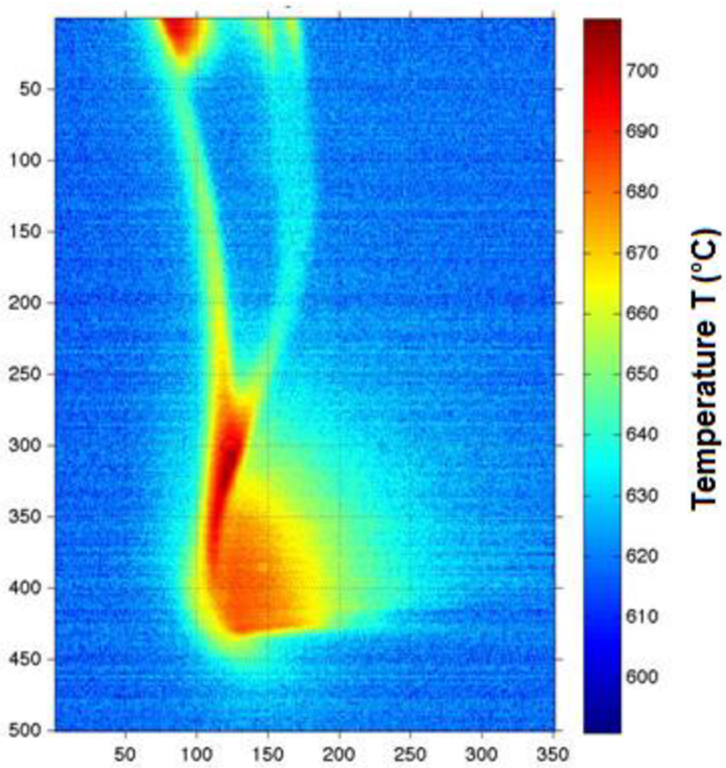

Fig. 5.2 – Treated and trimmed image with temperature scale

The surface roughness measuring is carried out on the distance of 2 mm using machine Somicronic Surfascan with moving the detector with tip radius 5 µm. Each disc is measured three times.

Fig. 5.3 Machine Surfascan for measuring of the surface roughness

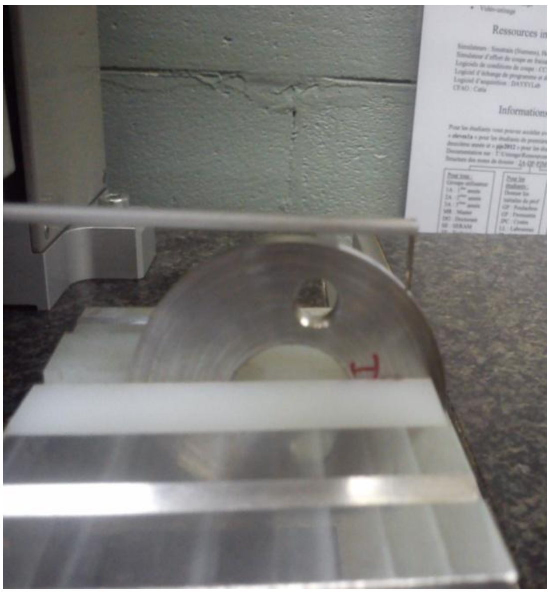

Fig. 5.4 – Surface roughness measuring process

5.2.2 Results summary

The results of the orthogonal cutting test can be divided into three groups: cutting forces, the temperature and the surface roughness.

We can see in the tables in the appendices, that generally the most influent parameter is the cutting speed. So all graphics are related to the cutting speeds and to the oils which have to be evaluated. Each graphic contains 2 columns for each oil (one column per cutting speed) plus there are 2 columns for dry cutting. That means 10 columns per graphic. The dry cutting tests have not been included into the experimental plan. They serve as supplementary test, but their representativeness is limited.

5.2.2.1 Cutting forces

The cutting force and the feed force are acquired. The average values are considered. Because the cutting force is the main and the highest components of cutting forces, the amplitude of the cutting force is taken also.

5.2.2.1.1 AISI 316L

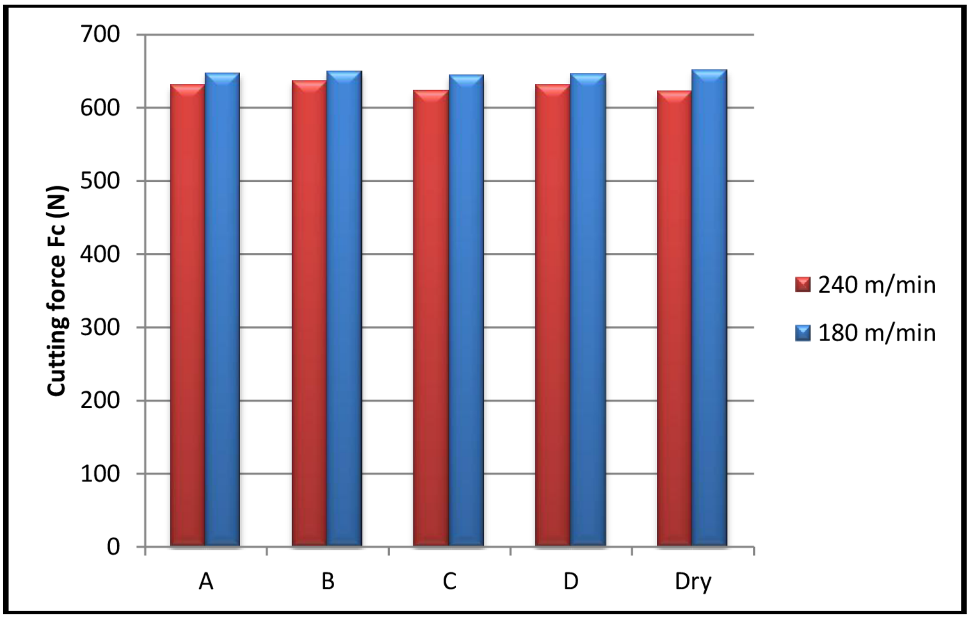

Fig. 5.5 – Average value of the cutting force by oils

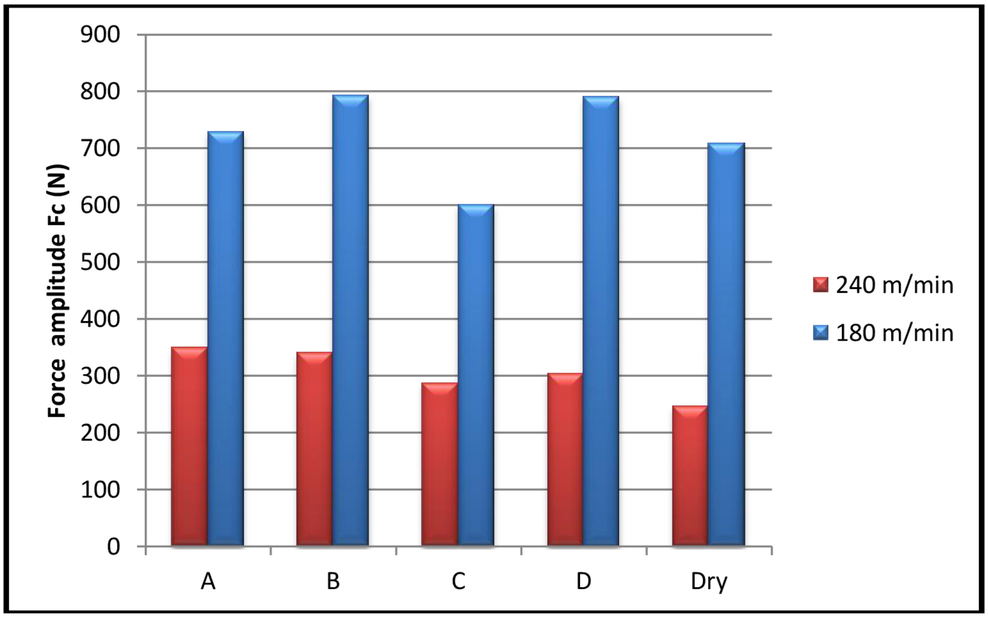

Fig. 5.6 – Amplitude of cutting force by oils

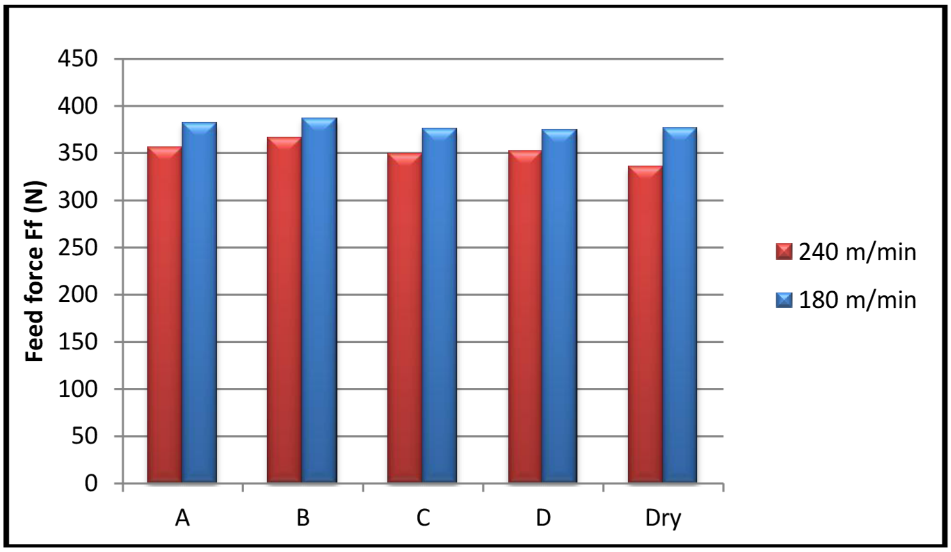

Fig. 5.7 – Average value of the feed force by oils

According to tables 1.1 – 1.3 in the appendices, we can notice that the only significant parameter is the cutting speed, which is evident in the graphics (Fig. 5.5 – 5.7), too.

