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Cutting Forces and Chip Shaping When Finish Turning of 17-4 PH Stainless Steel under Dry, Wet, and MQL Machining Conditions

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Abstract: This paper analyses three components of total cutting force and chip shape changes when finish turning 17-4 PH (precipitation hardening) stainless steel. A Finite Element Method (FEM) simulation of cutting forces was also performed using the Johnson–Cook constitutive model. The results were compared with those obtained from experimental studies. Variable feeds of 0.05–0.4 mm/rev and depth of cut of 0.2–1.2 mm with a cutting speed of 220 m/min were used. The studies were carried out under dry and wet cooling conditions and with the use of minimum quantity lubrication (MQL). This research was realized based on the Parameter Space Investigation (PSI) method. Statistical analysis of the obtained results was carried out using Statistica-13 software. It was found that the cutting force F_c and feed force F_f depend on the depth of cut and feed, and the passive force F_p depends mainly on the feed. Compared to dry cutting conditions, a reduction of 43% and 39% of the cutting force F_c was achieved for wet machining and MQL machining, respectively. Regardless of the cooling conditions, a favorable chip shape was registered for $a_p = 1\text{--}1.1$ mm and $f = 0.25\text{--}0.3$ mm/rev. Compared to the experimental studies, the FEM simulation showed differences of ~13% for the cutting force F_c and of ~36% for the feed force F_f .

Keywords: finish turning; stainless steel; cooling methods; cutting forces; FEM simulation; Johnson–Cook constitutive model; chip shaping

1. Introduction

17-4 PH (X5CrNiCuNb16-4) stainless steel is a relatively new material that has had increased use in industry [1,2] and that, due to its physical and mechanical properties, is considered to be difficult for cutting material. Good machinability is defined as the optimum combination of low cutting forces, high surface quality, low energy consumption, and good chip breaking [3].

Turning is a basic and important machining process and is widely used for production [4]. The determination of cutting forces is important for the design of cutting tools and devices [5]. During the turning process, long and tangled chips are formed because the rake face of the cutting tool is in constant contact with the work-piece surface. As a result, chips can become entangled around the cutting tool and cause difficulties in getting out of the machining zone [4,6].

Litak et al. [7] tested cutting forces while turning E-Z6NCT25 (X6NiCrTiMoVB25-15-2) stainless steel with a cutting depth of 1.0–2.3 mm, a constant spindle speed of 780 rpm, and a constant feed of 0.25 mm/rev. As the depth of cut increased, the cutting forces increased, and parametric and unstable vibrations were created. Servaraj et al. [8] analyzed the effect of cutting speed and feed on cutting forces. Two ASTM stainless steels, namely 5A (X2CrNiMoN25-7-4) and 4A (X2CrNiMoN22-5-3), were turned with cutting speeds of 80–120 m/min, feeds of 0.04–0.12 mm/rev, and a constant depth of cut of 0.5 mm under dry cutting conditions. The value of the feed had the greatest impact on the values of the cutting forces tested. Krolczyk et al. [9] examined the optimum turning conditions of 1.4462 (X2CrNiMoN22-5-3) stainless steel with three different cemented carbide tools, feeds of 0.2–0.3 mm/rev, cutting speed 100 m/min, and depth of cut 2 mm. The tests were carried out under dry conditions and with fluids based on mineral oils. Cutting forces were minimized when dry turning with lower feeds and higher cutting speeds. Uysal and Jawahir [10] studied the cutting forces and chip shaping when turning AISI 304 (X5CrNi18-10) stainless steel under dry machining conditions and using the minimum quantity lubrication (MQL) method with cutting speeds of 60–100 m/min. Compared to dry machining, lower cutting forces were observed with MQL conditions. A decrease in cutting forces was also observed with increasing cutting speed. The formation of serrated chips was clearly observed with the MQL conditions. Miyake et al. [11] tested chip breaking and cutting forces when machining AISI 304 (X5CrNi18-10) stainless steel under conventional and low frequency vibration cutting (LFV) conditions with feeds of 0.005–0.06 mm/rev, a constant spindle speed of 3752 rpm, and cutting depth of 0.5 mm. Regardless of the feed, the maximum cutting forces for LFV exceeded the cutting forces for conventional machining. The opposite was observed for the average values of the cutting forces. The cutting forces increased with increasing feed. Continuous chips and short chips occurred with traditional turning and LVF conditions, respectively. Fernandez-Abia et al. [12] studied cutting forces and chips geometry while turning AISI 303 (X8CrNiS18-9) steel in the range of cutting speeds 37–870 m/min, feed of 0.2 mm/rev, and depth of cut 1 mm, under dry machining conditions. Above a cutting speed of 450 m/min, a clear decrease in chip thickness has been noted and the cutting forces reach minimum values. Khanna et al. [13] analyzed changes of cutting forces and chip thickness ratio when turning 15-5 PH (X5CrNiCuNb15-5) stainless steel under dry, wet, MQL, and cryogenic conditions. Variable cutting speeds of 83–199 m/min, feeds of 0.111–0.333 mm/rev, and a constant depth of cut of 1 mm were used. Compared to cryogenic machining, an increase in the value of cutting forces of 29.26% for dry machining, 52.68% for wet machining, and 53.33% for MQL machining was noted at higher cutting speeds (199 m/min) and feed (0.333 mm/rev). Higher chip thickness ratios were observed under dry machining conditions compared to other methods.

