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RESEARCH ARTICLE-MECHANICAL ENGINEERING

An Analysis on Tool-Chip Interaction During Dry Machining of SS316 Using Textured Carbide Tools

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Abstract
This paper reports the research carried out to study the machinability of austenitic stainless steel SS316 using textured tungsten carbide cutting tool under dry environment. Experiments were planned with different combinations of cutting speed, feed rate and depth of cut to study the dynamics of tool-chip interactions i.e. chip morphology and tool wear. A detailed investigation was conducted where chip thickness ratio and shear angle corresponding to twenty-seven experiments were studied. It was found that at a medium cutting speed (120 m/min), plastically deformed metal chips adhered over the tool nose along with notch wear. However, at low cutting speed (70 m/min), sever damage of tool observed over cutting nose observed. Under higher magnifications on electron microscope, chip deformed with lamellar structure at different level of segmentations are notable based on shear angle. It is recommended to machine SS316 with textured tools at higher cutting speed and feed rate, and moderate depth of cut.

Keywords Stainless steel SS316 · Chip morphology · Tool wear

1 Introduction

Metal cutting or machining is an important segment of manufacturing industry where many basic and advanced machining processes are utilized to cut a wide range of engineering materials, shape and size different parts and components, and fabricate typical features using a wide range of processes such as turning, milling, drilling, boring, broaching, and grinding. In this modern era of technological advancements, to address the special machining and cutting requirements, there has been continuous research, development, and innovation in the metal cutting sector to facilitate big as well as small scale manufacturers. Engineering materials such as titanium and its alloys, superalloys, stainless steels, and shape memory alloys. are extensively used materials in various bio-medical, industrial, scientific, military, and domestic applications.

Austenitic Stainless Steel SS316 is one of the most important materials with high chromium and nickel contents, and possesses special properties such as high strength, corrosion resistance, and bio-compatibility. It is mostly used in appliances, storage devices and vessels, surgical equipment, scientific instrument, power plants and in pharmaceutical industries [1]. To manufacture products, parts and components to be used in the aforementioned applications, stainless steel undergoes extensive machining operations, such as turning, drilling, milling, and grinding. But, due to its high work-hardening, low thermal conductivity, and high toughness properties, it possesses poor machinability in terms of high probability of rapid tool wear, work surface quality deterioration, energy and resource consumption, and environmental footprints [2]. To overcome these limitations, significant efforts were made by researchers which include modified and coated tool-based machining, dry machining, machining using green lubricants and sustainable lubrication techniques, and heat assisted machining etc. [3, 4]. Material characteristics, parameters combinations, and process dynamics play major role to attain high productivity, long tool life and excellence in surface quality. Cutting speed, feed rate, and depth of cut are recognised as the most influential parameters in machining processes [5–7]. Therefore, the knowledge and information of the effects of these parameters on material properties and machinability are of major concern. The investigation of tool-chip interaction is of