In the fig. 5.5, a difference among the oils equally as a difference between the MQL and dry cutting is not important.

We can see in the fig. 5-6, that the cutting force amplitude is lower using v_c=240 m/min than using v_c=180 m/min. So the cutting process is more stable when using v_c=240 m/min, but this phenomenon has been already observed during machining. The best oil concerning the amplitude is the oil C.

For the oils C and D, it is noticed slightly lower values of feed force than for two other oils (Fig. 5.7).

5.2.2.1.2 EN-AW 7020

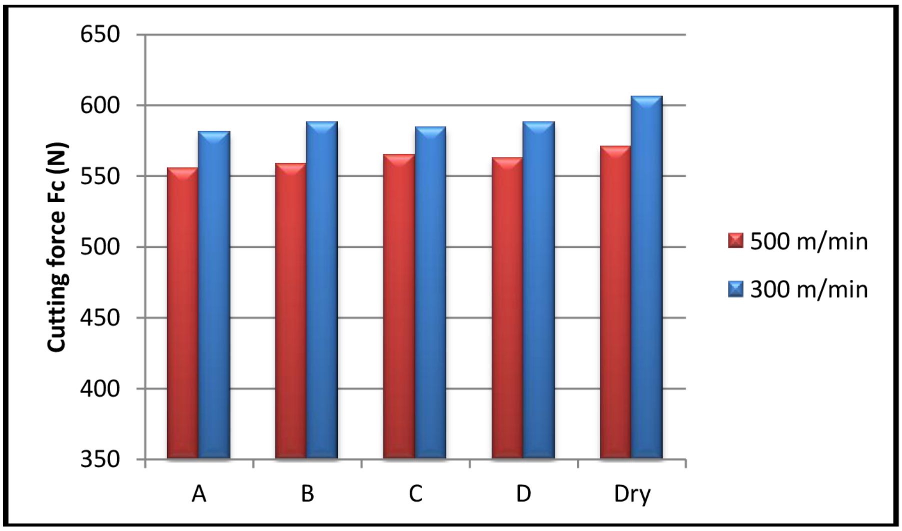

Fig. 5.8 – Average value of the cutting force by oils

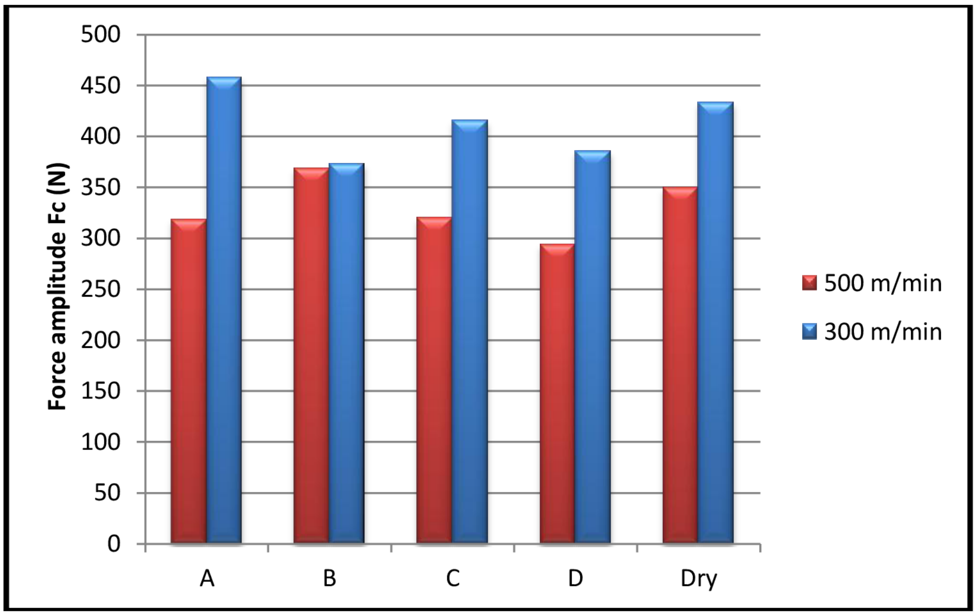

Fig. 5.9 – Amplitude of cutting force by oils

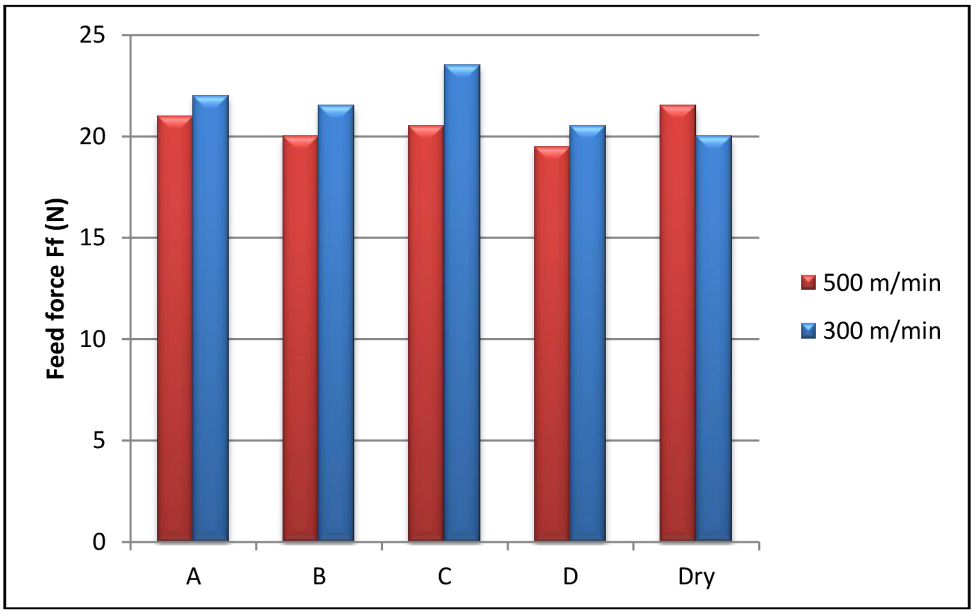

Fig. 5.10 – Average value of the feed force by oils

As seen in the tab. 2.1 – 2.3 in the appendix 2, the situation is similar as in the case of the AISI 316L. Only the cutting speed has an influence on the cutting force. No parameter has a significant influence on the feed force.
Average values of cutting force are lower when using the MQL than when dry cutting which is logical, tightly better result is remarked by oil A (Fig. 5.8).
The oil A has the worst results of cutting force amplitude for v_c=300 m/min, the best one is the oil D (Fig. 5.9).
The values of feed force are very low and the differences are negligible (Fig. 5.10)

5.2.2.2 Temperature

Since the camera is not able to measure below 450°C, the temperature measuring of the aluminum alloy is impossible. So there are only the results of the maximum temperature the stainless steel.
Significant parameters for temperature measuring are the cutting speed and the air pressure. A higher air pressure could have a better cooling effect.