Lekszycki et al. [6] analyzed chip shaping when turning 17-4 PH (X5CrNiCuNb16-4) stainless steel. The processing was carried out under conditions of dry, wet, MQL, and MQL + EP (extreme pressure) machining in the range of cutting speed 150–500 m/min, feeds 0.05–0.4 mm/rev, and constant depth of cut 0.5 mm. Short spiral chips under the machining conditions tested were observed at a cutting speed of 456 m/min and a feed rate of 0.27 mm/rev. Wagner et al. [14] studied the effect of high-pressure coolant on the chip fragmentation of martensitic stainless steel. Cutting speeds of 50–110 m/min, uncut chip thickness 0.2–0.6 mm, lubricant pressure 100–350 bars, and cutting depth 2–4 mm were analyzed. Regardless of the machining conditions, the pressure did not affect the chip type and shape, but only changed its rolling radius. Sivaiah and Chakradhar [15] studied the effect of cryogenic cooling on chip morphology while turning 17-4 PH (X5CrNiCuNb16-4) stainless steel and the results were compared to dry, wet, and MQL conditions. Cryogenic machining provides more favorable and lower chip thickness compared to other cooling methods.

Ning et al. [16] carried out experimental and modeling studies on cutting forces. Using iterative gradient search methods, they searched for stable parameters for the Johnson–Cook model that provided acceptable differences between predicted and experimental forces. The Johnson–Cook model used also took into account chip formation features, cooling conditions, and material properties. Close correlations between predicted and experimentally obtained forces were observed. Based on the

Johnson–Cook model, Ning et al. [17] analyzed cutting forces with respect to cutting temperatures. Cutting forces were predicted using the extended chip formation model. The experimental results were similar to those obtained in the simulation.

One of the methods of analyzing the process of stainless steel machining is the finite element method (FEM). Korkmaz and Günay [18] performed FEM simulations of the turning of AISI 420 martensitic stainless steel, based on three different levels of cutting speed, depth of cut, and feed. The difference between the values of experimental and simulated cutting force and feed force was on average 4.24% and 9.7%, respectively. Galanis and Manolakos [19] examined the FEM in predicting cutting forces when performing high speed turning of AISI 316L stainless steel. It was concluded that the values of cutting forces can be predicted by FEM software with high accuracy. Koyee et al. [20] presented a new methodology to inversely calculate the input parameters while simulating the machining of two different duplex stainless steels. After optimization of the friction coefficient, thermal contact conductance, etc., with special software, they were applied in a 3D-FEM simulation. It was shown that the optimization procedure allowed minimizing of the overall differences between the numerically obtained and experimentally measured cutting forces, tool nose temperature, and chip thickness at any specified cutting conditions.

