Surface Quality in Dry Machining of 55Cr3 Steel Bars

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Abstract

Lubricant and coolant can improve surface roughness in machining. In addition of ecological harms, thermal shock of coolant or lubricant may affect the surface integrity especially on surface residual stresses and micro-crack nucleation. Dry machining is ecologically desirable and it is considered as a necessity for manufacturing enterprises in the recent years. 55Cr3 steel grade is steel with high strength and very poor machinability. Therefore dry machining can provide good surface qualities in turning process of 55Cr3 steel bars. In this article, the effects of turning parameters (spindle speed, feed and depth of cut) on surface roughness variation will be investigated. The surface roughness was measured in straight turning and face turning processes. The Taguchi method was implemented for experiments designing and analyzing the measurements. The results showed that in order to obtain an optimum condition for dry turning of 55Cr3 steel bars, Ra, Rq, Rt, RSm and RSk should be analyzed simultaneously.

Keywords: Dry machining; Surface quality; 55Cr3 steel; Design of experiments.

1. Introduction

Dry machining is ecologically desirable and it is considered as a necessity for manufacturing enterprises in recent years. Industries are compelled to consider dry machining to enforce environmental protection laws for occupational safety and health regulations. The advantages of dry machining include: No pollution to the atmosphere (or water); no residue on the swarf which is reflected in reduced disposal and cleaning costs; no danger to health; and it is non-injurious to skin and is allergy free. Moreover, elimination of the use of cutting fluids in which it can be a significant incentive. The costs connected with the use of cutting fluids are estimated to be many more times than the labor and overhead costs. Hence the implementation of dry machining will reduce manufacturing costs. Also, at the interface between a cutting tool edge and a metallic work piece, the temperature can vary from 200 °C to over 1,300 °C. At such temperatures softer metals such as aluminum melt and the cut surface of the component can be damaged. However, with modern coatings and tool technology the expensive tooling is not badly affected by heat alone. It is thermal shock, or rapid temperature variations that weakens tools and this is far more likely to reduce tool life than simply exposing tools to high temperatures. In recent years some studies have been reported on dry machining. In 2017, Atlati et al. [1] proposed a predictive machining theory, based on a finite element model, for dry orthogonal cutting of aluminum alloy AA2024–T351. Also, they developed an Arbitrary Lagrangian Eulerian (ALE) model for analyzing the effects of chip formation process and

