metals Article

Determination of Energy Consumption during Turning of Hardened Stainless Steel Using Resultant Cutting Force 38

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Abstract: Downsizing energy consumption during the machining of metals is vital for sustainable manufacturing. As a prerequisite, energy consumption should be determined, through direct or indirect measurement. The manufacturing process of interest is the finish turning which has been explored to generate (near) net shapes, particularly for hardened steels. In this paper, we propose using measured cutting forces to calculate the electrical energy consumption during the finish turning process of metals where typically

the depth of cut is lower than the cutting tool nose radius . In this approach, the 24

resultant cutting force should be used for calculating the energy consumption, instead of only the main (tangential) cutting force as used in the conventional approach. A case study was carried out where a hardened stainless steel (AISI 420,

hardness of 47–48 HRC) was turned using a coated carbide tool 25

, with a nose radius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut. The experimental design varied the cutting speed (

100, 130, and 170 m/min) and feed (0 .10, 0 .125, and 0 .16 mm 42

) while other parameters were kept constant. The results indicate that the electrical energy consumption during the particular dry turning of hardened steel can be calculated using cutting force data as proposed. This generally means machining studies that measure cutting forces can also present energy consumption during the finish or hard turning of metals, without specifically measuring the power consumption of the machining process. For this particular dry turning of hardened stainless steel, cutting parameters optimization in terms of machining responses (i.e., low surface roughness, long tool life, low cutting force, and low energy consumption) was also determined to provide an insight on how energy consumption can be integrated with other machining responses towards sustainable machining process of metals. Keywords: turning; cutting force; energy consumption; stainless steel 1. Introduction With sustainable manufacturing in mind, a product's manufacture should minimize energy consumption and negative environmental impact [1]. From the sustainable man- ufacturing point of view, machining is a material removal process using machine tools, where it is wasteful in its use of both material and energy [2]. Yet, given that machining can produce shapes, sizes, and surface finishes with simplicity and accuracy, it is still the most widely used manufacturing process [1,3]. Researchers have introduced models to assess the environmental impact and energy consumption of machining.

Munoz et al. [4] developed modeling approaches specifically **to the environmental** issues **of machining** 50

processes. Later on, they presented a methodol- ogy for considering environmental factors in machining facilities which used

analytical process models embedded as the **attributes of systems resources to determine energy use and mass** flow **based on process time and volume of material removed** 16

. Choi et al. [5]

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developed the assessment methodology to measure the amount of the generated solid waste, the consumed energy, the incurred wastewater, and the noise level for machining processes. For energy consumption, the analytical models proposed in previous works differentiate the machine tool's energy consumption between constant and variable en- ergy consumptions. An empirical approach was presented by Kara and Li [6] in building models for machining processes in predicting their consumed energy for each unit pro- cess. They showed that the machining process's energy consumption could be predicted using the empirical models within the set cutting parameters for the selected machine tools. Their model can calculate the energy requirement for turning or milling processes to machine a product. An on-line approach proposed by Hu et al. [7] was developed

based on an energy consumption model of a **machine tool** 28

for energy efficiency monitoring. Another model was proposed by He et al. [8], seeing machining in a manufacturing system, by categorizing the machine tool's energy consumption based on the task. They found that the task flow's flexibility and variability influence the machining's energy consumption in a particular manufacturing system. These models were developed to reduce environmental impact and energy consumption when machining metals. Reducing energy consumption requires the capability of monitoring the machining process's energy consumption [9]. To better calculate the energy consumption, we need to incorporate the machining conditions into energy consumption. However, this is chal- lenging considering the complexity of manufacturing systems and a large amount of data. Previous studies on this include automated

monitoring and analysis of energy consumption in manufacturing systems 28

using event stream processing techniques [10]. Another work by Rajemi et al. [11] includes optimization of the energy footprint of a machined product in developing the energy consumption model. As a case study, they machined a part by turning and analyzed the total consumed energy of the process. Afterward, the minimum energy footprint was determined during the optimization of the total energy consumption concerning the machine tool's tool life. The turning process of hardened steels is gaining ground with empirical evidence that it can be done, to a certain extent, as a finishing process to get net shapes or near-net shapes of cylindrical or conical parts [12]. As a finishing process, hard turning is typically done at a low

depth of cut, lower than the nose radius of the cutting tool 41

. We identified that many works on hard turning reported the effect of machining parameters (e.g.,

cutting speed, depth of cut, and feed) to quantitative machining **responses** like cutting forces, **tool life, surface roughness, and** 39

cutting temperatures. There is only a limited number of studies that are addressing the electrical energy consumption as a machining response in turning of steels, even more for hard turning. Among the few are the works of Astakhov and Xiao [13] and Li and Kara [14] in the turning of steels. These works calculated the machining energy through the measured electrical power consumption and the machining time. These works also acknowledge that power consumption can also be obtained from the multiplication of the

main cutting force (i.e., tangential cutting **force) and the** cutting speed. **The** 26

only work related to hard turning is by Chudy et al. [15] which also indirectly measured the energy

as the product of the tangential **cutting force, the cutting speed** 51

, and cutting time. The simplification in calculating the machining power consumption through the use of the main cutting force only is derived from an established theory, with the assumption that the main force contributes the most to the resultant cutting force. However, we observed that the other force components other than the main cutting force are not negligible in finish hard turning. This is also true for the work on hard turning above [15], where the cutting force in the radial direction was higher than the main cutting force for some cutting parameters. Based on these observations, in this study, we propose the use of resultant cutting force to approximate the electrical energy consumption in the hard turning of steels. As a case study, hardened stainless steel was turned under varying cutting speed and feed conditions, using a carbide tool without cutting fluid. We calculated the energy consumption and