In summary, there are many scientific studies that analyze cutting forces and chip shapes under different cooling conditions and cutting parameters when turning stainless steels. The interest of researchers indicates that this problem is very important and has not yet been fully described. However, there is only a small amount of research on the changes in the three components of total cutting force and chip shape when finish turning 17-4 PH stainless steel. In particular, there is no information that allows for comparing of the effect of dry, wet, and MQL machining conditions over a wide range of depths of cut and feeds using FEM modeling. The aim of the article was to study the changes of three components of total cutting force and chip shape when 17-4 PH stainless steel finish turning, depending on the depth of cut and feed under dry, wet, and MQL machining conditions.

2. Materials and Methods

The 17-4 PH (X5CrNiCuNb16-4) stainless steel was used as the material machined. This is precipitation hardening chromium-nickel stainless steel containing ~3% copper. As was stated by Liu et al. [21], it is strengthened by the precipitation of copper-rich particles from the metal matrix. According to DIN EN 10088-1:2014-12, the material has an elastic modulus of 195 GPa, a tensile strength of 930–1100 MPa, and a yield strength of 720 MPa.

A cutter with a CoroTurn SDJCR 2525M 11 (SandvikCoromant, Sandviken, Sweden) tool holder and a CoroTurn DCMX 11 T3 04-WM 1115 (SandvikCoromant, Sandviken, Sweden) insert was used. Variable feeds of 0.05–0.4 mm/rev and depths of cut of 0.2–1.2 mm with a constant cutting speed of 220 m/min were applied.

The research was carried out under dry, wet, and MQL cutting conditions, because there is a growing need for not only technical but also ecological processing nowadays [22]. CheHaron et al. [23] concluded that dry processing is popular in production to reduce costs. However, as Ortega et al. [24] and Egea et al. [25] noted, dry machining affects tool life significantly. In turn, Nouari and Ginting [26] found that dry processing provides economic and environmental benefits. When wet machining, Maruda et al. [27] determined that cutting fluid based on machining oils reduces the temperature occurring in the cutting zone.

In this research, a water emulsion based on the machining emulsifying oil, Castrol Alusol SL 51 XBB, with working concentration of 7% was used as a cutting fluid. In the MQL method, FUCHS ECOCUT MIKRO 20 E oil was used, which was mixed with air and prepared as an mist with the Lenox 1LN Micronizer (Lenox, East Longmeadow, MA, USA). Constant preparing parameters were used, namely air flow of 5.8 L/m, oil flow of 39.4 mL/h, constant pressure of 70 Parameter Space Investigation (PSI) (0.48 MPa), and distance between nozzle and work-piece contact point of 0.2 m. According to Maruda et al. [28], such conditions of oil mist formation ensure favorable conditions.

Krolczyk et al. [29] found that the MQL method plays an important role in the approach to sustainable and clean production.

Samples were machined using a CU502 universal lathe (ZMM, Sofia, Bulgaria). The measurements of the three components of total cutting force (cutting F_c , feed F_f , and passive F_p) were carried out using a 9129A piezoelectric dynamometer from Kistler (Kistler Group, Winterthur, Switzerland). Processing, visualization, and recording of signals were carried out using Dyno Ware software (Kistler Group, Winterthur, Switzerland).

The cutting force F_c and the feed force F_f were also calculated by Finite Element Method (FEM) for orthogonal turning of steel tested under wet cutting conditions. The computer simulation was performed using DEFORM 2D/3D software 12 (Scientific Forming Technologies Corporation, Columbus, OH, USA) developed by Taylan Altan, Goverdhan D. Lahoti, and Soo Ik Oh. The Johnson–Cook constitutive model was used, which was effectively used for modeling the cutting forces of turning process [30].

The design of experiments was developed on the basis of the PSI method [31]. The 7 test points made it possible to perform statistical calculations, which were carried out using Statistica-13 software. The PSI method has been described in detail in [6].

The conceptual scheme and methodology of research are presented in Figure 1.

Figure 1. The conceptual scheme and research methodology.

3. Results and Discussion

3.1. Statistical Models of Cutting Forces

The statistical models for calculating the components of the cutting forces, depending on the depth of cut and feed, are presented in Table 1.

Table 1. Statistical models for calculating the cutting forces F_c , F_f , and F_p when turning 17-4 PH stainless steel under dry, wet, and minimum quantity lubrication (MQL) cooling conditions.