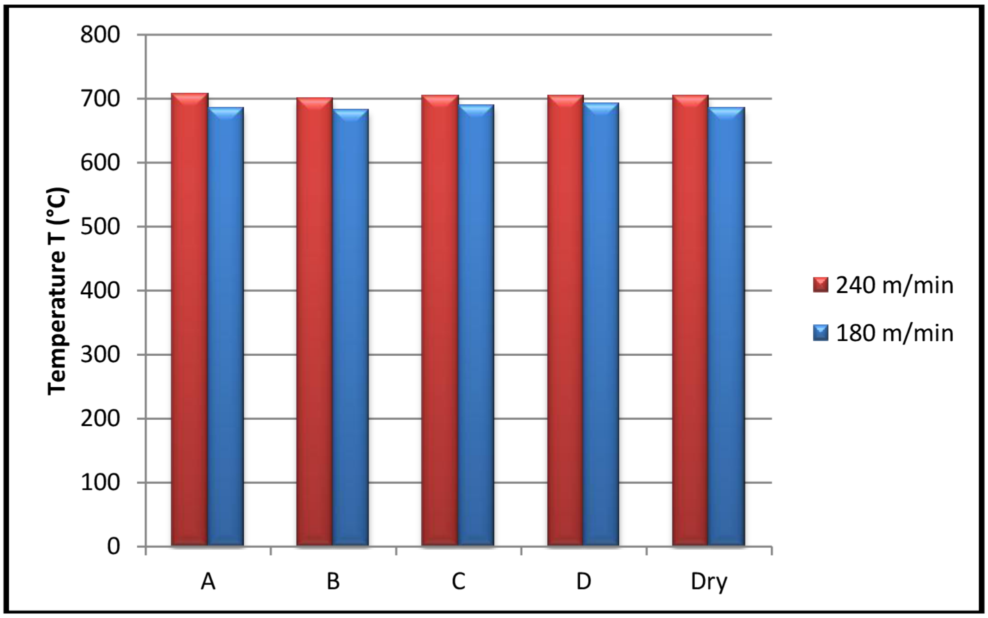

Fig. 5.11 – Maximum temperature at the interface by oils

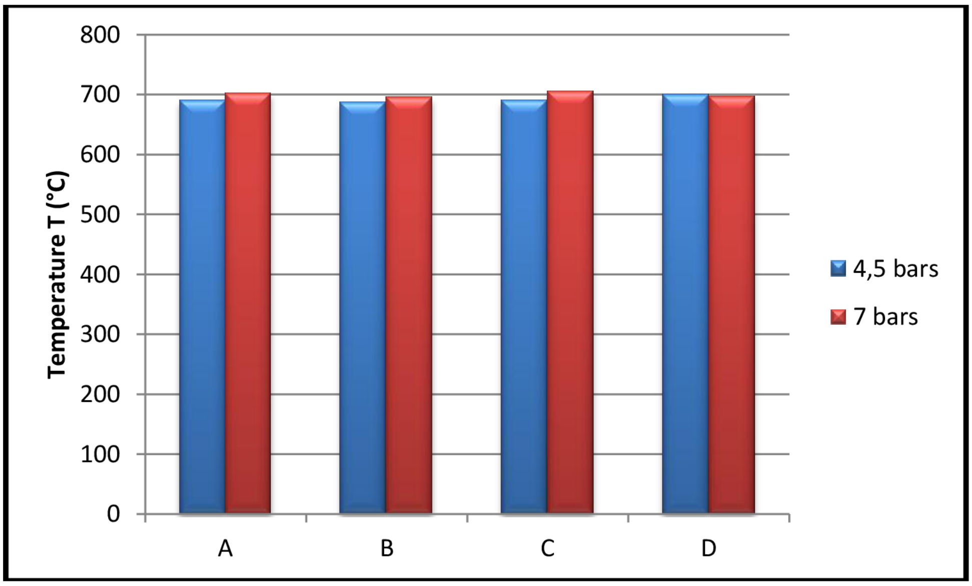

Fig. 5.12 – Maximum temperature according to air pressure by oils

The temperature is obviously superior for the higher cutting speed (Fig. 5.11). The table 5.12 is added because the air pressure has a significant influence on the temperature. However the hypothesis of cooling effect of higher pressure is disconfirmed by this figure. The synthesis of these two figures is that the oil B has tightly the best cooling effect.

5.2.2.3 Surface roughness

According to the appendices (tab. 1.5 and 2.4), there is not any parameter having influence to the surface roughness of the AISI 316L and the cutting speed influences the total surface roughness of the EN-AW 7020. Generally, the values are very low, because the surface quality in the orthogonal cutting is not dependant on the feed as usually.

5.2.2.3.1 AISI 316L

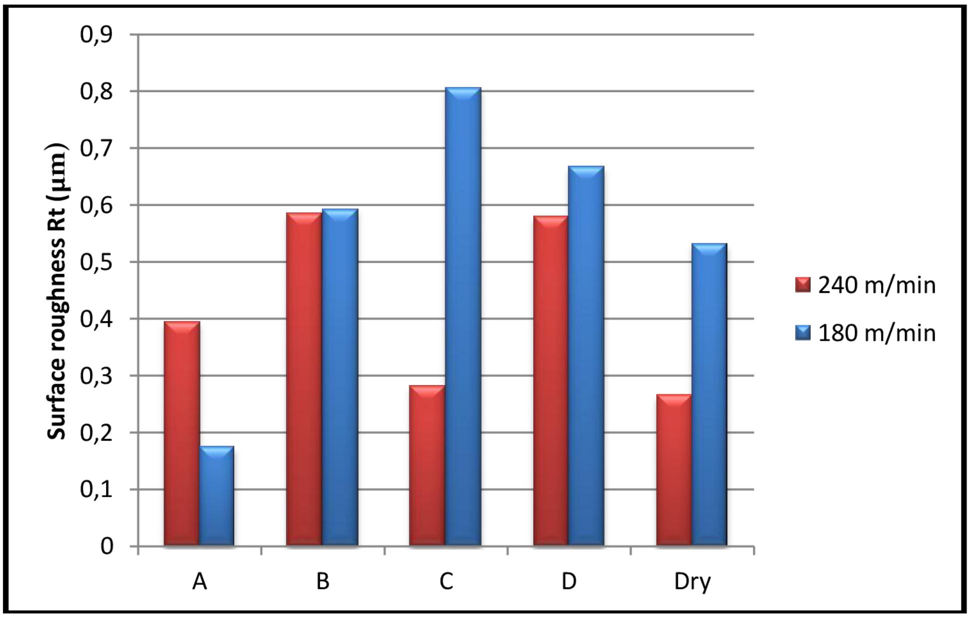

Fig. 5.13 - Total surface roughness Rt by oils

The results of the total surface roughness (Fig. 5.13) are very accidental. For example the oil C has remarked the best surface finish for v_c=240 m/min and at the same the worst one for v_c=180 m/min. The best results are observed in case of the oil A.

5.2.2.3.2 EN-AW 7020

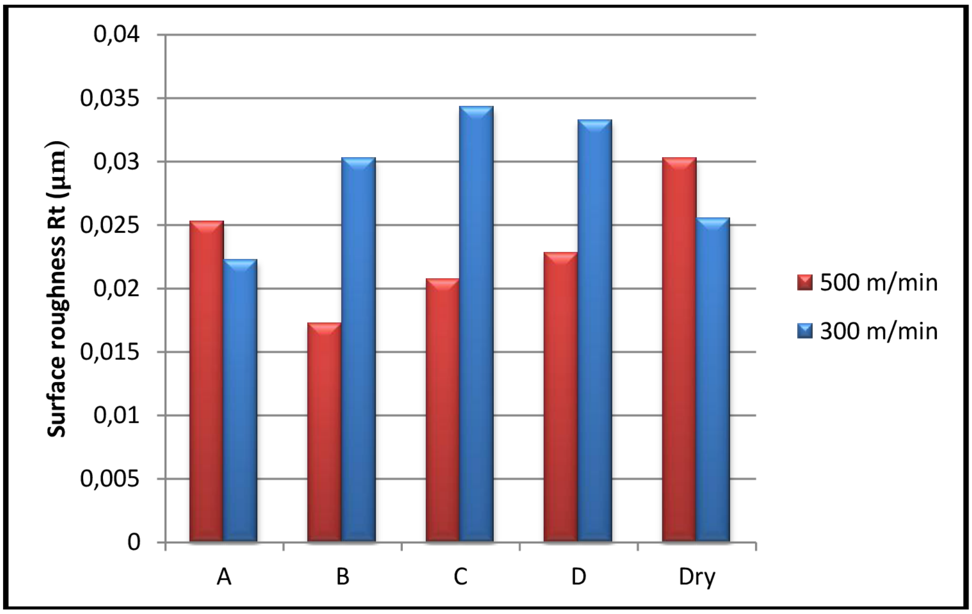

Fig. 5.14 - Total surface roughness Rt by oils

The values of the surface roughness are very low, so the differences among them are small and the distribution of results is really aleatory. Therefore any comparison cannot be made from the fig. 5.14

5.2.3 Conclusion of the orthogonal cutting tests

The main conclusion of the orthogonal cutting tests is the absence of a global significant difference among the oils. Even sometimes, the dry cutting remarks better results than MQL application. Nevertheless some hypothesis could be done. It seems that the oil B, whose viscosity is the highest, reaches the results slightly worse than three other oils.

One explanation of such results could be the fact, that the orthogonal cutting is not a difficult cutting operation. It is a cut carried out in exterior, so the cutting interface is easily cooled. It is a 2D cutting, there is no border effect of third side. It is possible that the oils properties could not be fully demonstrated.

5.3 Drilling tests

5.3.1 Results exploration

The same parameters as during the orthogonal cutting are evaluated: cutting forces, temperature and surface roughness.
Cutting forces and the temperature are recorded in the same DasyLAB file. The recording frequency is 1 kHz. Then the data are saved and exported in ASCII format. Useless data are deleted in Excel and the file is treated and the graphics are drawn in MATLAB. The MATLAB file calculates also the average values of torque and thrust force, their amplitudes in the stable area and maximum temperature. As shown in Fig. 5.15, the evolution of torque can be divided on three sections. The first one is from the beginning up to the depth of 2 mm, it corresponds to the entry of the drill point into the workpiece. Then there is an unstable area approximately up to 5,5 mm. Finally from 5,5 mm , the torque evolution is stable. Here is calculated the amplitude.