conditions, using a carbide tool without cutting fluid. We calculated the energy consump- tfiuornthaenrddfeutretrhmerindeedtetrhmeionpetdimthuemopmtiamcuhminimngacphairnaimngetpearrsarmegeitoernsbraesgeiodnobnatsheedmonacthheinminag- crehsinpoinngsersessppoencisfieesds,pwechificiehda,lwsohiinchclauldseo minaccluhdineinmgaecnheinrginyg. energy. 2. Cutting Forces and Energy Consumption Calculation in Finish Turning Process The information on cutting forces during various machining processes is essential for determining machinability. Some uses of measuring cutting forces during the machining process include machining economics analysis, adaptive control applications, andnnuummeerri-- ical modelingooffththee machining processA.Ass machining responsesc,uctutitntginfgorfcoersceasrearsetusdtuiedd- iiendvianrivoaursiomuascmhiancihnignipnrgocpersosceess.sMeso.dMeolsdoeflscoufttciungttifnogrcfeosrcaerse aforermfourlmatueldatteodcotorrceolrarteelbatee- betweetnhethmeamchaicnhininginpgarpaamraemteerstetros ctuotctiuntgtinfogrcfeosr.ceTsh.eTehmepemiripcairlimcaoldmeolsdaerles abraesebdasoendthone tehsteaebsltisahbelidshmedacmhiancihnigntinhgeotrhye.ory. There are three cutting force components of the cutting force (F) in a turning process, which are designated according totoththeedirection ofotfhtehecuctutitntigngtotoolo’sl’rselraetliavteivmeomvoevmeemnetntot tthoethweowrkoprikepciee(cFeig(Fuirgeu1re).1T)h.eThcuetctuintgtinfogrcfoerccoemcopmonpeonntesnatrseatraentgaenngteianltifaolrcfoer(cFec)(Finc)tihnetdhie- directionofotfhtehmemaianincuctutitntigngaction, rardadiailalforce (Fr)r)ininththeedirection toward tthhee axis of the workpiece, aanndd ffeeeedd ffoorrccee ((FFff)) in a parallel direction ttoo the workpiece aaxxiiss [[1166,,1177]].. Figure 1. Cutting force components in the turning process, where F is resultant cutting force, Fc Ftaingguernet1ia.lCfuotrtcien,gFfrorracdeicaolfmoprcoen,eanntds Finf fteheedtufornrcien.g process, where F is resultant

cutting force , Fc **tangential force** , Fr **radial force, and** Ff **feed force. During** the **turning** 23

process, power consumption can be an indicator of tool conditions and aDsuaridnegsitghne ctruirtenriinognporfotcheessm,pacohwinerincgoinnspuumt.pTtioondectaenrmbeinaenthinedpiocawtoerr coofntsouomlcpotniodni-, twiohnicshanisdcaaslcaudlaetseidgnacsrittheeriponroodfutchteomfathcheicnuinttginingpfuotr.cTeoadndetethrmeicnuetttihnegpsopweeerd,coonnsluymthpe- ttiaonng,ewnhtiiaclhcuisttcianlgcufolartceedisascothnesipdreordeducftoorfththeefocurmttienrg.Tfohricsesiamndpltihfiecactuiottninwgasspreoeodt,eodnilny the tuasnegoefnotirathlocugtotninaglcfuorttciengistchoenosriydienretdheforreltahteiofnosrhmiperb.eTtwhiesesnimmpalcifhiicnaitniognpwowaserroaontdedcuttitnhge ufosrecoe.f oltritshoagcoonmamlcounttipnrgactthieceortyhaintttahnegreenlattiaiolncsuhttipinbgeftowrceeenismuasechdintoinrgepproewseenrtatnhde cutting force.clotnissiadceorimngmiotnmparkaecstitcheetmhaatjotarnitgyeanmtioalncgutthtientghfroerecfeoirsceusceodmtpoorneepnrtesse[1n3t,t1h8e,1c9u].tting forceHcoonwseidveerr,inwgeitombsaekrvesedthtehamtafjoorrifityniashmtounrgnitnhge pthrroeceesfsoersceofcostmeeplos,nwenhtesr[e13th,1e8d,1e9p].th of cut isHlooww— evaetrt,imweesoebvseenrvloedwethrathtafonrtfhieninsohsteurrandiniugsporfothceescsuesttionfgstteoeolls—,wthheerraedtihael adnedptfheeodf cfourtceiss laorwen— oattnteigmliegsibelvee[n16l–o1w8]e.rTthheanfeethdefonrocseeisrainddiueesdotfhtehelocwuetstitnagmtoonogl—thtehtehrraede,iabluatnitds fveaelduefoisrcneostatrheantostmnaelgl.lilgnibsloem[1e6w–1o8r]k.Ts,htehefereaddfioarlcfeorisceinisdeevedenthheiglohweretshtaanmtohnegtathnegethnrteiael, bcuutttiintsgvfoalrucee fiosrnsootmtheactusttminagll.pIanrasmometeerws[o1r5k,s1,8]t.heHreandciea,linfotrhciesisstuedvey,nthheigchuetrtitnhganforthcee t(aFn)gwehnitciahl icsutthtiengrefsourlcteanfotrosfoamllethcuretteinfgorpcearcaommepteornse[n15ts,1i8s].uHseedn.celt, icnanthbisesctualdcyu,lathteedcubty- tEinqguaftoirocne((1F)), which is the resultant of all three force components is used. It can be calcu- lated by Equation (1), Pc = vc·F (1)

where Pc is the power consumption (W), **vc** is **the cutting speed** (m/min), **and** F is **the** 9

resultant cutting force (Newton). Studies on determining the machining process’s energy consumption commonly differentiate the electrical energy consumption in the idle, run-time, and production modes [10,11]. Idle mode is when the machine is ready for or in between machining. Although no material removal action is performed, there is still constant energy consump- tion in standby mode (for example, for the operation panel and fans). Run-time mode is when the auxiliaries are on (e.g., motor for the spindle and pump for the cutting fluid) but there is no material removal action. This consumes constant energy. Production mode is when the material removal action occurs. It varies and depends on the applied load towards the machine. Factors that affect energy consumption include cutting parameters, cutting tools, and workpiece material [16–20]. Studies found that compared to the total energy consump- tion, the energy consumption during production mode where material removal action occurs is small [21,22] Considering this, efforts to lower energy consumption are focused more on reducing the constant energy. Some approaches include specific components improvement or overall cycle time reduction [5,23]. We agree with the approach proposed in a previous study [6] that the total energy consumption (E) for the turning process is a summation of the energy consumption during setup (E1), when performing material removal (E2), for tool change (E3), to fabricate the cutting tool (with all its cutting edges) (E4) and in the manufacture of the

workpiece material (E5). Considering that **the workpiece material is** given **depending on the product** 3 and the machine shop has limited control over the energy contained in the particular workpiece material, this factor can be omitted during the machining process itself. From the above, for the turning process, the total energy

can be calculated as Equation (2), E = E1 + E2 + E3 + E4	3

(2) where E1 is the energy used during machine setup. It can be calculated as a product of the setup time and the corresponding power consumption, as shown in Equation (3), E1 = P0·t1 (3) where P0 is the power (W) in idle and run-time modes and t1 is the time (s) required for machine setup. E2 is the machining energy consumption. It is calculated by multiplying the actual machining time by the corresponding power consumption (Equation (4)) [21], E2 = P0 + k·v ·t2 . (4) where k is specific machining energy (