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local friction coefficient on the thermo-mechanical load along the tool rake face and the round cutting edge. Their results showed that a transition from a sliding contact to a sticking–sliding contact occurs when the local friction coefficient and the thermal softening are large enough. In 2017, Ramirez et al. [2] investigated the diffusion wear between a WC-10% Co tool and a Ti54M titanium alloy. Also the chemical composition in the reactive layers after different holding times at 1100 °C was analyzed using scanning electron microscopy (SEM) and electron probe microanalysis (EPMA). Their results showed that the diffusion couple revealed a rapid formation of TiC carbides at the interface and the layer growth was parabolic and was mainly toward the Ti54M side. In 2017, Furushima et al. [3] compared the wear response of tungsten carbide-iron aluminide (WC-FeAl) cutting tools with conventional cemented carbide (WC-Co) tools when of oxygen-free copper (Cu) round bars dry machined. In their study, using flank wear width as a metric, it was found through machining tests that WC-FeAl cutting tools exhibited longer lifetimes (30% longer) than WC-Co ones with the same cutting distance. Raykar [4] studied the surface topology in dry machining of EN-8 steels. The Ra, Rq and Rz surface roughness values were measured for the samples and a regression model has been developed for surface roughness of dry machining of EN-8 steel bars. In 2016, Chetan et al. [5] studied the tool wear characteristics of PVD TiN coated carbide inserts during turning of two aerospace alloys (Nimonic 90-Ni based alloy and Ti6Al4V- Ti based alloy) under dry and minimum quantity lubrication environment (MQL). It was concluded that due to high chip tool contact during machining of Nimonic 90, more intense nose wear was observed over the cutting inserts. Furthermore, due to the controlled wear during turning of Ti6Al4V, the cutting forces were found to be stable and significantly low as compared to Nimonic 90. In 2017, Bordin et al. [6] studied the effects of dry and cryogenic cooling strategies when turning an EBM Ti6Al4V. Their results showed that dry and cryogenic machining were intended as sustainable cooling strategies. Also, cryogenic machining gave better results and fulfilled potential applications in the biomedical field. Also, the surface roughness Ra was measured for dry and cryogenic machining. The results showed that the surface roughness was mainly influenced by the feed rate: the higher the feed rate was, the higher the roughness was, whereas, the increase in the cutting speed affects it to a less extent. Reduction of the Ra values happened when the cryogenic cooling was applied at the most severe cutting parameters, namely a cutting speed of 80 m/min and a feed rate of 0.2 mm/rev, whereas negligible differences result in the lowest feed rate. In similar study, Umbrello et al. [7] modeled the surface integrity in dry machining. Thakur and Gangopadhyay [8] studied the dry machining of nickel-based super alloy (Incoloy 825). The results showed that surface roughness obtained with TiN/TiAlN coated tool under dry condition had all along been minimum irrespective of machining condition. It can be attributed to the excellent anti-friction and wear resistance of TiN/TiAlN coated tool. Also, a gradual reduction in surface roughness in finish mode was observed and the surface roughness for roughing mode has always been higher compared to that in finish mode. In 2014, Ravankar et al. [9] investigated the machining of titanium alloy Ti–6Al–4V using poly crystalline diamond (PCD) tool under different coolant strategies in dry machining, MQL and flooded machining. Their results showed that the substantial benefit of the minimum quantity lubrication (MQL) and justified PCD inserts to be the most functionally satisfactory commercially available cutting tool material for machining titanium alloys for better surface finish and hardness. Sharma and Singh Sidhu [10] investigated the dry and near dry machining of AISI D2 steel. The results showed that an increase in the speed rate resulted in an increase in the surface roughness in most of the cases. But near dry machining has shown a great reduction in roughness as compared to dry machining. Particularly, feed rate has found a great influence on the surface integrity and the surface finish was found to be improved at the feed of 0.5mm/rev. In 2013, Haddag and Nouari et al. [11] studied tool wear in dry machining using a multi-step modelling strategy based on several numerical calculations. The first step was a 3D thermomechanical analysis of the chip formation process. The second step concerned the tool wear prediction using tool–chip interface parameters. The last step focused on a 3D thermal analysis of the heat diffusion into the cutting tool using adequate thermal loading. In 2012, Jahan et al. [12] proposed a novel technique of nanoscale electro-machining (EM) in atmospheric air, named dry nano-EM, by the use of scanning tunneling microscopy (STM) as the platform for nanomachining. The results showed that dry nano-EM was capable of fabricating consistent nano-features with good repeatability. In 2011, Devillez et al. [13] studied the effect of dry machining on the surface integrity. Wet and dry turning tests were performed at various spindle speeds, with semi-finishing conditions (0.5 mm depth of cut and 0.1 mm/rev feed rate) and using a coated carbide tool. In their work, it was demonstrated that dry machining with a coated carbide tool led to potentially acceptable surface quality with residual stresses and micro-hardness values in the machining affected zone of the same order than those obtained in wet conditions when using the optimized spindle speed value; in addition, no severe microstructure alteration was depicted.

Based on references [14] the machinability of 55Cr3 steel is very low and according to authors knowledge there is no report on dry machining of this steel. Therefore, in this article, the effect of turning process (spindle speed, feed and depth of cut) on surface roughness variation was investigated. The surface roughness was measured in straight turning and face turning. The Taguchi method was implemented for design of experiments and analyzing the measurements.

2. Materials and Methods

The dry machining tests were carried out using a numerically-controlled turning machine. The work materials were 55Cr3 steel round bars of 28 mm in diameter and 80 mm in length. Chemical composition of the work materials is listed in Table 1.

Table 1. Chemical composition (wt. %) of the 55Cr3 steel.

C	Cr	Mn	Si
0.57	0.8	0.85	0.3

A carbide cutting tool with a coating layer of TiAlN/TiN and chip breaker were attached to a tool holder and set in the turning machine. A pre-study for selecting the cutting tool had been implemented. Two tools with TiAlN/TiN coating and without coating were selected and turning operation was done on two samples. The surface quality showed that the tool with TiAlN/TiN coating was more suitable for machining. Hence, the experiments of current study was implemented by TiAlN/TiN coated tool. Rake and clearance angle of the cutting tool were –5° and 5° respectively. Fig. 1 shows the machining setup of dry machining in this work.