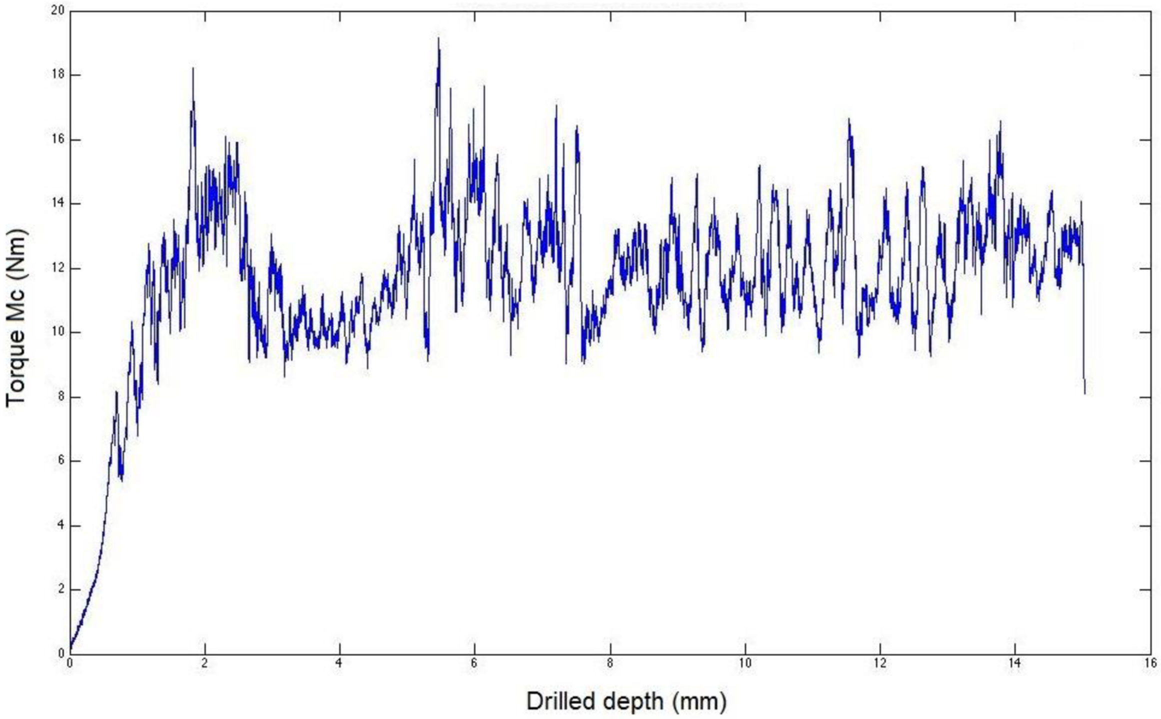

Fig. 5.15 – Example of a torque curve when drilling AISI 316L

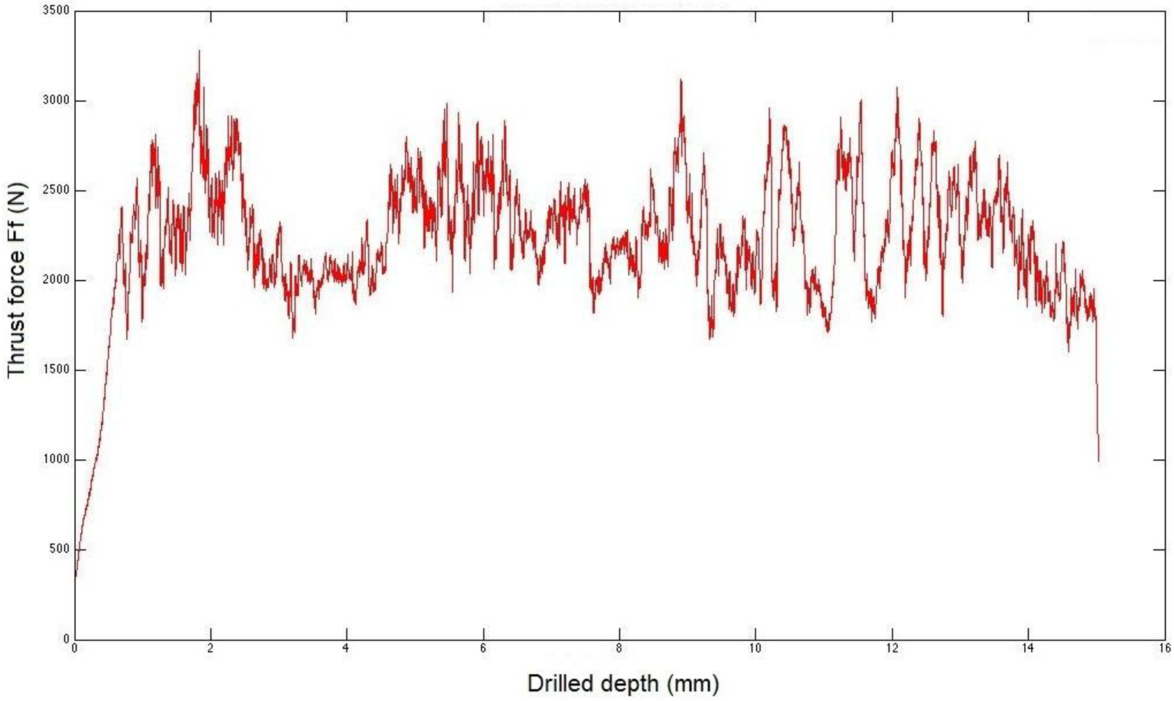

Fig. 5.16 - Example of a torque curve when drilling AISI 316L

The temperature curves are drawn independently for each of thermocouples (2 curves for AISI 316L and 4 curves for EN-AW 7020). Beside this, a curve of the global evolution of the temperature along the hole is made. Fig. 5.17 and Fig. 5.18 are examples of both curves.

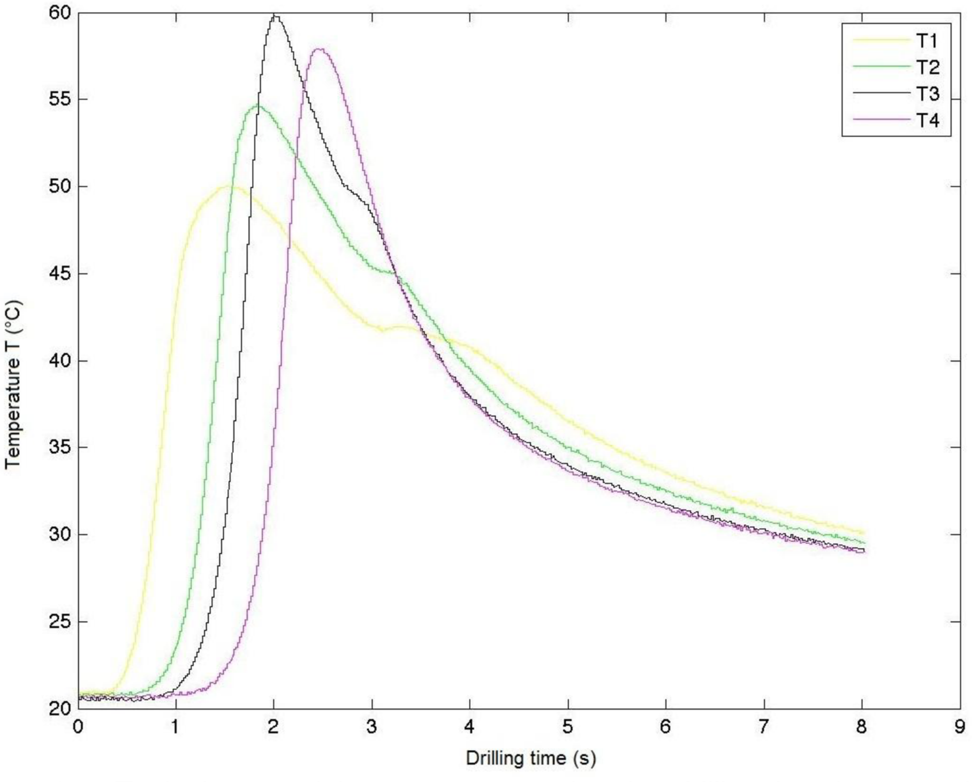

Fig. 5.17 – Typical curve of the temperature related to drilling time (measured by 4 thermocouples in EN-AW 7020)