Ws/(mm3), v. is)material removal rate (mm3/s) and t2 is	3

the accumulated material removal time of the turning process (s). In this context, t2 can also be identified as tool life T. The value for specific machining energy k can refer to [24]. Considering Equation (1), the calculation for E2 can also be done by using Pc which is the power of the machine tool, and acknowledging that t2 is tc which is the actual cutting time, making Equation (5), E2 = (Po + Pc)·tc. (5) Thus, the Equation for machining energy consumption becomes Equation (6), E2 = (Po + F·vc)·t2. (6) E3 is the energy used during the replacement of a tool and is calculated as a product of the time required for tool changes and the associated power. In the turning process, tool replacement is conducted manually or using an automated tool changer, both of which occur when the tool is retracted away from the workpiece. Thus, it can be assumed that the energy used during the replacement of the tool is as much as the power when the machine is in a no-load position, which is Equation (7). E3 = P0 ·t3· t2 (7) (T) where t3 is the time for a replacement tool (s) and T is tool life (s), which is the same with t2 and hence making the notation in the bracket a unity. E4 can be calculated as the sum of energy consumed to fabricate each cutting edge (yE) on a cutting tool. Note that cutting tools in the form of indexable inserts usually have multiple cutting edges. So, this energy should be divided by the number of edges needed to perform the turning process (Equation (8)), E4 = yE · t2 (T (8)) where yE can be obtained from the total energy per insert (MJ) for material and manufac- turing process and that refer to [24]. Based on the description above, the Equation to calculate the energy consumed in a turning process can be written as Equation (9), E = P0·t1 + (Po + Fc·vc)·t2 + P0·t3+ yE (9) or as Equation (10), E = P0·t1 + P0 + k·v t2 + P0·t3 + yE. . (10) Based on both Equations (9) an(d (10), th)e total energy consumption is only dis- tinguished in the calculation of energy during the actual cutting process (E2), which is categorized as the variable factor. Other factors, i.e., E1, E3, and E4 are the same for both Equations (9) and (10) and are considered as constant factors in energy consumption calculation [6]. 3. Case Study 3.1. Experimental As a case study, a previous experiment [25] is referred to. Briefly, it is a

hard turning process **of stainless steel using** a **coated carbide tool**	29

in a two-axis CNC lathe machine rated at 5.5 kW with a varied cutting speed

of 100, 130, and 170 m/min , with a varied **feed of 0.1, 0.125, and 0.16 mm** , and with a **constant depth of cut** of **0.4 mm**	6

. In determining the lower and upper values of the cutting parameters, the recommendation by the cutting tool manufacturer for finish turning a

stainless steel workpiece with a hardness of up to 48 HRC	1

was considered (ASSAB Steel, Shah Alam, Malaysia). As the depth of cut was 0.4 mm, the

selected lower and upper limit values for cutting speed were **100 and 170 m/min, respectively** , and **for feed** were **0** .1 **and 0** .16 **mm, respectively. The** middle **values**	17

were 130 m/min for cutting speed and 0.125 mm for feed	1

.

The turning process was performed dry (without any **cutting fluid**). The workpiece material **was**	49

an

AISI 420 martensitic stainless steel, with a chemical composition of 0 .38% **C** , 13.6% **Cr, 0** .3% V, **0** .9% **Si, 0**	32

.5% Mn, and balance Fe (ASSAB Steel, Shah Alam, Malaysia). The stainless steel was expected to have corrosion resistance, stability at a hardened state, and to result in a fine surface finish for plastic mold applications. The stainless steel was hardened throughout by heat treatment to reach a hardness value of 47–48 HRC. Before the machining trial, the workpiece surface was finish turned using the last set of cutting parameters. The

cutting tool used for the experiment was a TiAlN coated **carbide** 9

tool (Kennametal, Shah Alam, Malaysia) that is designated as CNMG 120408. The

cutting tool was a fine-grained WC-6% Co substrate coated with 3.0 to 35 m **thick TiAlN** 31

through physical vapor deposition. The cutting

tool was mounted on a holder with an ISO designation of MCLNL 1616-H12, giving the 10◦ rake angle, −5 ◦ side cutting edge **angle, and 5** ◦ relief **angle. The** 1

positive rake angle—commonly

Metals 2021, 11, x FOR PEER REVIEW 6 of 14 coated with **3** 46

.0 to 35 m thick TiAlN through physical vapor deposition. The cutting6 otof1o4l

was mounted on a holder with an ISO designation of MCLNL 1616-H12, giving the 10° rake angle, −5 ° side cutting edge **angle, and 5** ° relief **angle. The** 1