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prominent significance to obtain the desired machinability. Moreover, by maintaining the appropriate machining conditions in terms of cooling and lubrication environment, engineering of cutting tool, and process parameters combination etc., a favourable tool-chip interaction can be obtained. Chip morphology, friction, tool wear mechanism, shear angle, and forces are some important machinability indicators that require a sincere investigation for machinability enhancement. A detailed literature review indicates on the use of coated, treated and textured tool-based machining of various materials for machinability enhancement [7–10]. Cutting tools coated with TiAlN outperformed uncoated tool and significantly reduced built-up edge formation and tool wear. The life of coated cutting tool was found two hundred percent higher than the uncoated tool. Thinner chips and better surface finish when machined with coated tools were also the findings of their investigation. Liu et al. studied significant reduction in tool wear during machining of alumina ceramic using textured carbide cutting tool [11]. Kurniawan et al. [12] successfully machined martensitic stainless steel using TiAlN-coated carbide tool having wiper geometry. In an interesting study, coated and uncoated carbide cutting tools were textured and filled with MoS_2 for machining of H-13 steel [13]. Cutting tools with various texture patterns and filled with solid lubricant MoS_2 significantly reduced cutting temperature, force, and coefficient of friction at tool-chip interface. Khan and Maity [14] investigated the performance of cryogenically treated carbide tools while machining titanium grade 2. Excellent results were obtained in machinability enhancement i.e. superior resistance to flank and crater wear, and reduction in chip compression ratio and coefficient of friction. Another research work identified dimple texture to be most effective on tungsten carbide tool to facilitate dry machining by improving the anti-adhesion of aluminium alloys [15]. Micro-dimples helped to brake-off the adhesions from the tool surface and consequently improved tool-chip tribology. A novel study on use of microwave treated tungsten carbide tool reveals significant enhancement of tribological properties (i.e. tool wear and surface roughness) of the tool during dry machining of AISI 1040 steel [16]. A significant reduction i.e. 30% in tool wear was observed. The performance of treated tool was found much improved at higher feed rate and depth of cut. Hao et al. [17] conducted an extensive study where titanium grade 5 was machined under dry and minimum quantity lubrication environment with textured and non-textured tools. They identified surface textures very effective for reduction of friction, cutting force, temperature, and tool wear during machining under any environment. Hybrid textures were found most effective. Spot and dimple texturing on high-speed steel cutting tool were done for turning of Ti–6Al–4V [18]. Spot-textured tool was found more effective towards improving machinability due to the greater assistance in heat dissipation from the machining zone through textures that subsequently reduced temperature and tool wear to a great extent. Segmented chips were observed while machining Ti–6Al–4V at high speed with spot-textured tool. However, performance of dimple-textured tool was found better comparted to non-textured tool. An important investigation to facilitate the orthogonal cutting of aluminium alloy was conducted where geometry (diameter, depth, pitch, and distance from cutting edge) of micro-textures of circular dimple form was varied at various levels [19]. Diameter was found the most significant parameter affected adhesion of work material to the tool and cutting force. A reduction of 61% in actual contact area of the tool with work surface was achieved after using textured tool that was effective to reduce friction, temperature, and tool wear further. A research work on textured tool-based turning of AISI 316 SS was conducted by Vasumathy et al. [20]. Textures were produced on tungsten-cobalt cemented carbide tools in two directions i.e. perpendicular and parallel to the chip flow direction. A significant reduction in contact area, cutting force by 5%, and built-up edge formation was obtained in case of machining with texture in the direction of parallel to chip flow.

Literature review concludes that textured carbide cutting tools have potential to be identified as viable alternate of plain tools for machining of various difficult-to-machine materials. It has also been observed that the research on textured tool-based machining of stainless steel needs further attempt. Therefore, the present study aims to fulfil the research gaps where machining of austenitic stainless steel (SS316) under dry machining conditions using textured tungsten carbide cutting inserts has been done. Cutting speed, feed rate, and depth of cut are considered as process parameters, and chip thickness, chip thickness ratio, and shear angle are investigated. Further, tool-chip interaction has been analysed and studied with a focus on chip morphology and tool wear.

2 Experimental Procedure

Cylindrical turning of austenitic stainless steel (SS316) has been done under dry environment using textured tungsten carbide cutting tools on manual lathe machine tool. The straight-line texture pattern using wire electro-discharge machining was made on the rake face of cutting tools. Hard brass wire (of diameter 0.25 mm) is used to mark texture on the tool. The cutting tools used for texturing is procured from the standard supplier of Sandvik Coromant with a designation TCMT 11 02 08-UM K20 Carbide inserts cutting tools. The texture parallel to the work axis is made at the nose of the tool insert for a dimension of 500micros to depth of 300 microns. After texture, the tool nose found clear in shape with any surface influences due to the dielectric medium used in the WEDM process. The cutting speed, feed rate and depth of cut were considered as input turning process parameters and varied at three levels each. A total of twenty-seven experiments have been conducted based on Taguchi design of experiments with L_{27} orthogonal array. Figure 1 depicts the experimental setup and work plan flow chart, whereas Table 1 presents the details of process parameters, tool geometry, and work material composition. Chip thickness has been measured by micrometre, and chip thickness ratio and shear angle are mathematically calculated using Eqs. 1 and 2, respectively [21, 22]. Scanning electron microscopy (Model: VEGA3 TESCAN) is used for chip morphology and tool wear study.

$$\text{Chip thickness ratio } (r) = \frac{t_0}{t_c} \quad (1)$$

where t_0 = Thickness before cut and t_c thickness after cut.

$$\text{Shear Angle } (\tan\phi) = \frac{r\cos\alpha}{1 - r\sin\alpha} \quad (2)$$

α-tool rake angle 6 degree

3 Results and Discussion

Table 2 presents the values of responses/machinability indicators chip thickness, chip thickness ratio, and shear angle corresponding to all twenty-seven experiments. In this section, an analysis of tool-chip interaction is presented in order to evaluate the machinability of SS316.