In this study, two series of turning experiments including straight turning and face turning processes were carried out. In both series of experiments, the effects of process parameters on the surface roughness were investigated. Spindle speed, depth of cut and feed with three levels were taken as controllable parameters and so, a L9 orthogonal array experiments were designed and conducted based on Taguchi design of experiments for straight and face turning. Preliminary experiments were conducted to limit the controllable turning parameters. In Table 2, turning parameters and their levels considered for both straight turning and face turning processes were presented. The literature study showed that the spindle speed and feed rate were the main important parameters of machining affecting the surface quality. The levels of parameters were selected among the available levels of turning machine so that level 2 increases 50% from level 1 and level 3 increases 100% from level 2. The levels

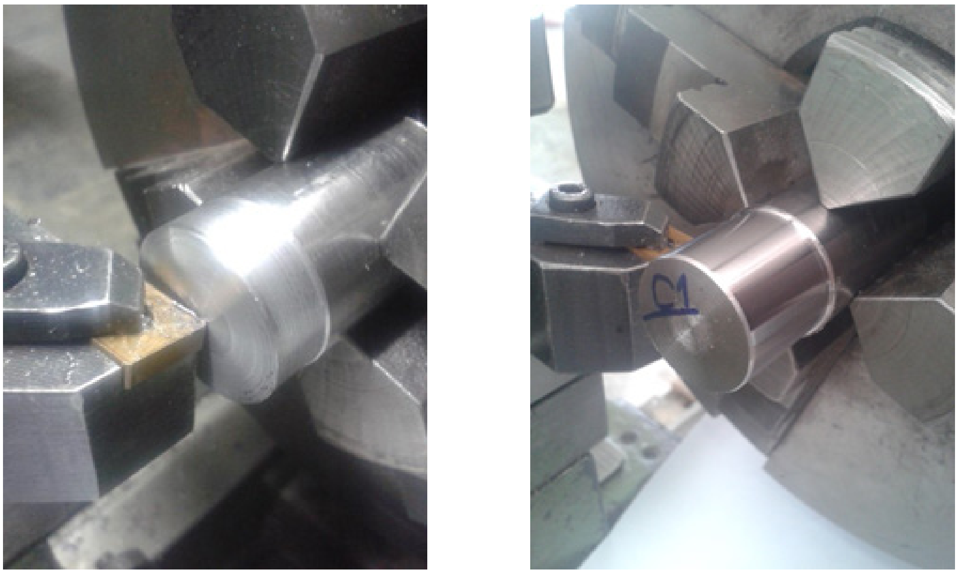

Fig. 1. Machining setup of dry machining.

Table 2. Process parameters and their corresponding levels for both straight and face turning processes.

Process parameters	Levels		
	1	2	3
Spindle speed (rev/min)	710	1000	2000
Feed Rate (mm/rev)	0.08	0.11	0.20
Depth of cut (mm)	0.3	0.5	1

vary in a wide range to find proper condition of machining. The levels of parameters should be selected in a way all of the experiments can be completed and have meaningful results.

3. Results and Discussion

In this section, firstly, the results of turning operation on 55Cr3 steel bars were presented, then the results of facing operation were investigated. At last, the chip morphology of produced chips in turning and facing operations were showed. Table 3 shows the results of surface roughness for designed experiments. After five times measurements, the average of data was calculated. Different surface roughness calculation methods could be used for identification of surface property. Among all the arithmetical mean roughness value, Ra, is the most used approach. The arithmetical mean roughness value, Ra, is hardly affected by individual peaks or valleys because it is the mean value of the whole profile. So, this approach cannot describe the whole profile of the surface. This way, two approaches, root mean square, Rq, and maximum height of profile, Rt, can be used. These surface roughness values can show the average and maximum of variation in the whole length of the measured profile. The periodic behavior of measured profile is important in turning operation. Therefore, two roughness values, RSm and Rsk, were measured by surface roughness tester. RSm showed the mean spacing between the periodic elements of measured profile. Rsk showed the skewness of the profile or lack of symmetry.

For selecting the proper condition of dry machining, the Signal to Noise S/N ratio should be calculated for above results. It is desired to decrease the surface roughness as much as possible so, “smaller value is better”. Equation 1shows the S/N ratio associated with the condition of “smaller is better” for each trial of the data.

$$S / N\, value = -10 \log_{10} (R^2) \qquad \text{Eq. (1)}$$

Figs. 2-4 show the S/N ratio for Ra, Rq and Rt surface roughness values respectively.