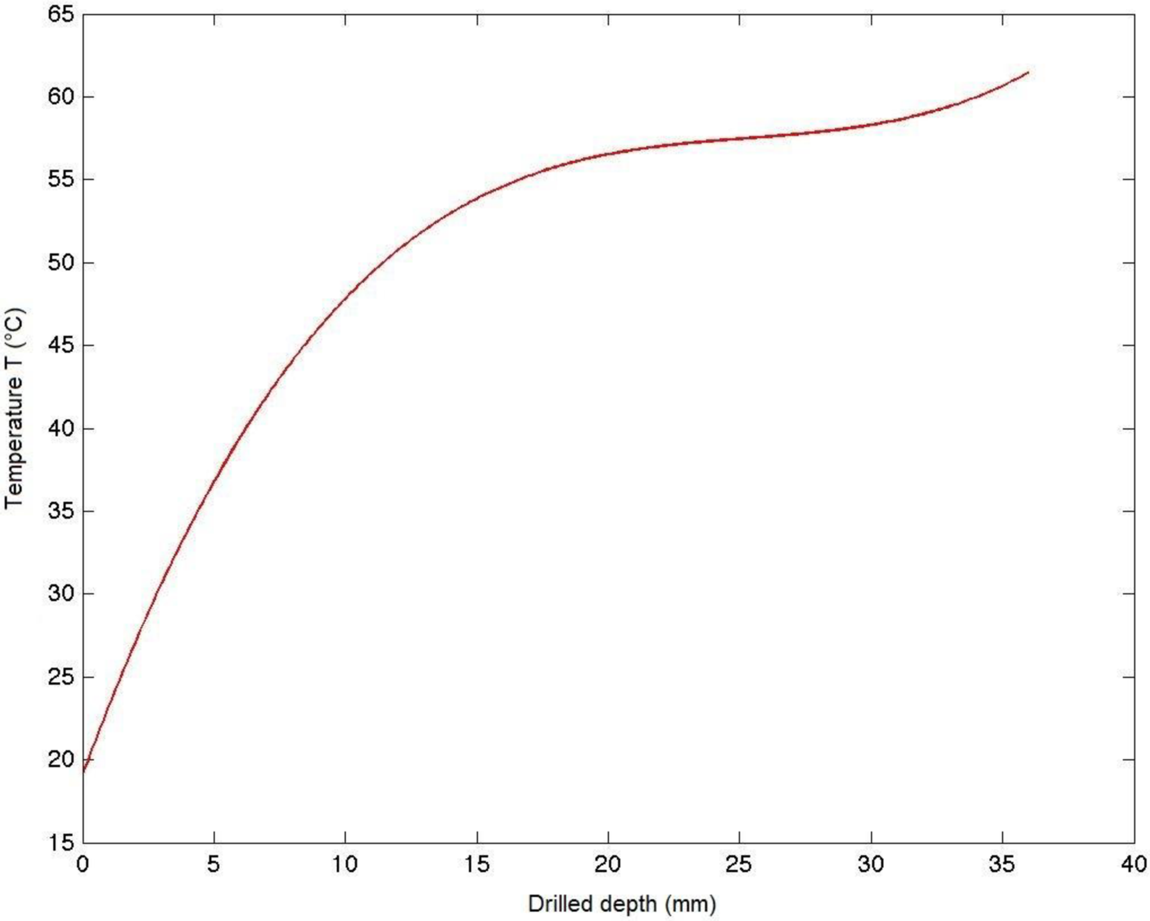

Fig. 5.18 – Example of temperature evolution along the hole in EN-AW 7020

The way of measuring the surface roughness of the hole wall is identical as when measuring the discs. The machine SOMICRONIC Surfascan (fig. 5.3 and fig. 5.19) and a moving detected with 5 µm tip radius. Each hole surface is measured three times on the length of 5,6 mm. The value of Ra and Rt are taken, but only Rt is chosen to be used to the oils comparison. The average value Rt of three measures is considered.

Fig. 5.19 – Surface roughness measuring

5.3.2 Results summary

The organization of this results summary is the same as the summary 5.2.2 ; three parts (cutting forces, temperature, roughness surface) and each part is divided accordance with material. The results of variance analysis are accessible in the appendix 3 for the stainless steel and in the appendix 4 for the aluminum alloy.
Concerning the graphs, there are 4 oils. There are two columns per oil, each column represents one oil rate. Certain graphs contain also dry cutting results. Dry cutting tests are carried out as preliminary COM tests. Since the dry cutting tests are not included in the experimental planning, their results are not regularly saved and included into the graphs. The status of dry cutting results is rather illustrative, the main aim is compare the oils among them.

5.3.2.1 Cutting forces

The average value of the torque and the thrust force and measured. In the case of the torque, its amplitude in the stable area (chapter 5.3.1) is included.

5.3.2.1.1 AISI 316L

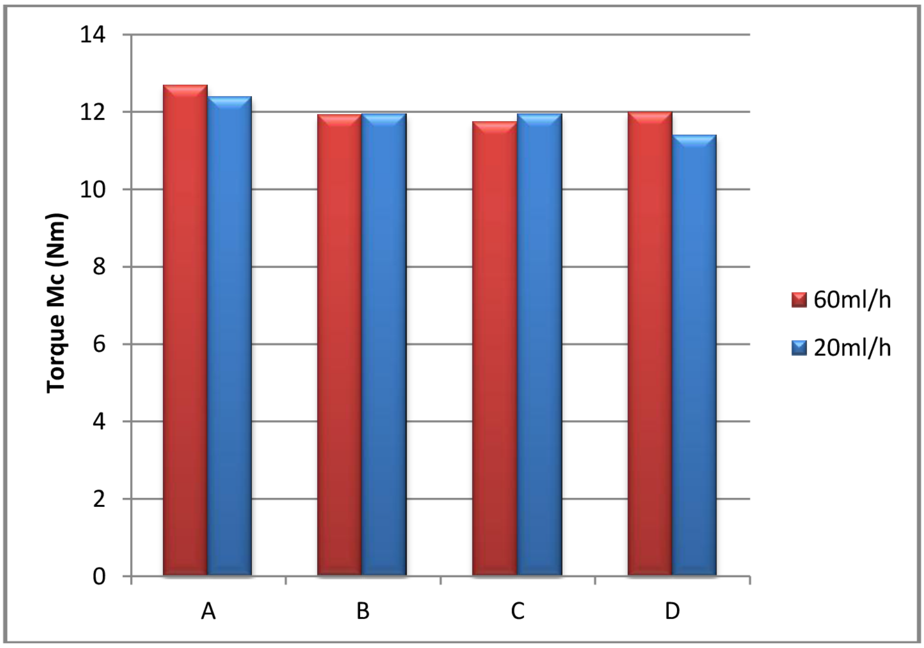

Fig. 5.20 – Average value of the torque by oils

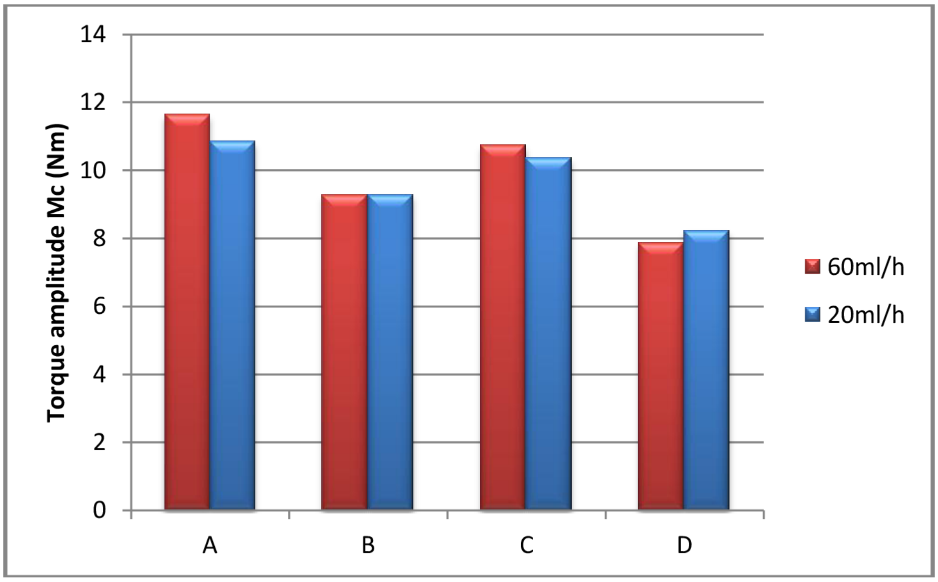

Fig. 5.21 – Amplitude of the torque by oils

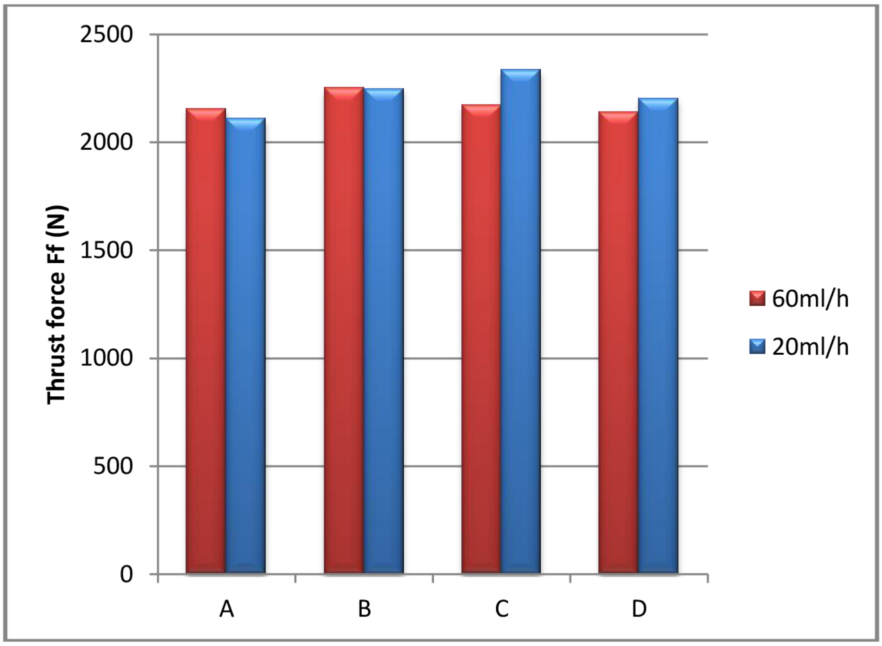

Fig. 5.22 – Average value of thrust force by oils

Concerning the torque (fig. 5.20 and fig. 5.21) it is evident, that the oil A has the worst properties. On the other side, the oil D is tightly the best comparing the average values and with great difference concerning the torque amplitude. A quite low amplitude is also observed when using oil B. But generally the amplitudes are high relative the average value.