3.1 Chip Deformation

The photo images of the metal chips deformed at different process conditions are shown in Fig. 2. At lower cutting speed 70 m/min, 0.15 mm/rev, and 1 mm depth of cut, chips are linear due to low shear angle, when the feed rate and depth of cut increases the chips turn into a coil form. This is due to shearing and twining effect while material deformation. Subsequently, on increasing the cutting speed and feed rate, the effect of twinning was more profound as can be seen in Fig. 2. At maximum cutting speed (170 m/min) and feed rate (0.15 mm/rev), the metal chips deformation occurs in discontinuation with. A significant reason in the change of

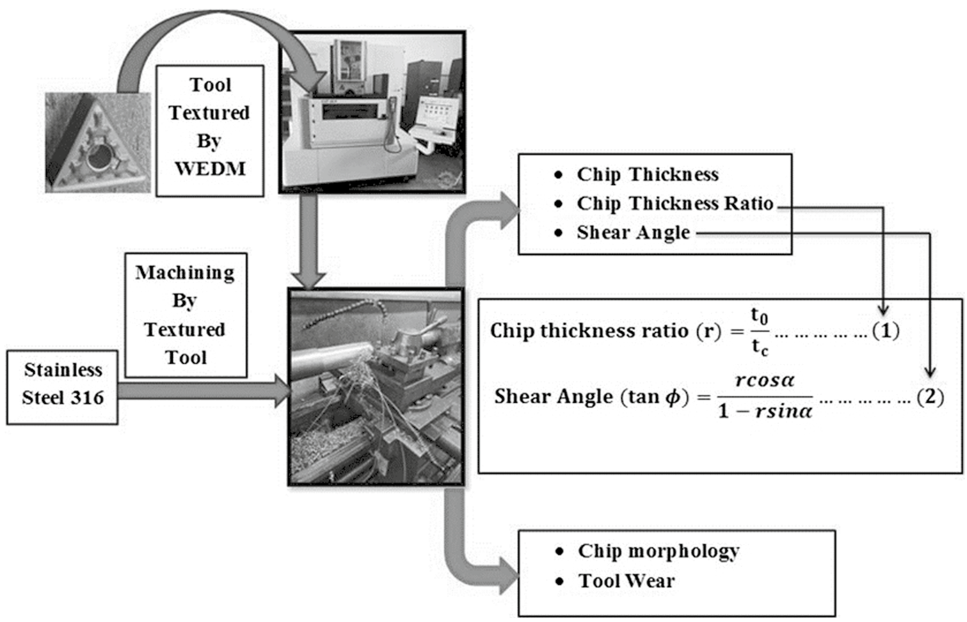

Fig. 1 Experimental plan and flow chart

Table 1 Details of process parameters, tool geometry and work material composition

Parameter (Unit)	Levels		
Cutting speed (m/min)	70	120	170
Feed rate (mm/rev)	0.5	0.15	0.2
Depth of cut (mm)	0.5	1	1.5
Tool geometry	(TNMG-160408-45) 6–6°–6°–6°–15°–75°–0.8 mm		
Composition of SS316 (% weight)	Cr-16–18%, Ni-10–14%, Mo- 2–3%, K-0.045%, S-0.030%, C-0.08%, N-0.10%, Mg- 2%, Si- 0.75%, Fe- balance		

Table 2 Experimental combinations of process parameters and corresponding values of responses

Run no	Cutting speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Chip thickness (mm)	Chip thickness ratio	Shear angle (°)
1	120	0.2	1	1.5	0.67	28.37
2	70	0.2	1	1.69	0.59	26.00
3	120	0.15	0.5	1.01	0.50	22.68
4	120	0.15	1	1.39	0.72	29.92
5	170	0.15	1.5	2.13	0.70	29.48
6	70	0.15	1	1.39	0.72	29.92
7	120	0.15	1.5	2.31	0.65	27.84
8	120	0.2	1.5	2.47	0.61	26.51
9	170	0.15	0.5	1.01	0.50	22.68
10	70	0.15	1.5	2.34	0.64	27.58
11	170	0.5	1	1.39	0.72	29.92
12	120	0.5	0.5	1.09	0.46	21.34
13	120	0.5	1.5	2.28	0.66	28.10
14	170	0.2	1	1.66	0.60	26.35
15	70	0.5	1	1.65	0.61	26.47
16	120	0.2	0.5	1.01	0.50	22.68
17	70	0.5	1.5	2.54	0.59	25.97
18	70	0.2	0.5	1.09	0.46	21.34
19	120	0.5	1	1.43	0.70	29.34
20	70	0.15	0.5	0.99	0.51	23.04
21	70	0.2	1.5	2.55	0.59	25.89
22	170	0.2	1.5	2.63	0.57	25.30
23	170	0.5	1.5	2.13	0.70	29.48
24	170	0.15	1	1.39	0.72	29.92
25	170	0.5	0.5	0.88	0.57	25.22
26	170	0.2	0.5	0.77	0.65	27.84
27	70	0.5	0.5	1.54	0.32	15.96

chip deformation is probably due to the effect of shear angle and chip thickness ratio. The subsequent section describes the effects of machining parameters on chip thickness ratio and tool wear, with a brief on shear angle.