Dry Terms
$F_c = -117.27 + 999.94f + 359.51a_p$
$F_f = 58.04 + 159.24f + 182.75a_p$
$F_p = 74.82 + 304.21f - 17.11a_p$
Wet Terms
$F_c = -100.45 + 690.46f + 313.27a_p$
$F_f = -35.88 + 103.19f + 192.73a_p$
$F_p = 30.06 + 189.93f + 14.82a_p$
MQL Terms
$F_c = -108.19 + 708.15f + 347.71a_p$
$F_f = -20.93 + 84.03f + 205.11a_p$
$F_p = 39.34 + 206.11f + 12.33a_p$

The dependences of cutting force F_c , feed force F_f , and passive force F_p on the depth of cut and feed in dry, wet, and MQL cooling conditions are shown in Figures 2–4.

Figure 2. Changes in the cutting force F_c depending on the depth of cut and feed under (a) dry; (b) wet; (c) MQL machining conditions.

Figure 3. Changes in the feed force F_f depending on the depth of cut and feed under (a) dry; (b) wet; (c) MQL machining conditions.

Figure 4. Changes in the passive force F_p depending on the depth of cut and feed under (a) dry; (b) wet; (c) MQL machining conditions.

When machining 17-4 PH stainless steel under the considered conditions, lower values of the cutting force were observed in the range of lower cutting depths and feeds. Smaller feed force values were obtained in the range of lower cutting depths and feeds. Smaller values of passive cutting force were obtained for smaller feeds in the studied range of depths of cut. Krolczyk et al. [9] noted that the passive force plays an important role in forming the dimensional and shape accuracy of the work-piece. On the basis of Figures 2–4, it can also be concluded that in comparison to dry machining, wet and MQL machining provide smaller values for the cutting, feed, and passive forces. The same conclusions were made by Uysal and Jawahir [10].

3.2. Percentage Changes of Cutting Forces

The average percentage changes of the cutting, feed, and passive forces obtained in 7 PSI test points under wet machining conditions and using the MQL method compared to dry cutting conditions, depending on the depth of cut and feed, are shown in Figures 5–7.

Figure 5. Percentage changes of the cutting force F_c under (a) wet and (b) MQL cooling conditions compared to dry machining.

Figure 6. Percentage changes of the feed force F_f under (a) wet and (b) MQL cooling conditions compared to dry machining.

Figure 7. Percentage changes of the passive force F_p under (a) wet and (b) MQL cooling conditions compared to dry machining.

Compared to dry machining, the cutting force decreases in the range of ~2–43% or increases by ~9% when wet turning; it decreases in the range of ~3–39% or increases by 1–13% while MQL turning. The increase in the cutting force is noted only in point 4 of the PSI matrix ($a_p = 1.1$ mm and $f = 0.27$ mm/rev). When wet cutting compared to dry cutting, the feed force decreases by ~61–73% or increases by ~12–52% and in the presence of MQL, it decreases by 55–72% or increases by 26–85%. In both cases, a significant reduction in the feed force rate occurs at points 1 ($a_p = 0.7$ mm and $f = 0.22$ mm/rev), 2 ($a_p = 0.45$ mm and $f = 0.31$ mm/rev), and 3 ($a_p = 0.95$ mm and $f = 0.14$ mm/rev). Compared to the conditions of dry machining, wet turning ensures a decrease in the value of the passive force in the range of cutting depths and feeds examined by 3–60%, while when MQL machining, it decreases by ~42–55% or increases to ~18%.

The build-up edge appears at the tool–chip contact area when turning stainless steels. Jemielniak [32] described that the build-up edge increases the rake angle and shortens the seizure zone and the total length of chip contact with the rake face, thus, reducing cutting forces. However, Ahmed et al. [33] revealed that the build-up edge can increase the nose radius of the cutting tool and cutting forces.

3.3. Chip Shaping

The chip shapes of 17-4 PH stainless steel obtained when finish turning in PSI test points, under dry, wet, and MQL conditions, are shown in Figure 8.