The values of the thrust forces are not very different among oils (fig. 5.22), however lower forces are measured for oils A and D.

5.3.2.1.2 EN-AW 7020

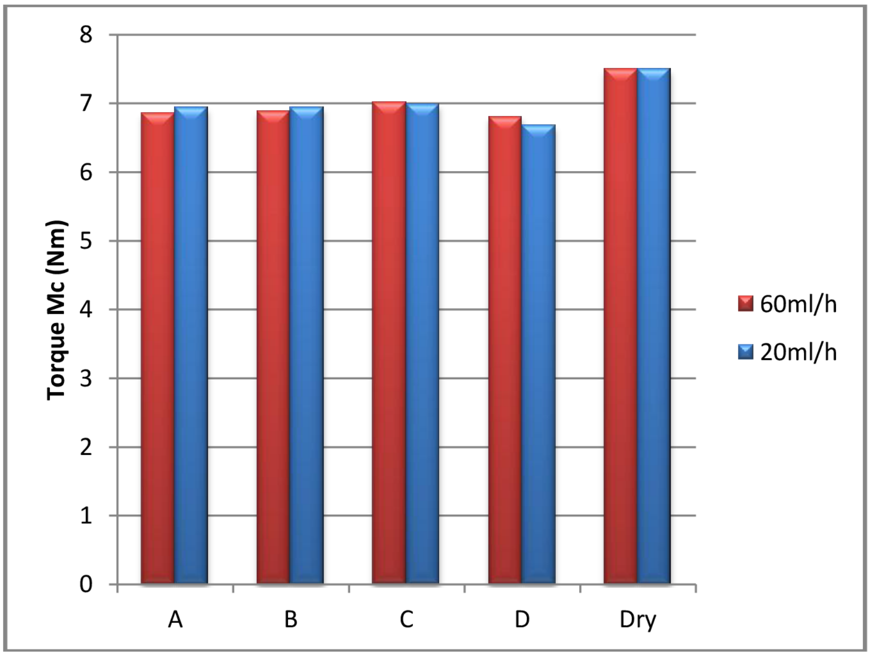

Fig. 5.23 – Average value of torque by oils

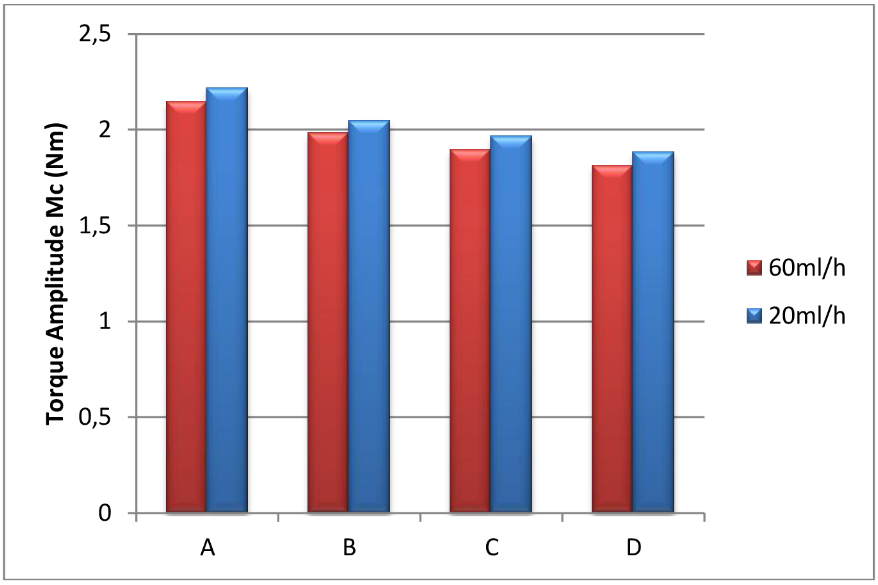

Fig. 5.24 – Amplitude of the torque by oils

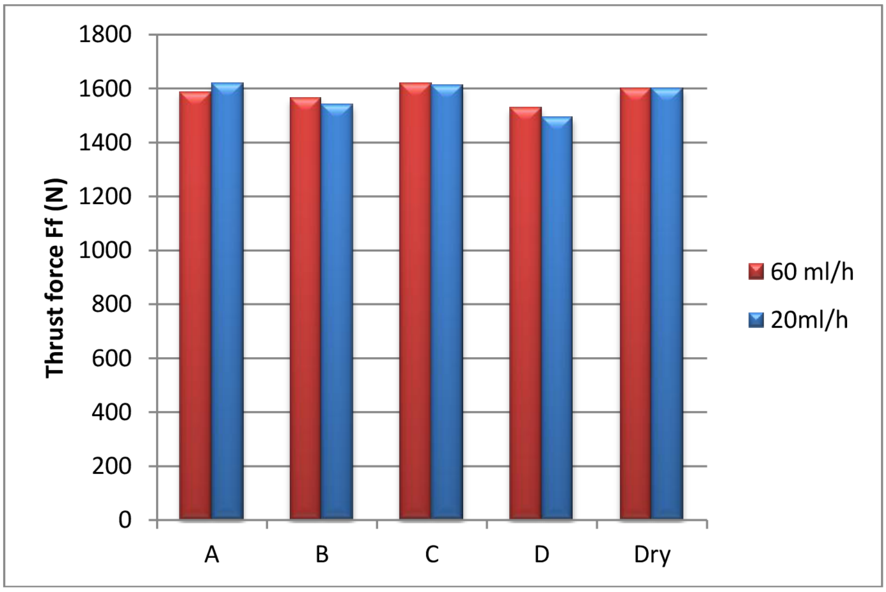

Fig. 5.25 - Average value of thrust force by oils

The lowest average value of torque (fig. 5.23) is noticed for oil D, the highest one for oil C. An important difference is observed between dry cutting and MQL application. The torque amplitude (fig. 5.24) is the highest for oil A and decreases progressively by oils until the best oil D. The difference between dry cutting and MQL application from point of view of the thrust force (fig. 5.25) is not so great as in the case of the torque. The oils A and C reach the same result as dry cutting, the oils B and D are more efficient.

5.3.2.2 Temperature

The temperature is measured by 2 thermocouples for AISI 316L and by four ones for the aluminum alloy. In all cases, the maximum value measured by whatever thermocouple in the hole is considered. There are 2 tests by configuration (i.e. test 3.1 and 3.2), so the column contains the mean of two maximum temperatures.

5.3.2.2.1 AISI 316L

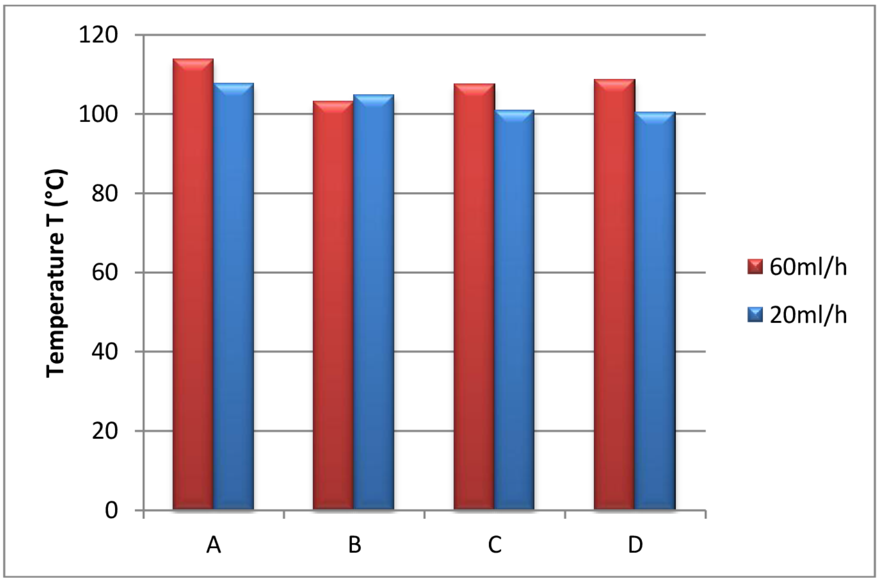

Fig. 5.26 - Maximum temperature by oils

The results of oils B,C and D are balanced according to fig. 5.26. The oil A seems to have a lower cooling capacity then the others.