3.2 Chip Thickness Analysis

While machining the austenitic stainless steel (SS316) with textured tungsten carbide cutting tool, the metal chips produced were collected for individual experiments for analysis. To find the cutting performance, plastically deformed metal chips were measured to find the chip thickness and morphology study. The variation of the measured chip thickness values with respect to input machining process parameters is illustrated in Fig. 3a–c. The minimum thickness of chip is measured as 0.77 mm for a machining processing condition; cutting speed of 70 m/min with a minimum feed rate of 0.2 mm/rev at 0.5 mm depth of cut. During plastic deformation, the feedrate has high impact towards the cutting tool feedrate. When the feed rate increases or depth of cut, the bulk material removed will be more. The thicknesses of the chips are in wide variations to a maximum of 2.63 mm at 170 m/min-0.2 mm/rev 1.5 mm depth of cut. The rate metal deformation has is also maximum due to the intensity of cutting load. When the depth of cut is increased the energy required for shearing of metal and cutting force simultaneously. It also depends on the work material and cutting tool properties in addition to the features discussed. The average thickness of chip is found 1.5 mm at 120 m/min, 0.2 mm/rev and 1 mm depth of cut for the proposed textured cutting tool. The chip thickness ratio for all the experiments is greater than a unit, indicating the deformed thickness is maximum than that of uncut thickness during machining process.

3.3 Shear Angle

The shear angle during machining at various experimental combinations calculated based on chip thickness ratio using Eq. 2. The shear angle represents primary slip line, converting the uncut thickness to plastically deform metal chips. In the proposed experimental design, the shear angle varied from 15°- 30° based on the input process conditions. At a