Fig. 2 shows that optimal machining condition for arithmetical mean roughness value, Ra, obtained at depth of cut of 1.0mm (A3), spindle speed of 710 rpm (B1) and feed rate of 0.08 mm/rev (C1). Fig. 3 shows that optimal machining condition for root mean square roughness value, Rq, obtained at depth of cut of 1.0 mm (A3), spindle speed of 2000 rpm (B3) and feed rate of 0.08 mm/rev (C1). Fig. 4 illustrates that optimal machining condition for maximum height between the peaks and valleys of profile, Rt, obtained at depth of cut of 0.3mm (A1), spindle speed of 2000 rpm (B3) and feed rate of 0.08 mm/rev (C1). These three roughness values were measured in full range of profile. Feed rate parameter was the common parameter. Comparing Ra and Rq optimal conditions showed higher spindle speed led to a decrease in the average height of both peaks and valleys. Depth of cut was similar in this situation. If the maximum difference between the peaks and valleys, Rt, was selected as choosing criterion, decreasing the depth of cut and increasing spindle speed would lead to a better surface roughness. As it can be seen, according to the attitude, different machining conditions can be chosen. It shows that just using the Ra value, as the decision criterion, was not true. Figs. 5 and 6 show the S/N ratio for RSm and RSk surface roughness values respectively.

Fig. 5 shows that optimal turning condition for average space between the intervals RSm roughness value obtained at depth of cut of 1.0mm (A3), spindle speed of 710 rpm (B1) and feed rate of 0.08 mm/rev (C1). Fig. 6 demonstrates that optimal turning condition for skewness and lack of symmetry RSk roughness value obtained at depth of cut of 1.0mm (A3), spindle speed of 1000 rpm (B2) and feed rate of 0.11 mm/rev (C2). The conditions to obtain optimal surface roughness values, Ra and RSm, were similar. But, the condition for smaller RSk roughness value differed with the other criteria. It was because of the nature of symmetry and the associated equation in which defined this value.

The results of the surface quality showed in Table 3 varied in a wide range. The value of the surface quality changed from 0.299 (C3 experiment) to 1.867 Ra (C6 experiment). Both of the experiments were done at 710 rpm spindle speed. The depth of cut decreased from 1 mm to 0.5 mm and the feed rate increased from 0.08 to

Table 3. Surface roughness obtained for turning of 55Cr3 steel bars.

Experiment #	Depth of Cut (mm)	Spindle Speed (rpm)	Feed Rate (mm/rev)	Ra	Rq	Rt	RSm	RSk
C1	1.0	2000	0.20	1.291	1.483	5.239	0.2500	0.0251
C2	1.0	1000	0.11	0.989	1.168	5.559	0.1250	0.0141
C3	1.0	710	0.08	0.299	0.373	1.880	0.0416	0.7490
C4	0.5	2000	0.11	0.575	0.662	2.640	0.1388	0.3350
C5	0.5	1000	0.08	0.625	0.804	5.239	0.1388	0.6200
C6	0.5	710	0.20	1.867	2.331	17.000	0.2083	2.5060
C7	0.3	2000	0.08	0.538	0.665	3.160	0.0520	0.7460
C8	0.3	1000	0.20	1.251	1.399	4.800	0.2500	0.1070
C9	0.3	710	0.11	0.670	0.790	4.079	0.1562	0.0060

0.20 mm/rev. Comparing these two experiments declared that for a better surface quality the feed rate should be decreased and depth of cut should be increased. But, the basics of machining science states inverse conditions for a better surface quality. This shows that the rules are not always true and there are always exceptions. The surface quality relates to the variation of cutting force due to the machining. The material fracture behavior (ductile or brittle) affects the chip formation and breakage of it. Temperature of shear zone in turning can change the value of machining force. So, the surface quality depends on different parameters and sophisticated phenomena in the machining and the researchers can only investigate the effect of process parameters to find a proper condition of machining. The optimum condition is not on offer due to the lack of mathematical models for machining operation.

Table 4 shows the results of surface roughness obtained in facing operation. The diameter of bars was equal to 28 mm. The spindle speed decreased by approaching the tool to the center of bar. Best surface roughness obtained at the outer diameter. Fig. 7 shows the surface roughness, Ra obtained in facing operation. Best condition for roughness value obtained at depth of cut of 1.0mm (A3), spindle speed of 2000 rpm (B3) and feed rate of 0.08 mm/rev (C1).