positive rake angle— choamrdmtuornnlyinhgasredtstnuergnaintigvesertaskeneagnagtliev—ewraaksedaunegtloe—thweatosodluheastoa 1th5◦e cthoiopl bhraesakae1r5p°rocfihliep, bdreesapkiteer tphreotfoiloel, dheosldpeitreatchteuatolloyl phooslditeiornascttuhaellcyutptoinsgititoonosl athte-c5u◦ttainngglteo.oTlhaet t-o5o°lawngealer. wThaes tmooealswueraedr wacacsomrdeinasgutroedANacSclo/rAdiSnMgEtoBA94N.5S5IM/A-S1M98E5 Bst9a4n.d55aMrd-,1s9u8b5jesctatenddatordth,esumbjaexcitmedumto tflhaenkmwaxeiamruwmidtfhla(nVkBmwaxe)arwwithidinthth(eVnBmoasx)e wraidthiuins otfhtehenotosoelr(azdoinuesCo)f. Athne otpootilca(IzomniecrCos)c.oApne o(Sptteimcail 2m00ic-Cro,sCcoaprleZ(eSitsesm,Pie2ta0l0i-nCg, JCayaarl, MZeailsasy,sPiae)tawliinthg aJnayiam,aMgealaanyasilya)zewriwthasaunseimdafgoer athniaslypzuerrpowsaes. Suuserfdacfeorrothuigshpnuesrpso(Rsea.) Swuarsfamceearosuurgehdnbeyssa(Rsuar)fawcaespmroefialsoumreedtebry(Aacscurertfeacche pHraonfidloymsuertfe,rTo(AkyccoreSteeicmhitHsua,nTdoyksyuorf,,JaTpoakny)oatSe0i.8mmitsmu,cTuotkoyffol,eJnagptahna)nadt 40.m8mmmsamcuptlinofgf length iannedac4hmmmeassaumrepmlienngt.leTnhgethtoionl leifaechcrmiteeraiasuwreemreeantta. Tmhaextimooulmlifoefc0r.i1te4rmiamwoerfeflaantka mweaaxrimwuidmtho,fa0t.1th4emmmacohfifnlaendksuwrefaacrewrioduthg,hantetshseRmaabcehyionnedd s1u.6rfμamce, roorusgehvneeresslyRdaabmeyaognedd 1cu.6ttμinmg, toorosl.everely damaged cutting tool. The experiments measured the cutting force elements in all three directions (Fcc,, FFrr,, and FFff is the schematic layout below (Figure 2). A three-component turning dynamometer (Kistler, Type 9265B, Singapore) with data acquisition software was used for this purpose. For measuring the electrical power consumption of the turning process, three portable power monitors (Omron ZN-CTX21, Johor Bahru, Malaysia) with three clamp meters (Omron ZNCTM11, Johor Bahru, Malaysia) were used. One power monitor was used to measure the main power while the other two ttoo the spindle and axis drives. The measured ppoowweerr ddaattaa wwaass aaccqquuiirreedd aanndd vviissuuaalliizzeedd uussiinngg WWaavvee IInnssppiirree EESS ((OOmmrroonn,, JJoohhoorr BBaahhrruu,, MMaallaayyssiiaa)) ssooffttwwaarree.. Figure 2. Schematic layout of cutting force measurement setup. 33..22.. EExxppeerriimmeenntTaall DDeessiiggnn Response SSuurrffaacceeMethodology (R(RSSMM))wwasaschcohsoesnenfofrotrhtehdeedsiegsnigonf oefxpeexrpiemriemntesn.tAs. cAommercial sofstowftawrea(rDee(DsigesnigEnxpEexrpt,eSrtt,atSEtaatsEea,sMe,inMnienanpeoalipso,lMisN,M,UNS,AU)SwAa)swuassedusfoedrtfhoirs pthuirsppouserp.Fooser.thFeorRtShMe,RrSegMr,esrseigornesissiounseids tuoseadpptoroaxpimpraotexitmheatmeathcheimninacghriensipnognrseespboansesde obnastehdeorneltahteiorneslahtiiponbsehtwipebeentwoneeenoornmeoremfaocretofrasct(oinrpsu(itnpvaurtiavbalreia)balned)atnhde tehsetiemstaitmedatreed-responsey,eyst.esTt.hTehfeittfiinttgingofotfhtehemodel Equationwwaass using the least square technique through residual error minimization. The model Equation and its coefficients were tested for statistical significance. Analysiosfovfavriaarniacenc(eAN(AONVOAV)Aw)awsuasseudsfeodr fthoristphuisrppousrep.oFsoer. tFhoerctahseecaatsheaantdh,aantdh,reaet-hlerveee-llfeavcetolrfiaacltdoreisailgdnehsaigvninhgatvwinogintpwuot ifnacptuotrsfaacntdor2s caenndte2r cpeonintetrs wpoaisntaspwplaiesda,pmplaiekdin,gm1a1kirnugn1s1inrutnostailn(Ttoatballe(T1a).bTleh1e).tyTphee 1tyeprero1re(rαr)orva(αlu)evawluase sweatsatse0t.0a5t f0o.0r5thfoermthoedmelsodanelds iatnsdcoitesffcicoieefnfitcsietontbsetocobnescidoenrseiddesriegdnisfiigcnanifit.cant. Table 1. Factor and levels for the experiments. Factor −1 Coded Form 0

1 x1−cutting speed (m/min) x2−feed (mm 12

) 100 0.10 130 0.125 170 0.16 4. Results and Discussion 4.1. Surface Roughness and Tool Life The experimental results for surface roughness and tool life for all eleven trials are summarized in Table 2 [25]. Table 2. Experimental results for surface roughness and tool life. (Note: vc is cutting speed, f feed, Ra surface roughness, and T tool life). vc f Ra T (m/min) (mm) (μm) (min) 100 0.10 130 0.10 170 0.10 100 0.125 130 0.125 170 0.125 100 0.16 130 0.16 170 0.16 130 0.125 130 0.125 0.60 30.50 0.54 8.84 0.47 3.93 0.87 19.20 0.73

5.50 0.50 3.90 0.92 15.00 0.78 4.65 0.74 2.50 0.42 5.18 0.68 7.00 Based on the results of surface roughness and tool life, a selection of models using regression calculations were made [26]. The linear model was chosen for modeling the surface roughness while the quadratic model was most suitable for the tool life. The back- ward

elimination procedure was **selected to automatically reduce the terms that are not significant and the resulting ANOVA table for the reduced** linear **model for** 20

surface rough- ness and the reduced quadratic model for tool life is displayed in Table 3 [25].

The ANOVA table shows the statistics used to test the **hypotheses about the population means** . Table 3. Result **of** 35

ANOVA table for tool life and surface roughness.

Source Sum of Degrees of Mean Squares Freedom Square F Value p Value Surface roughness **Model** 40

x1 x2 Residual Cor Total 0.19 2 0.07 1 0.12 1 0.09 8 0.28 10 0.095 8.94 0.07 6.8 0.12 11.13 0.01 0.009 0.031 0.01 Tool Life Model x1 x2 x12 Residual Cor Total 5.73 4.92 0.53 0.57 0.13 5.86 3 1.91 1 4.92 1 0.53 1 0.57 7 0.018 10 104 <0.001 267.93 <0.001 28.99 0.001 31.27 0.008

In an analysis of variance, the total **variation in the response measurements** 5

, in this case, the surface roughness and tool life values, are partitioned into variation

which can be explained by the independent variables or factor effects (**Model) and the** variation **which is not explained by the independent variables** 14 **(Residual** which is also **called Error**). In **the** case **of** surface roughness, **the model** is made **up** of **the**

main effects of cutting speed , x1, **and feed** , x2. Thus, **the** Sum **of** 26

Squares for the independent variables, x1 and x2, add up to become the Sum of Squares for Model. Whilst the Sum

of Squares for Model and Residual add up to the Total Variance 7

.