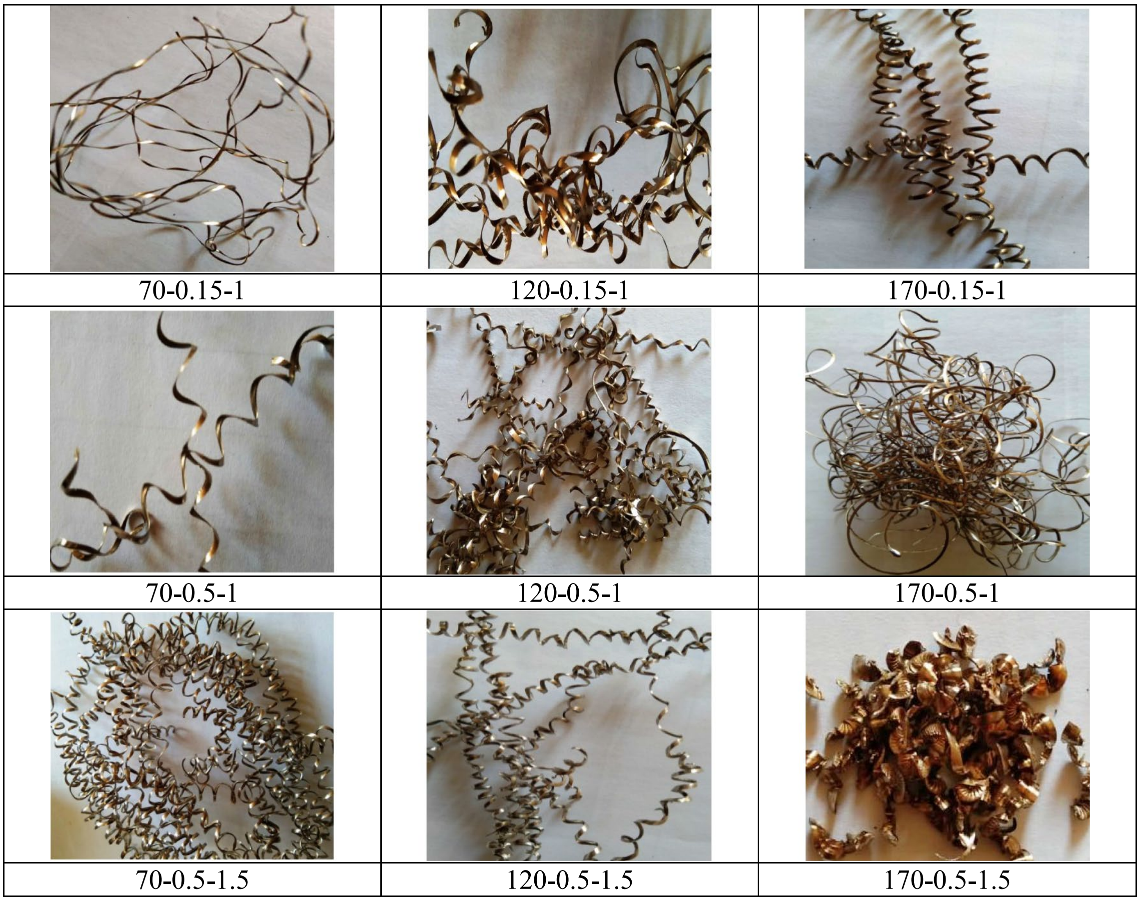

Fig. 2 Photo images of metal chips deformed at different cutting conditions

minimum cutting speed of 70 m/min, the uncut thickness of 0.5 mm was sliding to deform plastically to a thickness of 1.54 mm with a shear angle of 15°. This shear angle is variable with reference to the speed of work and cutting tool interactions. It is worth mentioning that when the shear angle is minimum, friction in the tool-chip interface will be more to cause severe damage over the cutting edge of the tool [22]. Minimum shear may also lead to high compression over chip deformation at primary shear zone. The micrographs, as given in Figs. 4 and 5, show the metal chips with a saw tooth deformed at cutting speed 70 m/min, feed rate 0.5 mm/rev and 0.5 mm depth of cut, respectively. Further, a set of metal chips with different feed rate (0.15, 0.2 and 0.5 mm/rev) at a speed 120 m/min and 1 mm depth of cut were also observed using electron microscope.

3.4 Chip Morphology

On machining the hard material, the cutting parameter especially feedrate and the depth of cut induces the material to fold during shearing. Based on the depth of material removed and the basic physical properties, the material behaviour occurs. In this case, the heat generated during machining has made the material to shear in the form of lamellar. The bulk metal deformed continuously with reference to the slip line has been observed and represented in Fig. 4a–c. In all the three conditions, deformations of the metal are revealing in a lamellar structure due to adiabatic shear. Over the edge of chip, the sharp crest was noted due to tear on compressive stress-induced during machining. The pitch of lamellar at minimum feed rate (0.15 mm/rev) and maximum feed rate (0.5 mm/rev) found similar in nature with maximum tears and cracks at the edge. It is due to the maximum shear angle of 29.92° causing high compression and twining effect while machining SS316 metal. Rapidly deformed metal chips at 0.5 mm/rev have severe shear and sliding of lamellar structure due to strain hardening of work during machining. While machining the material is induced to shear with respect to cutting edge and creating local strain on shear zone. As a result, the material has ductile—to—brittle transition and shear layer varies. However, at an average feed rate, shearing in laminar found very close with less strain.