When turning with $a_p = 1.07$ mm and $f = 0.27$ mm/rev in the cutting conditions considered, loose curved chips were registered which are beneficial and, as Maruda et al. [27] indicated, allow easy removal from the machining zone. When turning with $a_p = 0.45$ mm and $f = 0.31$ mm/rev and $a_p = 0.35$ mm and $f = 0.36$ mm/rev, regardless of cooling conditions, open short and long spiral chips were registered. When turning with $a_p = 0.7$ mm and $f = 0.22$ mm/rev under dry cutting conditions, open short screw chips were observed; under wet and MQL conditions, short ribbon chips appeared. When turning with $a_p = 0.95$ mm and $f = 0.14$ mm/rev under dry cutting conditions, open short screw chips were noted, while under wet cooling conditions and using the MQL method, open tangled screw chips were observed, which are unfavorable and, according to Michailidis [34], may leave traces on the machined surface. When turning with $a_p = 0.57$ mm and $f = 0.09$ mm/rev and $a_p = 0.82$ mm and $f = 0.18$ mm/rev under dry cutting conditions, long ribbon chips were recorded; under wet cooling, tangled ribbon chips appeared; under MQL conditions, short ribbon chips were registered.

It should be mentioned that besides the depth of cut and feed, the cooling conditions also affect chip shapes when turning the steel tested. Clear differences are observed between dry machining, wet cooling, and the MQL method. More favorable chip shapes are observed under dry machining conditions.

Figure 8. Chip shapes when finish turning the steel tested.

3.4. FEM Modeling and Its Results

The material constitutive model used to simulate the machining process was the Johnson–Cook model, which can be determined using the equation for the equivalent stress:

$$\bar{\sigma}_{JC} = [A + B(\bar{\epsilon})^n] \cdot [1 + C \ln(\dot{\bar{\epsilon}}/\dot{\bar{\epsilon}}_0)] \cdot \left[1 - \left(\frac{T_w - T_0}{T_m - T_0} \right)^m \right] \quad (1)$$

where: $\bar{\sigma}_{JC}$ —Johnson–Cook plastic equivalent stress (MPa); A —Initial yield stress (MPa); B —Hardening modulus (MPa); C —Strain rate dependency coefficient (MPa); m —Thermal softening coefficient; n —Work-hardening exponent; T_w —Work-piece computed temperature ($^{\circ}\text{C}$); T_m —Melting temperature ($^{\circ}\text{C}$); T_0 —Reference temperature ($^{\circ}\text{C}$); $\bar{\epsilon}$ —Plastic strain; $\dot{\bar{\epsilon}}$ —Equivalent plastic strain rate (s^{-1}); $\dot{\bar{\epsilon}}_0$ —Reference plastic strain rate (s^{-1}).

The values of A , B , n , C , and m coefficients for the stainless steel 17-4 PH were taken from the literature [35] and are presented in Table 2. In order to determine the coefficient of friction μ , preliminary simulations in the range $\mu = 0.08$ – 1.0 were carried out. The results closest to the experimental ones were obtained for $\mu = 0.58$. The reference temperature and the reference plastic strain rate were accepted as 20°C and 0.001 s^{-1} , respectively.

Table 2. Johnson–Cook model coefficients for 17-4 PH stainless steel (data from [35]).

Material	A (MPa)	B (MPa)	<i>n</i>	C	<i>m</i>
17-4 PH	1279	630	0.64	0.02	0.56

The results of the simulation performed in DEFORM 2D/3D software 12 (Scientific Forming Technologies Corporation, Columbus, OH, USA) for PSI point No. 1 ($a_p = 0.7$ mm, $f = 0.22$ mm/rev) and $\mu = 0.58$ are shown in Figure 9.

Figure 9. Results of Finite Element Method (FEM) simulation for $a_p = 0.7$ mm, $f = 0.22$ mm/rev and $\mu = 0.58$.

The formulas for calculating the cutting force F_c and the feed force F_f depending on the depth of cut and feed under wet cooling, determined from the experimental studies and FEM modeling, are presented in Table 3.

Table 3. Formulas for calculating the cutting forces depending on the depth of cut and feed, under wet cooling conditions.