Degrees of freedom are **associated with the sources of variance. The total variance has N-1 degrees of freedom** , where **N** is **the total** 22

number of experiments.

In this case, there were N = 11 experiments, **so the** degrees of freedom **for total is** 10. **The degrees of freedom** for **the** 7

model is the sum degrees of freedom of the independent variables or factor effects which explains the variation. In the case of independent variables or factor effects, the degrees of freedom for each independent variable or factor effect is the number of levels −1. Thus, for cutting speed, the degrees of freedom is 2 − 1 = 1 and this is similar to the

degrees of freedom for feed. **The degrees of freedom for the** model **is** 5

therefore 1 + 1 = 2. The

degrees of freedom residual **is the degrees of freedom** total **minus the degrees of freedom** model, which **is** 10 − 2 = 8. **The** respective Mean **squares** are computed **by** dividing **the** 5 respective

Sum of squares by their respective degrees of freedom. The respective **F**	19

ratios

are computed by dividing the respective **Mean squares by the Mean square**	19

residual or error and these are used

to test the significance of the predictors in the model. The p- **value**	8

associated with these F values are small, 0.031 or less.

The p value is compared to the **alpha level (typically 0.05) and, if** it is **smaller**	37

, then the independent variable or factor effects

is statistically significant. Therefore, the null hypothesis is rejected and the **alternative hypothesis is accepted**	36

thus indicating differences in the mean values of the respective independent variables or factor effects. The final equation, in terms of actual factors, acquired from the model for surface roughness is as in Equation (11), Ra = 0.4793 − 0.0031·vc + 4.6513·f (11)

where Ra is surface roughness (μm), vc is cutting speed (m/min), and **f is feed (mm/rev**). For tool life, **the**	30

logarithmic

transformation is recommended based on the best lambda value found at the minimum point of the Box–Cox **curve generated by the natural log of the sum of squares of the residuals** . The final equation, **in**	11

terms of actual factors, achieved from the model for tool life can be expressed as in Equation (12), Ln T = 13.4177 − 0.1297·vc − 9.8739·f + 0.0004·vc2 (12) where T is tool life (min) and the other variables were as defined previously. 4.2. Cutting Force The experimental results for cutting force and the respective calculated machining energy for all trials are summarized in Table 4. The machining time t2 is the tool life in second. F is the resultant cutting force calculated from the measured

tangential force Fc, radial force Fr, and feed force Ff	23

. The trend in cutting force values where the feed

force is the lowest **among the three force components** and where **the**	27

radial force is higher than the tangential force at some cutting parameters is in agreement with previous work on the hard turning of AISI 5140 (55 ± 1 HRC hardness) using CBN (cubic boron nitride) tool at 150–300

m/min cutting speed, 0.05 −0.2 **mm feed, and 0** .2 **mm depth of cut** [15]. Table **4**	34

. Experimental results for cutting force and machining energy. (Note: vc is cutting speed, f feed, t2 tool life (in second), Fc tangential force, Fr radial force, Ff feed force, F resultant cutting force, E2 calculated machining energy based on Equation (6), and E2# calculated machining energy based on Equation (4)). vc f t2 Fr Fc Ff F E2 E2 # (m/min) (mm) (s) (N) (N) (N) (N) (kWs) (kWs) 100 0.10 130 0.10 170 0.10 100 0.125 130 0.125 170 0.125 100 0.16 130 0.16 170 0.16 130 0.125 130 0.125 1830 103 530.4 100 235.8 96 1152 128 330 125 234 123 900 127 279 118 150 114 310.8 120 420 124 80 39 75 38 73 35 110 44 115 42 100 41 124 45 120 43 118 41 106 40 113 43 136.12 417.11 130.65 152.07 125.58 85.82 174.41

336.80 174.97 127.03 163.74 110.48 183.11 276.59 173.70 106.93 169.12 73.80 165.03 111.13 173.19 112.84 428.93 162.81 95.46 337.93 127.05 117.95 337.93 137.33 97.13 119.77 161.18 The model selection and its subsequent reduction as well as the empirical Equation development for cutting force were performed in the same manner as those for surface roughness and tool life [25]. The resulting ANOVA is as shown in Table 5. Table 5. Result of ANOVA for cutting force F.

Source Sum of Square Degrees of Freedom Mean Square F Value p Value Model 13

x1 x2 x22 Residual Cor Total 3988.78 205.99 594.82 1154.27 69.29 4058.06 3 1 1 1 7 10 1329.59 205.99 594.82 1154.27 9.90 134.33 20.81 60.10 116.62 <0.001 0.003 <0.001 <0.001 The final Equation obtained from the model for cutting force can be expressed in terms of actual factors as in Equation (13), F = −299.88 − 0.17·vc + 6895.59·f − 23667.19·f 2 (13) where F is the resultant cutting force (N). The final model Equation for cutting force can be shown as a 3D contour graph (Figure 3). From Equation (13) and

Figure 3, it can be observed that the cutting force is 21

affected significantly first by the feed and second

by the cutting speed . Generally, the **feed is proportional to** the **cutting** 29

force while the cutting speed is inversely proportional to the cutting force. The proportionality relation between feed and cutting force is as expected since feed increase means the higher surface area of the workpiece to machine by the cutting tool [25]. The finding on cutting speed effect to cutting force was analyzed to be due to the higher cutting temperature at high cutting speed softened the workpiece and there was a

transition from low to high cutting speed indicated by the change in **chip type from continuous to segmented** 1