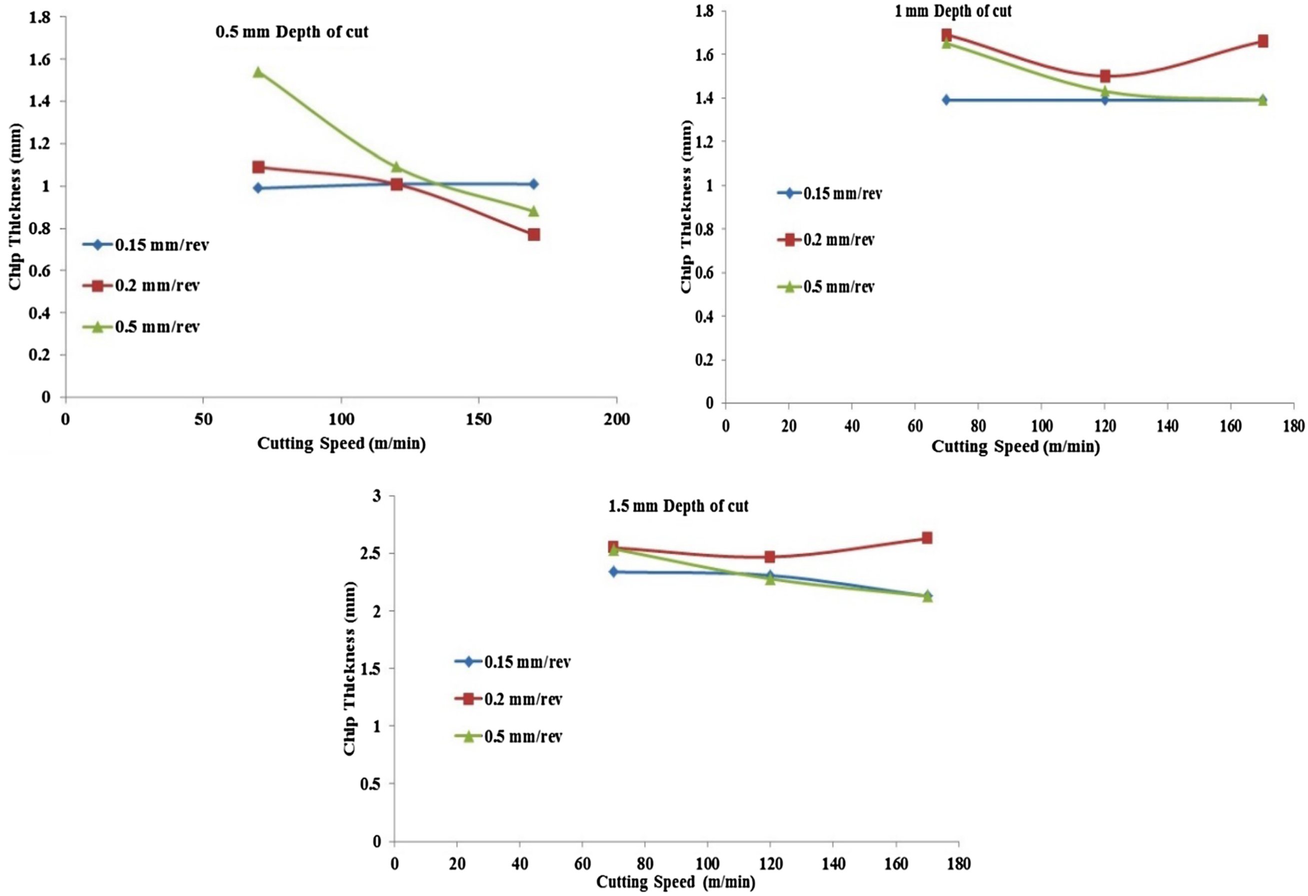

Fig. 3 Effects of process parameters on chip thickness ratio

Subsequently, the comparison of deformation occurred at varying speed (70, 120 and 170 m/min) and at 0.15 mm/rev-0.5 mm is given in Fig. 5. The sliding of deformed layers is just similar to feed rate conditions revealing lamellar structures. However, at higher cutting speed, very thin segmentations are revealed due to low strain at the surface. At these process conditions, the shear angle is very close to 22° (~average) and chip thickness was 1 mm. Thus the morphology of the chip at higher magnification revealed same for all the three speed values. It confirms that the effect of metal deformation is due to variation in tool interface rather than cutting speed.

3.5 Tool Wear

The performances of the cutting tools are evaluated based on the tool failure considering rough machining process. Figure 6a–c shows the flank wear measured for every combination of process conditions as per experimental design. The graph infers the tool wear in relation to the depth of cut at varying cutting speed and feed rate. At a minimum depth of cut, maximum tool wear was measured (V_{bmax} = 530.96 μm) with 50 m/min speed and 0.5 mm/rev feed rate. For the same depth of cut, minimum tool wear (V_{bmax} = 150.29 μm) was noticed at higher cutting speed of 170 m/min in the entire three (0.15, 0.2 and 0.5 mm/rev) tool feed conditions. The significant reason for minimum tool wear is the less machining time at high speed to have tool and work interactions, and subsequently the energy produced during machining at high speed will support to shear the bulk with less stress. It has been evidently proved that at these machining conditions, the shear angles are on average (22°) with an optimal chip thickness ratio. When the cutting speed was increased with different depth of cut and feed rate, tool wear was found slightly varying and maintaining the range of tool wear between 120 and 500 μm. In correlation to tool material and shear angle, the mechanism of tool wear varies. To analyze in detail the effect of wear, worn cutting edges are observed with electron microscope.

Worn-out tool edges at different cutting conditions are given in Fig. 7a–c. At a minimum feed rate of 0.5 mm/rev, 70 m/min cutting speed, and 1.5 mm depth of cut, highest tool wear has been observed (Fig. 7a). At this machining condition, tool edge was prone to rough cutting to cause