5.3.2.2.2 EN-AW 7020

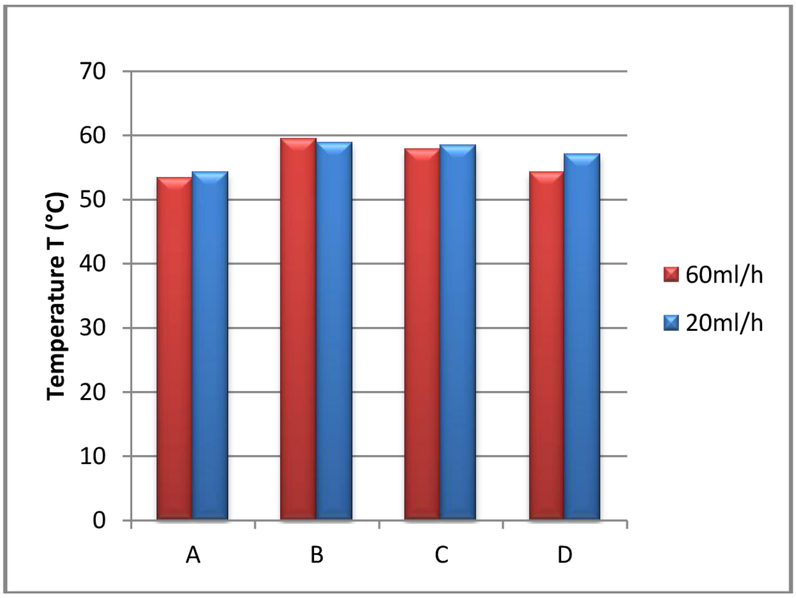

Fig. 5.27 Maximum temperature by oils

Unlike the previous graphic, the oil A reaches the lowest temperature in EN-AW 7020 (fig. 5.27). The highest value is measured when using the oil B, but the results are not very different.

5.3.2.3 Surface roughness

5.3.2.3.1 AISI 316L

As described above (chapter 5.3.1), the total surface roughness value (Rt) is the arithmetic mean of 3 measured. The surface roughness is the only acquired result of the dry cutting of AISI 316L, because it can be measured after preliminary tests.

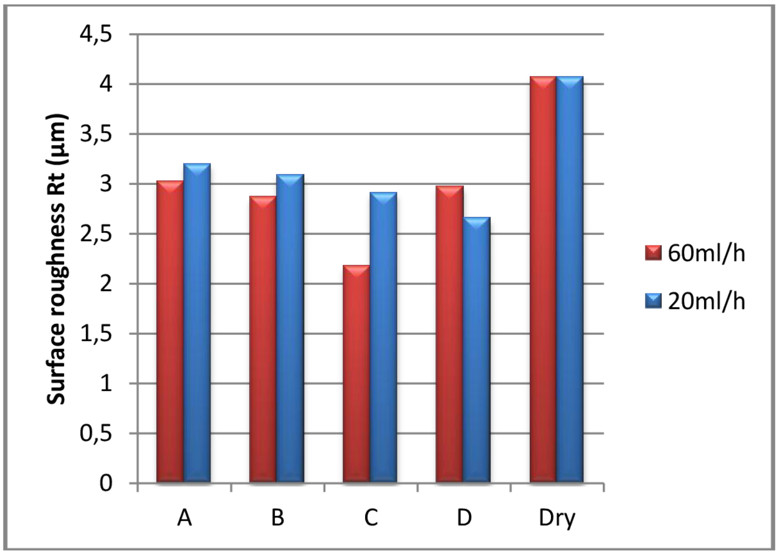

Fig. 5.28 - Total surface roughness Rt by oils

The difference is apparent between dry and microlubrified tests. The best results are reached by oil C, oils D and B are placed on the two following positions.

5.3.2.3.2 EN-AW 7020

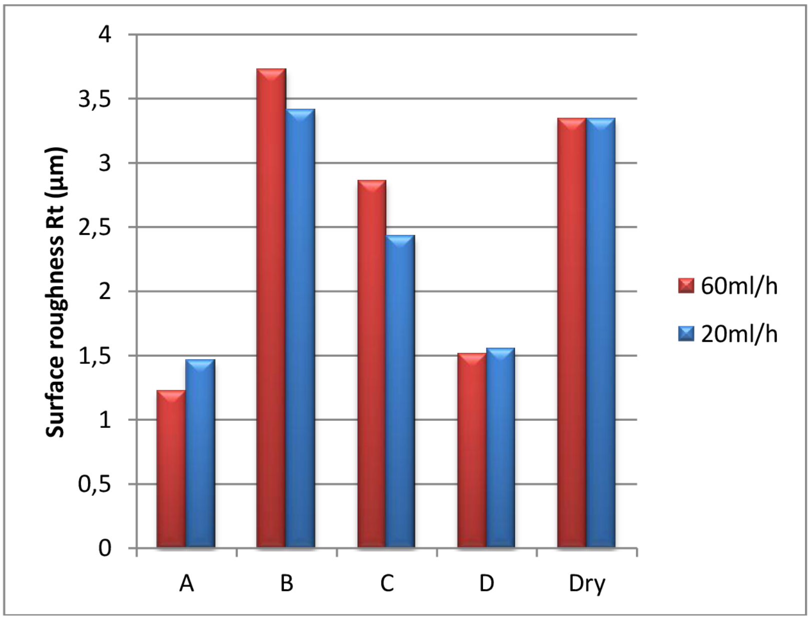

Fig. 5.29 - Total surface roughness Rt by oils

A giant difference between the oils effect is observed in fig. 5.29. Oils A and D remark very good results, the oil C is evidently worse and with oil B, a higher surface roughness is reached than when dry cutting.

5.3.3 Conclusion of the drilling tests

Some differences between the oils performances are observed. It is confirmed by the variance analysis (appendix 3 and 4), where the oil type has a significant influence on all measured parameters.

It can be concluded that the torque is much more influenced by the way of lubrication than the drilling thrust. The winner from point of view of cutting forces is the oil D, on the last position there is the oil A.

The results of the temperature are difficult to explain. It is suspected that oil A is the worst for one material and the best for the other. The differences are not very significant, but the chosen measuring system could be a reason of the obtained results.

The surface roughness results are not very surprising for AISI 316L, but rather for EN-AW 7020. Oil B and C do not improve the surface roughness compared to dry cutting of this aluminum alloy. The results when using oil A and D are much better.

Overall, the best oil of drilling test is the oil D, which has a synthetic base. Three other oils are very similar. The oil A is indeed the worst concerning cutting forces, but it is better than the others at the temperature and the surface roughness.

6 CONCLUSION

6.1 Summary of the work

This project, especially its practical part, is very complex, although it is not evident at beginning. It contains not only machining in form of oil evaluation test, but also samples fabrications. Besides machining, there are the cutting fluid issues and working with all measuring accessories.

The aim of this diploma thesis is to compare the performance of four oils on chosen parameters. Two types of tests have been executed; orthogonal cutting and drilling. The orthogonal cutting test did not show a significant difference among oils. The cutting speed was the only significant parameter. Drilling test has brought a lot of information by contrast with the orthogonal cutting. Differences among the oils were not always coherent, but generally the most efficient oil is the D one. The effect of the three other oils depends on the observed domain, but overall, the performance of them is balanced.
The oil rate has not significant influence neither during the orthogonal cutting, nor drilling, which could seem to be a surprising result.
The hypothesis expressed after the orthogonal cutting test, that a high viscosity could decrease the oil performance, is not confirmed by drilling test. The difference between the oils performance is probably due mainly to the chemical composition of the appropriate oils.

6.2 Development for the future

As recommended in the literature, it would be interesting to add the tool life test in drilling. However the tool life tests are extremely time-consuming. Moreover the repeatability is low. Unfortunately, it was not possible in the time options of this project.

To conclude, I would like to mention some practical recommendations of the use of MQL withdrawn from the experiences.
The drilling with MQL works very well in the aluminum alloys. In case of AISI 316L, the difficulties appeared during the preliminary test and also during the evaluation test, three drills were broken despite reducing the cutting speed and drilling depth. According to the provided experiment the MQL drilling of AISI 316L is very difficult and probably not economically profitable to use in the production.
When using one-channel internal supply of MQL, there are really some problems with the mist formation because of the long channel where the mixture has been already formed. It could be advantageous to form the mixture just before the spindle (two-channel system). Another problem is the centrifugal force due to the spindle rotation, but it is impossible to avoid.
The MQL is environmentally friendlier than conventional cooling concerning the fluid consumption. But the mist formed by MQL is not healthy for the operators. Therefore, the MQL application should be accompanied by an aspiration system in the machine.