[25]. MMeettaallss22002211,,1111,,5x65FOR PEER REVIEW Figure 3. Response surface graph of 3D surface for F. 4.3. Energy Consumption The maximum energy for the turning process (E2) was calculated using cutting force data, as in Equation (6). The power consumption in idle and run-time modes P0 was measured to be 1925 W. The maximum energy for the turning process, E2, of 417.11 kWs was shown by the lowest of cutting speed and feed, while the minimum energy for the Fmigaucrhei3n3..iRnegsppornosceessusrf(a7c3e.8grkapWhsoo)ff f33oDDr scuurftaticnegffoorsrpFF.e.ed and feed rate is high (Figure 4). We calculated that E1, E3, and E4 were 3.85 kWs, 5.58 kWs, and 1325 kWs, respectively. 44C..33o..mEEnpneearrrggeyydCCtooonntshsuuemmtopptttaiioolnnmachining energy, the actual machining energy E2 is low (5–20% of totalTehneermgayx),iminuamgreenemergenytfworitthheatpurrenviniogupsrsotcuedsys ([E212),2w2]a.s calculated using cutting force data,TFahoserimncoaEmxqipumaarutiimsoonnen,(6ew)r.egyTahlfsoeorpcthoaelwctueulrrancteoindngsEup2mruopscitenisogsn(EEiqn2)uiwadtalieosnacan(l4dc)u,rluwantiet-dhtimuspseienmcgifoiccduemttsianPcgh0fiwonriancseg mdeaneteaars,guyrekdin3t.o5EbWqeus1a/t9mi2om5nW3(a6.n)T.dhTemhmeatapexroiiwamleurremmcoeonnvseaurlgmryaptfteoior$v$ṅthi(enintuimdrlnmein3a/gns)dpcraroulccneus-ltsai,tmeEde2,bmoyfo4md1eu7s.l1tPi1p0klywWinassg wmcuaestatssinhugorewsdpnetboeydb,tehfe1ee9ld2o5,waWensd.tTodfheecputmthtaionxfgimcsupute.meWdeenanefordgufyneedfodtr,hwtahthetihlteuetrhvneainlmugeinpsiramorceuem e wmaaschshinopiwnrgonceebnsysert(hg73ye.8lEok2wWceasslct)ufoolfartceudttuinsignsgpreeesdualtnadntfeceudtt,riwantgehiiflsoerhctihegehams(Fpiingrioumpreuosm4e).deWnineerc tmHhaaatcdhEit1nh,ienEgt3a,napgnreodnceEtisa4slw(c7eu3rt.et8in3k.g8W5foskr)Wcfeoswr,5ac.su5t8utiskneWgdssl,ipkaeeneddin1at3nh2de5cfkoeWendvse,rnraettiseopniesaclthiavip tcrhaeelscutuolltaaatlnemtdactuchhtatiitnniEgn1g,feoEnr3c,eerag,nytd,htehEe4caawclcteuuralealt3me.d8a5chmkinaWicnhsg,in5einn.5eg8rgekynWEers2g,iysanloEdw21w(352i–l52l0kb%Weos5f,7tr–oe7tsa0pl%eecntoeivrfgeytlhy),e. iCcnaoalmcguprelaaertmeeddentvotawltuhieethstoiantaptlhrmeisvaiscothuuidsnysint.ugdeyn[e2r1g,y2,2t]h.e actual machining energy E2 is low (5–20% of total energy), in agreement with a previous study [21,22]. For comparison, we also calculated E2 using Equation (4), with specific machining energy k 3.5 Ws/mm3 and material removal rate $\dot{v}$ (in mm3/s) calculated by multiplying

cutting speed, feed, and depth of cut . We found that **the** values **are** comparable with **the** 12

machining energy E2 calculated using resultant cutting force as proposed in this study. Had the tangential cutting force was used like in the conventional approach instead of resultant cutting force, the calculated machining energy E2 will be 57–70% of the calculated values in this study. FFiigguurree44..EEnneerrggyyffoorrttuurrnniinnggpprroocceessss((EE22))aattvvaarriioouussccuuttttiinnggssppeeeeddssaannddffeeeedd.. energy k 3.5 Ws/mm3 and material removal rate v (in mm3/s) calculated by multiplying For comparison, we also calculated E2 using. Equation (4), with specific machining

cutting speed, feed, and depth of cut . We found that **the** values **are** comparable with **the** 12

machining energy E2 calculated using resultant cutting force as proposed in this study. Had the tangential cutting force was used like in the conventional approach instead of resultant cutting force, the calculated machining energy E2 will be 57–70% of the calculated vFaiglluurees 4in.Etnheirsgsytufodryt.urning process (E2) at various cutting speeds and feed. The quadratic model was chosen to represent the data of E2 because it has the least probabilistic value. ANOVA of the selected regression model and its coefficients was performed (Table 1

6). Table 6. ANOVA for machining energy consumption (E2).

Source Sum of Square Degrees of Freedom Mean Square F Value p Value Model 13

x1 x2 x1 2 x1 ·x2 Residual Cor Total 130,900.00 93,449.15 5854.92 35,360.36 3578.67 1994.99 132,900.00 4 32,715.34 1 93,449.15 1 5854.92 1 35,360.36 1 3578.67 6 332.50 10 98.39 281.05 17.61 106.35 10.76 <0.001 <0.001 0.006 <0.001 0.017 The final Equation obtained from the machining energy consumption can be expressed in terms of actual factors as in Equation (14), E2 = 2949.55 - 33.00·vc - 4851.99·f + 0.0954·vc2 + 28.26·vc·f (14) where E2 is machining energy consumption (kWs). Equation (14) shows that the lower machining energy (E2) can be obtained by choosing higher feed and cutting speed. This result is in agreement with the previous work on the hard turning of steel that also resulted in the highest machining energy was

at the lowest cutting speed and feed while the lowest machining energy was at the highest cutting speed 3

and feed [15]. In addition, for the turning of unhardened steel (AISI 1045), it was reported that lower feed and depth of cut increases the machining energy [14]. It should be noted that the results of machining energy calculation proposed for finish hard turning of steel in this study have not been tested extensively. Nevertheless, for this particular case study where an AISI 420 martensitic stainless steel (47–48 HRC hardness), turned using a TiAlN coated carbide mounted on a particular tool holder, with parameters set

at a constant depth of cut and cutting speed and feed 47

within their particular ranges, without cutting fluid, the results are encouraging. The machining energy can be calculated and an empirical model can be developed based on the results, within the cutting speed and feed range.