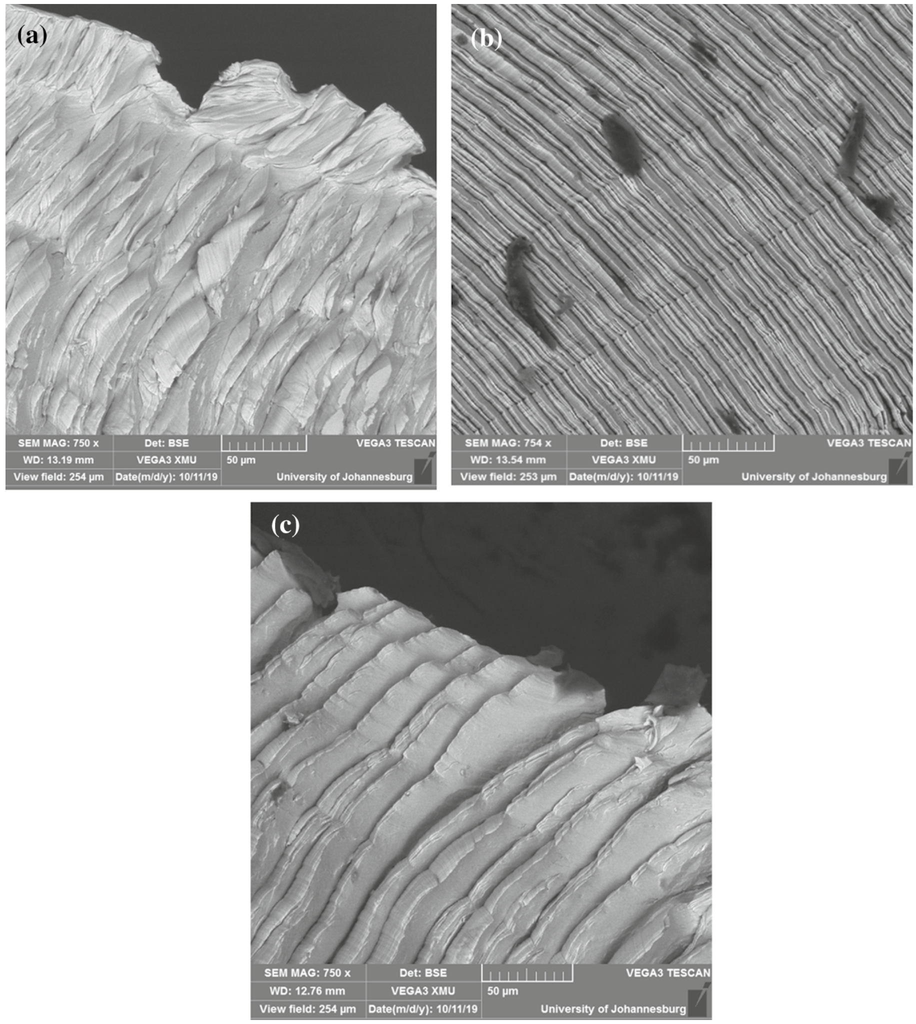

Fig. 4 Chip morphology at 0.15 mm/rev feed rate (**a**), 0.2 mm/rev feed rate and 0.5 mm/rev feed rate

severe damage in tool nose and flank face. The abrasive wear mechanism is noticed over the flank face in extending to cutting edge of texture. However, at 0.2 mm/rev and 0.5 mm/rev the sliding of bulk was less with a minimum abrasion adjunct to the tool texture (Fig. 7b, c, respectively). On Maximum feed rate machining, the effect of shear plan can be controlled and its intensity over the tool wear is also controlled.

From the analysis, it is clear that the tool wear is minimum and in acceptable range on cutting austenitic stainless steel SS316 at higher cutting speeds (120 and 170 m/min). SEM micrographs (Fig. 8a, b) represent the wear morphology appeared on the tool edge used to cut the metal at higher cutting speed. Maximum wear (V_{bmax}) is in the range of 120 ± 5 μm for both cutting speeds. At 120 m/min, the tool nose found with notch wears having abrasive tracks over the flank face along with adhesion over the tool texture as indicated in Fig. 8a. This abrasion may be due to the effect of sharp cutting edges produced over metal chips on plastic deformation. The deformed material will be with high strain hardened due to compression on shear. At the same in 170 m/min chips are in the form of serration due to sliding at average shear angle.