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NOMENCLATURE

Abbreviation / symbol	Unit	Signification
A	-	Matrix of coefficients
AISI	-	American Iron and Steel Institute numbering system
BUE	-	Built-up edge
CCD	-	Charged Coupled Device – type of camera similar to a thermal camera
CNC	-	Computer Numeric Control
COM	-	Couple Outil-Matière (from French) – Specific cutting force in function of the cutting speed or of the feed rate
Cte	-	Constant
DoF	-	Degrees of Freedom
DLC	-	Diamond Like Carbon - coating
e_i	-	Residual error
E_{Ai}	-	Effect of a factor (oil A in this case) on the level i
EN	-	European Norm
EP	-	Extreme Pressure additives into the oils
f	[mm]	Feed per revolution
F_c	[N]	Tangential cutting force
F_{cal}	-	Calculated value of ratio variance of factor/ residual variances (to be compared with $F_{theoretic}$)
F_f	[N]	Feed force (when turning) Thrust force (when drilling)
$F_{theoretic}$	-	Theoretic value from the Snedecor-Fischer table corresponding to degree of freedom (to be compared with F_{cal})
HSS	-	High Speed Steel

l/D	-	Length/diameter ratio
JIS	-	Japanese Industrial Standard
L_0	[mm]	Contact length at the chip/tool interface
M_c	[Nm]	Drilling torque
MQL	-	Minimum Quantity of Lubrication
n	-	Contact length factor
n_A	-	Number of tests with one factor
N	-	Number of tests in one experimental plan
NDM	-	Near Dry Machining
Q_{ch}	[J]	Heat dissipated in the chip
Q_{ct}	[J]	Heat dissipated in the cutting tool
Q_w	[J]	Heat dissipated in the workpiece
Q_Σ	[J]	Total heat produced by machining process
R	-	Response column matrix
Ra	[µm]	Mean arithmetic surface roughnes
Rt	[µm]	Total surface roughness
T	[°C]	Maximum temperature at the tool/chip interface
UNS	-	Unified Numbering System
v_c	[m/min]	Cutting speed
V_A	-	Variance of a factor (oil A in this case)
V_R	-	Residual variance
VBa	-	Flank wear measured in the point a
VBb	-	Flank wear measured in the point b
WMD	-	Water Micro Droplets
X	-	Trial matrix
X^T	-	Transposed trial matrix
γ	[°]	Tool rake angle
κ_r	[°]	Tool entering angle
λ_s	[°]	Tool chisel edge angle

LIST OF APPENDICES

Appendix 1

Fig. 1.1 – Effect of variables factors on the average value of the cutting force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	190,79688	3	63,59896	1,12716	3,59	Insignificant
Oil rate	54,39063	1	54,39063	0,96396	4,84	Insignificant
Air pressure	23,76563	1	23,76563	0,42120	4,84	Insignificant
Vc	1080,76563	1	1080,76563	19,15440	4,84	Significant
Residues	620,66287	11	56,42390			
Total	1767,48438	15	117,83229			

Fig. 1.2 – Effect of variables factors on the amplitude of the cutting force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	35620,42188	3	11873,47396	1,05716	3,59	Insignificant
Oil rate	5531,64063	1	5531,64063	0,49251	4,84	Insignificant
Air pressure	9481,89063	1	9481,89063	0,84423	4,84	Insignificant
Vc	667284,76563	1	667284,76563	59,41211	4,84	Significant
Residues	123546,07151	11	11231,46105			
Total	1767,48438	15	117,83229			

Fig. 1.3 – Effect of variables factors on the average value of the feed force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	475,50000	3	158,50000	1,16891	3,59	Insignificant
Oil rate	36,00000	1	36,00000	0,26549	4,84	Insignificant
Air pressure	2,25000	1	2,25000	0,01659	4,84	Insignificant
Vc	2304,00000	1	2304,00000	16,99163	4,84	Significant
Residues	1491,55828	11	135,59621			
Total	3744,00000	15	249,60000			

Fig. 1.4 – Effect of variables factors on the maximum temperature.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	129,68750	3	43,22917	1,19826	3,59	Insignificant
Oil rate	76,56250	1	76,56250	2,12223	4,84	Insignificant
Air pressure	264,06250	1	264,06250	7,31951	4,84	Significant
Vc	1139,06250	1	1139,06250	31,57351	4,84	Significant
Residues	396,84171	11	36,07652			
Total	1860,93750	15	124,06250			

Fig. 1.5 – Effect of variables factors on the total surface roughness.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	0,28377	3	0,09459	0,46703	3,59	Insignificant
Oil rate	0,03691	1	0,03691	0,18225	4,84	Insignificant
Air pressure	0,00167	1	0,00167	0,00825	4,84	Insignificant
Vc	0,03985	1	0,03985	0,19676	4,84	Insignificant
Residues	2,22787	11	0,20253			
Total	2,12308	15	0,14154			

Appendix 2

Fig. 2.1 – Effect of variables factors on the average value of the cutting force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	134,67188	3	44,89063	0,74874	3,59	Insignificant
Oil rate	2,64063	1	2,64063	0,04404	4,84	Insignificant
Air pressure	23,76563	1	23,76563	0,39639	4,84	Insignificant
Vc	2512,51563	1	2512,51563	41,90681	4,84	Significant
Residues	659,50319	11	59,95484			
Total	3097,98438	15	206,53229			

Fig. 2.2 – Effect of variables factors on the amplitude of the cutting force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	4885,54688	3	1628,51563	0,70501	3,59	Insignificant
Oil rate	27680,64063	1	27680,64063	11,98336	4,84	Significant
Air pressure	6662,64063	1	6662,64063	2,88436	4,84	Insignificant
Vc	27266,26563	1	27266,26563	11,80397	4,84	Significant
Residues	25409,16185	11	2309,92380			
Total	83653,85938	15	5576,92396			

Fig. 2.3 – Effect of variables factors on the average value of the feed force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	9,18750	3	3,06250	1,35891	3,59	Insignificant
Oil rate	0,56250	1	0,56250	0,24960	4,84	Insignificant
Air pressure	0,56250	1	0,56250	0,24960	4,84	Insignificant
Vc	10,56250	1	10,56250	4,68685	4,84	Insignificant
Residues	24,79008	11	2,25364			
Total	34,93750	15	2,32917			

Fig. 2.4 – Effect of variables factors on the total surface roughness.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	0,00006	3	0,00002	0,49190	3,59	Insignificant
Oil rate	0,00007	1	0,00007	1,65302	4,84	Insignificant
Air pressure	0,00006	1	0,00006	1,46427	4,84	Insignificant
Vc	0,00029	1	0,00029	6,61208	4,84	Significant
Residues	0,00048	11	0,00004			
Total	0,00087	15	0,00006			

Appendix 3

Fig. 3.1 - Effect of variables factors on the average value of drilling torque.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	1,62037	3	0,54012	4,37247	3,41	Significant
Oil rate	0,10726	1	0,10726	0,86827	4,67	Insignificant
Residues	1,60586	13	0,12353			
Total	1,05700	15	0,07047			

Fig. 3.2.- Effect of variables factors on the amplitude of the drilling torque.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	23,85422	3	7,95141	5,74444	3,41	Significant
Oil rate	0,15406	1	0,15406	0,11130	4,67	Insignificant
Residues	17,99446	13	1,38419			
Total	12,37062	15	0,82471			

Fig. 3.3 - Effect of variables factors on the average value of the thrust force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	43123,25000	3	14374,41667	4,98690	3,41	Significant
Oil rate	8010,25000	1	8010,25000	2,77899	4,67	Insignificant
Residues	37471,68321	13	2882,43717			
Total	38159,37500	15	2543,95833			

Fig. 3.4 - Effect of variables factors on the temperature.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	125,84750	3	41,94917	4,26168	3,41	Significant
Oil rate	89,30250	1	89,30250	9,07238	4,67	Significant
Residues	127,96332	13	9,84333			
Total	138,07875	15	9,20525			

Fig. 3.5 - Effect of variables factors on the surface roughness Rt.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	0,72794	3	0,24265	3,97433	3,41	Significant
Oil rate	0,16221	1	0,16221	2,65680	4,67	Insignificant
Residues	0,79370	13	0,06105			
Total	0,72200	15	0,04813			

Appendix 4

Fig. 4.1 - Effect of variables factors on the average value of the drilling torque.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	0,14445	3	0,04815	6,67250	3,41	Significant
Oil rate	0,00022	1	0,00022	0,03118	4,67	Insignificant
Residues	0,09381	13	0,00722			
Total	0,08650	15	0,00577			

Fig. 4.2 - Effect of variables factors on the amplitude of the drilling torque.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	0,24092	3	0,08031	5,25174	3,41	Significant
Oil rate	0,01891	1	0,01891	1,23640	4,67	Insignificant
Residues	0,19879	13	0,01529			
Total	0,16422	15	0,01095			

Fig. 4.3 - Effect of variables factors on the average value of the thrust force.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	27248,18750	3	9082,72917	6,47055	3,41	Significant
Oil rate	280,56250	1	280,56250	0,19987	4,67	Insignificant
Residues	18248,14526	13	1403,70348			
Total	14937,96875	15	995,86458			

Fig. 4.4 - Effect of variables factors on the temperature.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	69,31567	3	23,10523	7,05869	3,41	Significant
Oil rate	3,29422	1	3,29422	1,00639	4,67	Insignificant
Residues	42,55293	13	3,27330			
Total	39,40129	15	2,62675			

Fig. 4.5 - Effect of variables factors on the surface roughness Rt.

	Suma of squares	DoF	Variances	Fcal	Ftheoretic	Signification
Oil type	12,95468	3	4,31823	8,34952	3,41	Significant
Oil rate	0,05468	1	0,05468	0,10572	4,67	Insignificant
Residues	6,72338	13	0,51718			
Total	6,64701	15	0,44313			