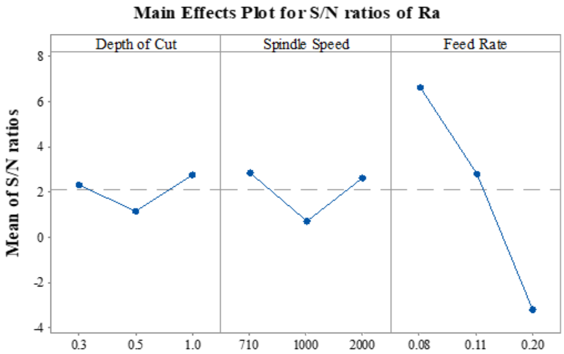

Fig. 2. Signal to Noise ratio for Ra.

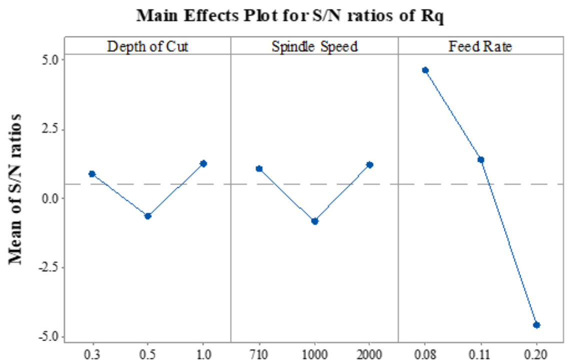

Fig. 3. Signal to Noise ratio for Rq.

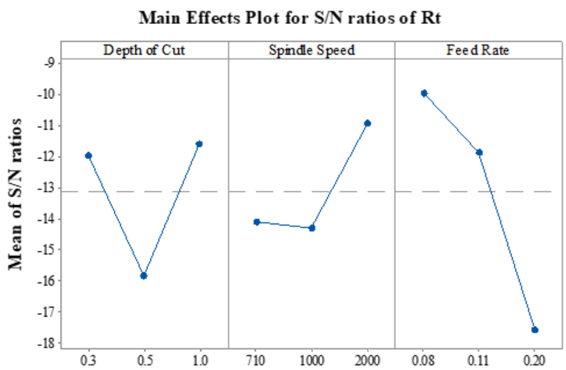

Fig. 4. Signal to Noise ratio for Rt.

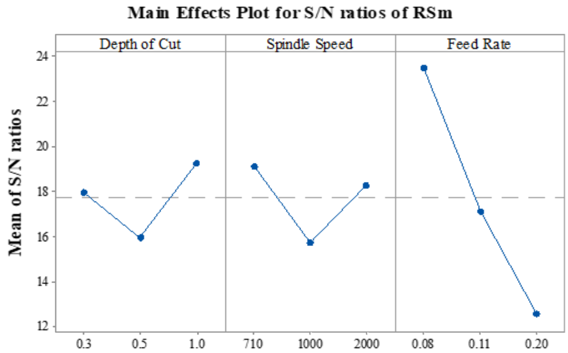

Fig. 5. Signal to Noise ratio for RSm.

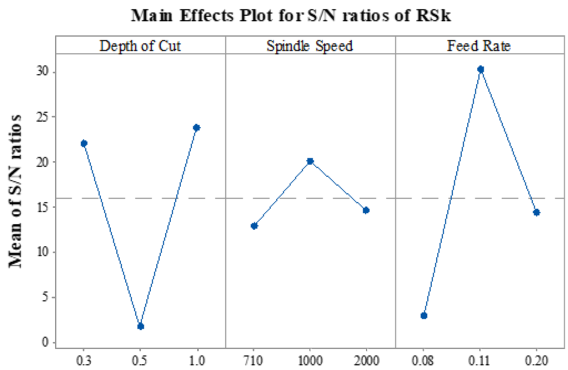

Fig. 6. Signal to Noise ratio for RSk.

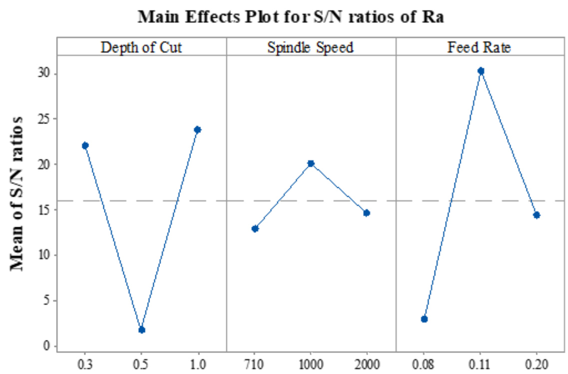

Fig. 7. Signal to Noise ratio for Ra in face turning.