In addition to the cutting speed and feed themselves, the interaction between cutting speed and 21

feed was found to affect the machining energy. This indicates that when any of the machining conditions change, the trend showed by the modified model of machining energy might change as well. 4.4. Optimum Cutting Parameters for the Case Study Having all empirical models for surface roughness, tool life, cutting force, and machin- ing energy consumption; optimization can be performed to determine the suitable cutting parameters that result in preferred machining responses. Some things to consider related to machining responses are: • hard turning as a final operation must produce a smooth surface finish to meet customer demand for the geometric accuracy of machined components • the machine shop would prefer the cutting tools to last longer • cutting force should be low to minimize damage on the machined surface, and • energy consumption should be minimized for each workpiece volume removed. As mentioned above, some machining responses require contradicting cutting param- eter settings. Therefore, a compromise solution is necessary to select the cutting parameters. A relatively straightforward approach that is used to optimize several responses is to overlay or superimpose the contour plots for each response. This can be performed using the Graphical Optimization function of the statistical software. Based on this approach and using Equations (11)–(14), the overlay plot as shown in Figure 5 is obtained. The criteria

 performed using the 15

Graphical Optimization function of the statistical software. Based on this approach and using Equations (11)–(14), the overlay plot as shown in Figure 5 is
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design variables are chosen to maximize the overall | desirability D (Equation (17)) DD= ((dd 1	43

..dd22.d.3d.3........ddmm)1/⁄mm ((1177)) wwhheerreetthheerreeaarree mrreessppoonnsseess..TThheeoovveerraallllddeessiirraabbilitityywwiillllbbeezzeerrooiiffaannyyooffttthheeiinnddiivviidduuaall rreessppoonnsseessiissuunnddeessiirraabbllee.. The Numerical Optimization function of the statistical software can be utilized to solve the previous example using the desirability function approach. The optimization criteria for the responses are set to minimize E2, subject to Ra ≤ 0.65 μm, T ≥ 6 min, and F ≤ 163 N. Based on these criteria, the optimum

cutting speed is 132.42 m/min and feed is 0 .12 mm , at the desirability of	44

0.93. At this optimum cutting parameters, the surface roughness Ra is predicted to be 0.62 μm, tool life T is 6 min, resultant cutting force F is 163 N, and the machining energy E2 will be 121 kWs. 5. Conclusions This study proposes the use of the resultant cutting force (instead of the tangential cut- ting force in the conventional approach) for calculating the machining energy consumption in the finish turning process of hardened steels where typically

the depth of cut is lower than the cutting tool nose radius	24

. A case study was carried out where a hardened AISI 420 stainless steel (

47–48 HRC hardness) was turned using a coated carbide tool	25

, with a nose ra- dius of 0.8 mm, without cutting fluid, and at 0.4 mm depth of cut,

100, 130, and 170 m/min cutting speed, and 0 .10, 0.125, and 0.16 mm	6

feed. Machining responses in addition to the machining energy E2 were surface roughness Ra, tool life T, and resultant cutting force F. Empirical models of the machining responses were developed using response surface methodology. The following were obtained. 1. For the cutting forces, the tangential force was lower than the radial force at some cutting parameters

and the feed force is the lowest among the three force components	27

. This is typical for finish turning. 2. 3. 4. The cutting speed

is inversely proportional to the cutting force while the feed is proportional to the cutting	45

force. Machining energy is inversely proportional to the cutting speed and the feed. There was also an effect of the interaction between cutting speed and feed to the machining energy. Comparison with another machining energy calculation approach using specific ma- chining energy and material removal rate found the calculated machining energy using resultant cutting force proposed in this study to be similar. When the conven- tional approach was used where the tangential cutting force was used, the calculated machining energy will be much lower (57–70%) than the proposed approach's values. 5. Through optimization to minimize E2, subject to Ra ≤ 0.65 μm, T ≥ 6 min, and F ≤ 163 N, it was found that for the particular finish hard turning, the optimum

cutting parameters were cutting speed is 132.42 m/min and feed is 0 .12 mm	48

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[CrossRef] 7. Hu, S.; Liu, F.; He, Y.; Hu, T. An on-line approach for energy efficiency monitoring of machine tools. J. Clean. Prod. 2012, 27, 133–140. [CrossRef] 8. He, Y.; Liu, B.; Zhang, X.; Gao, H.; Liu, X. A modeling method of task-oriented energy consumption for machining manufacturing system. J. Clean. Prod. 2012, 23, 167–174. [CrossRef] 9. Sihag, N.; Sangwan, K.S. A systematic literature review on machine tool energy consumption. J. Clean. Prod. 2020, 275, 123125. [CrossRef] 10. Vijayaraghavan, A.; Dornfeld, D. Automated energy monitoring of machine tools. CIRP Ann. Manuf. Technol. 2010, 59, 21–24. [CrossRef] 11. Rajemi, M.F.; Mativenga, P.T.; Aramcharoen, A. Sustainable machining: Selection of optimum turning conditions based on minimum energy considerations. J. Clean. Prod. 2010, 18, 1059–1065. [CrossRef] 12. Bartarya, G.; Choudhury, S.K. State of the art in hard turning. Int. J. Mach. Tools Manuf. 2012, 53, 1–14. [CrossRef] 13. Astakhov, V.P.; Xiao, X. A methodology for practical cutting force evaluation based on the energy spent in the cutting system. Mach. Sci. Technol. 2008, 12, 325–347. [CrossRef] 14. Li, W.; Kara, S. An empirical model for predicting energy consumption of manufacturing processes: A case of turning process. Proc. Inst. Mech. Eng. Part. B J. Eng. Manuf. 2011, 225, 1636–1646. [CrossRef] 15. Chudy, R.; Grzesik, W.; Zak, K. Influence of machining conditions on the energy consumption and productivity in finish hard turning. In Advances in Manufacturing; Springer: Cham, Switzerland, 2018; pp. 697–705. 16. Elmunafi, M.H.S.; Noordin, M.Y.; Kurniawan, D. Effect of cutting speed and feed in turning hardened stainless steel using coated carbide cutting tool under minimum quantity lubrication using castor oil. Adv. Mech. Eng. 2015, 7, 1–7. [CrossRef] 17. Huang, Y.; Liang, S.Y. Cutting forces modeling considering the effect of tool thermal property—application to CBN hard turning. Int. J. Mach. Tool Manuf. 2003, 43, 307–315. [CrossRef] 18. Grzesik, W.; Denkena, B.; Żak, K.; Grove, T.; Bergmann, B. Energy consumption characterization in precision hard machining using CBN cutting tools. Int. J. Adv. Manuf. Technol. 2016, 85, 2839–2845. [CrossRef] 19. Zorev, N.N. (Ed.) Metal Cutting Mechanics; Pergamon Press: Oxford, UK, 1966. 20. Nur, R.; Noordin, M.Y.; Izman, S.; Kurniawan, D. Machining parameters effect in dry turning of AISI 316L stainless steel using coated carbide tools. Proc. Inst. Mech. Eng. E J. Process. Mech. Eng. 2017, 231, 676–683. [CrossRef] 21. Gutowski, T.; Dahmus, J.; Thiriez, A. Electrical energy requirements for manufacturing processes. In Proceedings of the 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 31 May–2 June 2006; Volume 31, pp. 623–638. 22. Li, W.; Zein, A.; Kara, S.; Herrmann, C. An investigation into fixed energy consumption of machine tools. In Glocalized Solutions for Sustainability in Manufacturing; Springer: Berlin, Germany, 2011; pp. 268–273. 23. Mori, M.; Fujishima, M.; Inamasu, Y.; Oda, Y. A study on energy efficiency improvement for machine tools. CIRP Ann. Manuf. Technol. 2011, 60, 145–148. [CrossRef] 24. Walsh, R.A. Handbook of Machining and Metalworking Calculations; McGraw-Hill Education: New York, NY, USA, 2001. 25. Noordin, M.Y.; Kurniawan, D.; Tang, Y.C.; Muniswaran, K. Feasibility of mild hard turning of stainless steel using coated carbide tool. Int. J. Adv. Manuf. Technol. 2012, 60, 853–863. [CrossRef] 26. Ambhore, N.; Kamble, D. Experimental investigation of tool wear and induced vibration in turning high hardness AISI52100 steel using cutting parameters and tool acceleration. Facta Univ. Mech. Eng. 2020, 18, 623–637. 27. Derringer, G.; Suich, R. Simultaneous optimization of several response variables. J. Qual. Technol. 1980, 12, 214–219. [CrossRef] 28. Montgomery, D.C. Design and Analysis of Experiments; John Wiley & Sons: Hoboken, NJ, USA, 2012.