Statistical Models	FEM Simulation
$F_c = -100.45 + 690.46f + 313.27a_p$	$F_c = -100.15 + 692.44f + 304.84a_p$
$F_f = -35.88 + 103.19f + 192.73a_p$	$F_f = 19.83 - 80.15f + 133.57a_p$

Analyzing the mathematical models obtained for experimental research and the FEM simulation, it can be seen that the feed and depth of cut affect the value of the cutting force F_c with almost identical results. For the feed force F_f , the models are different.

The dependences of the cutting force F_c and the feed force F_f on the depth of cut and feed under wet cooling conditions, obtained for experimental research and the FEM simulation, are shown in Figures 10 and 11.

Figure 10. Changes in cutting force F_c according to the depth of cut and feed under wet conditions: (a) experimental research; (b) FEM simulation.

Figure 11. Changes in feed force F_f according to the depth of cut and feed under wet conditions: (a) experimental research; (b) FEM simulation.

Analyzing the graphs presented above, it can be concluded that the directions of change of the cutting force F_c for both the experimental research and the FEM simulation are identical. For the feed force F_f , the directions of change are different. Clear differences are observed as the depth of cut increases.

The percentage changes of the cutting force F_c and feed force F_f values obtained in the experimental research and FEM simulation are shown in Figures 12 and 13.

Figure 12. Percentage changes of the cutting force F_c between experimental research and FEM simulation obtained in 7 points according to the Parameter Space Investigation (PSI) method.

Figure 13. Percentage changes of the feed force F_f between experimental research and FEM simulation obtained in 7 points according to the PSI method.

For the cutting force F_c , the biggest difference of up to 13.2% between the experimental tests and the FEM simulation is observed at PSI point 2. At the other test points, changes do not exceed 2.4%. For the feed force F_f , significant differences of up to 35.6% can be observed. This is due to the effect of nose radius and radius of cutting edge rounding on the F_f force, which cannot be taken into account in the 2D FEM modeling.

4. Conclusions

In this paper, the changes of three components of total cutting force and chip shape when finish turning 17-4 PH stainless steel, depending on the depth of cut 0.2–1.2 mm and feed 0.05–0.4 mm/rev under dry, wet, and MQL methods, were analyzed. The FEM simulation of changes in cutting forces was carried out with the Johnson–Cook constitutive model. On the basis of the obtained results, it was determined that:

1. The cutting force F_c and feed force F_f depend on the depth of cut and the feed, while the passive force F_p is primarily determined by the feed value.
2. Regardless of the cooling conditions, lower cutting forces are reached for lower cutting depths and feeds. Therefore, in order to minimize the cutting forces, it is recommended to reduce the depth of cut and at the same time, use smaller feeds.
3. Compared to dry machining, wet cooling conditions resulted in a reduction in the cutting force of ~43%, feed force of ~73%, and passive force of ~60%, while with MQL conditions of ~39%, ~72%, and ~55% respectively.
4. When turning with $a_p = 1.0$ –1.1 mm and $f = 0.25$ –0.3 mm/rev under dry, wet, and MQL machining, favorable chip shapes, i.e., loose curves, were observed; it is recommended to use parameters in the ranges mentioned above. Unfavorable chip shapes, i.e., open screw, tangled, long ribbon, and long tangled, were registered in the ranges $a_p = 0.5$ –0.1 mm and $f = 0.05$ –0.2 mm/rev. Compared to wet MQL cooling conditions, more favorable chip shapes were recorded under dry processing.
5. Compared to the experimental research, the FEM simulation for the cutting force F_c showed almost identical mathematical models and minimal differences depending on the machining parameters at the PSI tested points, which reached to ~13%. For the feed force F_f , larger discrepancies were obtained, up to ~36%, due to the unaccounted effect of the nose radius and radius of cutting-edge rounding. It is concluded that the modeling of cutting forces of 17-4 PH stainless steel should be further developed and experimental research works are still desirable.
6. The main novelty of the work is the detailed analysis of the three components of the total cutting force and chip shape when finish turning new 17-4 PH stainless steel under different cooling conditions and a wide range of cutting parameters that allow their direct comparison. The results obtained can be successfully used in scientific modeling research as well as in industrial practice.

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