Table 4. Surface roughness obtained for facing operation of 55Cr3 steel bars.

Experiment #	Depth of Cut	Spindle Speed	Feed Rate	Ra
K1	1.0	2000	0.20	1.2
K2	1.0	1000	0.1	11
K3	1.0	710	0.08	1.8
K4	0.5	2000	0.11	0.8
K5	0.5	1000	0.08	0.9
K6	0.5	710	0.20	6.4
K7	0.3	2000	0.08	1.4
K8	0.3	1000	0.20	1.8
K9	0.3	710	0.11	4.2

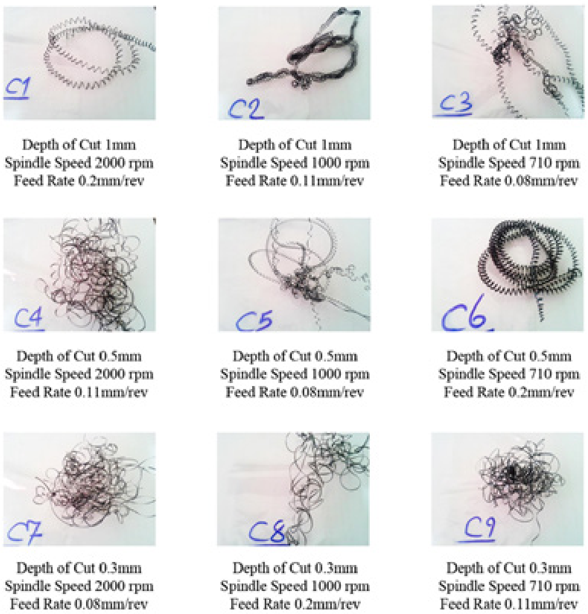

Fig. 8. Chip morphology obtained in turning operation of 55Cr3 steel bars.

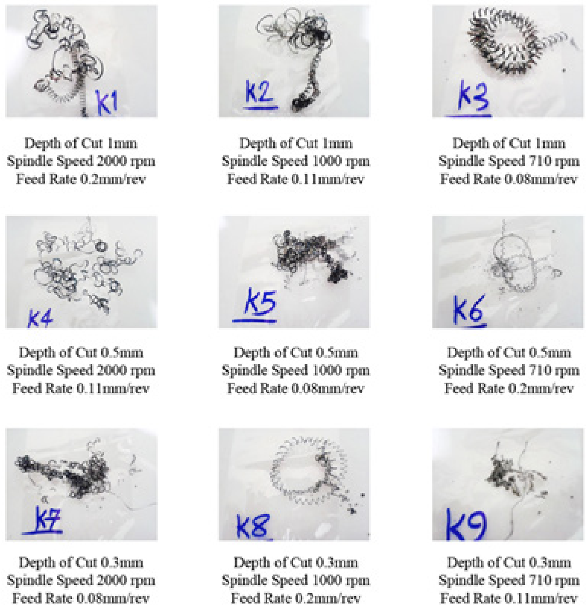

Fig. 9. Chip morphology obtained in facing operation of 55Cr3 steel bars.

3. 1. Chip Morphology

Figs. 8 and 9 show the chip morphology obtained in turning and facing operations of 55Cr3 steel bars in the implemented Taguchi tests. The shape of chip is important in machining. Four different types of chip morphologies are discontinuous, continuous, continuous with built up edge (BUE) and serrated (shear localized) chips. The continuous type of chip can reduce the surface roughness in turning due to its continuity. The forms of produced chips were continuous in all of the situations. The chips morphologies showed that the thickness of chip decreased by increasing the spindle speed but the thickness was always greater than the depth of cut. No evidence of BUE chip has been observed in the tests.

4. Conclusion

In this article, the effects of process parameters such as spindle speed, feed and depth of cut on surface roughness in dry turning of 55Cr3 steel bars were investigated experimentally. Two series of turning experiments including straight turning and face turning processes were carried out. The results indicated that for selecting the optimum condition of dry turning of 55Cr3 steel bars, analysis of the Ra value was not sufficient for making a decision and it was needed, the Rq and Rt were also included in decision making. Also, RSm and RSk values could help with the selection of optimum conditions of dry turning of 55Cr3 steel bars.

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