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18 23 words / < 1% match - Crossref
Muralimohan Gurusamy, Siddharth Sriram. "Investigations on the choice of Johnson-Cook constitutive model parameters for the orthogonal cutting simulation of Inconel 718", Journal of Advanced Manufacturing Systems, 2022

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27 19 words / < 1% match - Crossref
Pham Minh Duc, Le Hieu Giang, Mai Duc Dai, Do Tien Sy. "An experimental study on the effect of tool geometry on tool wear and surface roughness in hard turning", Advances in Mechanical Engineering, 2020

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Bhushan, Rajesh Kumar. "Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites", Journal of Cleaner Production, 2013.

29	18 words / < 1% match - Internet Elmunafi, Mohamed Handawi Saad, Yusof, Noordin Mohd., Kurniawan, Denni. "Effect of cutting speed and feed in turning hardened stainless steel using coated carbide cutting tool under minimum quantity lubrication using castor oil", 'SAGE Publications', 2015
30	18 words / < 1% match - Internet from 27-Oct-2018 12:00AM link.springer.com
31	17 words / < 1% match - Crossref Denni Kurniawan, Noordin Mohd. Yusof, Safian Sharif. "Hard Machining of Stainless Steel Using Wiper Coated Carbide: Tool Life and Surface Integrity", Materials and Manufacturing Processes, 2010
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34	15 words / < 1% match - Crossref Ahmad Hamdan, Ahmed A. D. Sarhan, Mohd Hamdi. "An optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool for best surface finish", The International Journal of Advanced Manufacturing Technology, 2011
35	15 words / < 1% match - Internet from 11-May-2020 12:00AM fr.scribd.com
36	14 words / < 1% match - Internet from 02-Dec-2021 12:00AM ijream.org
37	14 words / < 1% match - Internet from 29-Apr-2022 12:00AM stats.oarc.ucla.edu
38	14 words / < 1% match - Internet from 15-Nov-2021 12:00AM www.mmscience.eu
39	13 words / < 1% match - Crossref Ingarao, Giuseppe, Paolo C. Priarone, Francesco Gagliardi, Rosa Di Lorenzo, and Luca Settineri. "Subtractive versus mass conserving metal shaping technologies: an environmental impact comparison", Journal of Cleaner Production, 2015.
40	13 words / < 1% match - Internet from 29-Jun-2020 12:00AM docplayer.net
41	12 words / < 1% match - Internet from 12-Jan-2020 12:00AM www.tandfonline.com
42	11 words / < 1% match - Crossref "Hard turning of stainless steel using wiper coated carbide tool", International Journal of Precision Technology, 2007
43	11 words / < 1% match - Publications Asian Journal on Quality, Volume 10, Issue 3
44	11 words / < 1% match - Crossref Guoyong Zhao, Chunhong Hou, Jianfang Qiao, Xiang Cheng. "Energy consumption characteristics evaluation method in turning", Advances in Mechanical Engineering, 2016
45	11 words / < 1% match - Crossref Xiang Wang, Qing-Feng Wang, Yun-Pei Liang, Okan Su, Lin Yang. "Dominant Cutting Parameters Affecting the Specific Energy of Selected Sandstones when Using Conical Picks and the Development of Empirical Prediction Models", Rock Mechanics and Rock Engineering, 2018
46	11 words / < 1% match - Crossref Yong Xu, Yongfeng Liang, Lin Song, Guojian Hao, Bin Tian, Rongfu Xu, Junpin Lin. "Experimental Phase Equilibria and Isopleth Section of 8Nb-TiAl Alloys", Metals, 2021
47	10 words / < 1% match - Crossref "Advances in Machining of Composite Materials", Springer Science and Business Media LLC, 2021
48	10 words / < 1% match - Crossref Chunhui Chung, Po-Chieh Wang, Benvolence Chinomona. "Optimization of turning parameters based on tool wear and machining cost for various parts", The International Journal of Advanced Manufacturing Technology, 2022

49 10 words / < 1% match - Crossref
Rusdi Nur, MY Noordin, S Izman, D Kurniawan. "Machining parameters effect in dry turning of AISI 316L stainless steel using coated carbide tools", Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2015

50 10 words / < 1% match - Internet from 12-Jul-2015 12:00AM
diva-portal.org

51 10 words / < 1% match - Internet from 08-Nov-2020 12:00AM
silo.pub