While machining, the plastic deformation of the material may cause surface defect during machining. In a straight line, while a tool edge slide over the bulk will cause the material to shear and induce the work to surface damage. It can be controlled or monitored by the input process parameters. It is worth mentioning that the analysis of surface roughness and material removal rate conducted in this study revealed lower surface roughness and higher material removal rate at high values of cutting speed [21]. Multi-performance optimization based on hybrid entropy and grey relational technique resulted in optimal combination of machining parameters i.e. 170 m/min cutting speed, 0.5 mm/rev feed rate and 1.5 mm depth of cut for the best values of machinability indicators i.e. 3.436 μm average roughness, 105,187 mm^3/min MRR, and tool wear 234.63 μm. It was followed by a comparative evaluation between textured and non-textured/plain tungsten carbide tool for machining SS316 under dry environment. It

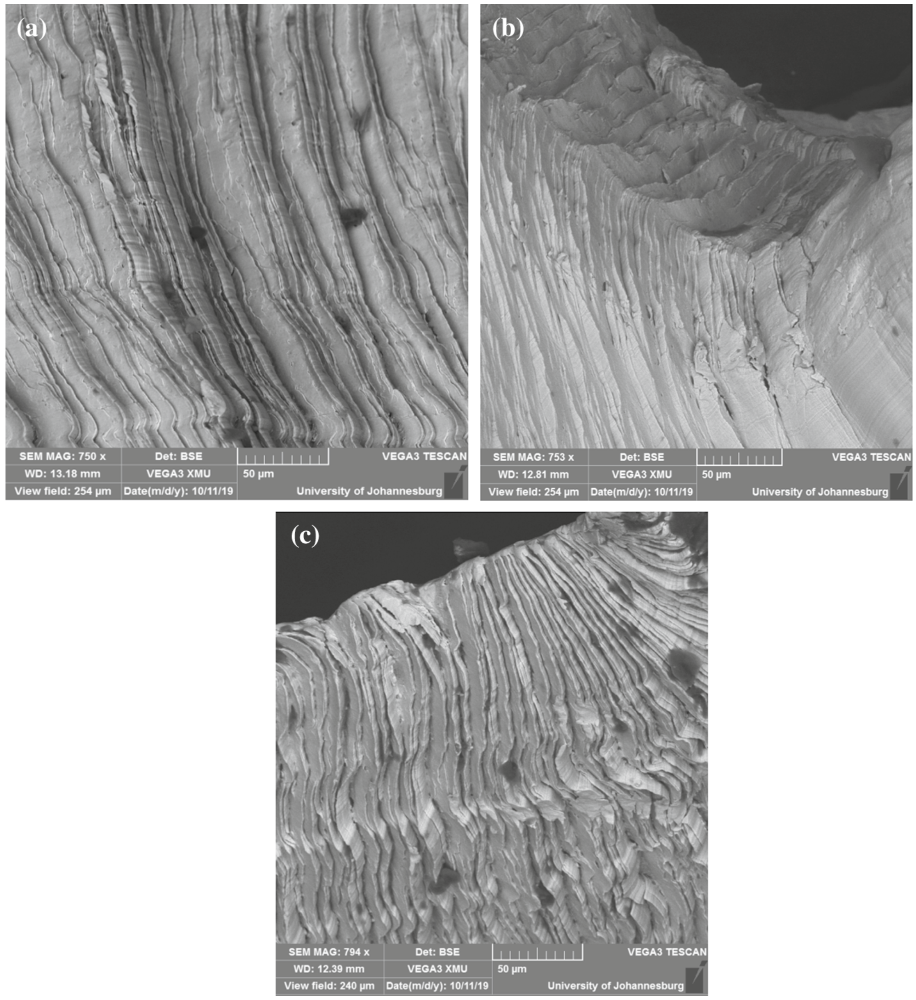

Fig. 5 Chip morphology at **a** 70 m/min, **b** 120 m/min, and **c** 170 m/min cutting speed

was found that textured tool outperformed with less severity of wear and longer tool life was obtained. Overall, improved machinability of SS 316 under dry machining environment at high speed can be obtained using textured tool.

4 Conclusions

In this paper, a detailed analysis of tool-chip interaction when machining SS316 under dry environment using tungsten carbide textured tool is reported. Following conclusions can be drawn from this study-

- The chip deformation at slow-speed machining produced in continuous with a regular sliding pitch and it was found discontinuous segmented chips at high cutting speed due to high friction and built-up edge on cutting nose.
- The thickness of deformed chip found maximum at high cutting speed (170 m/min) with a maximum depth of cut (1.5 mm) to produce an average chip thickness ratio to confirm the removal of material is maximum during machining process.
- On considering the slip line and shear angle, the minimum cutting speed of 70 m/min has produced minimum shear angle of 15° to deform the metal while machining. At minimum shear angle, saw tooth chips were produced due to high friction.
- From SEM analysis, the rapid shearing of the metal chip was found due to compression in minimum cutting speed and segmentation at higher speed. With increasing speed, the friction between chip tool interfaces was found maximum and causing adhesion over the textures while machining. Thus the chips deformed were discontinuous due to built-up edge on the cutting tool, and tool nose reveals occurrence of notch wear due to high friction.

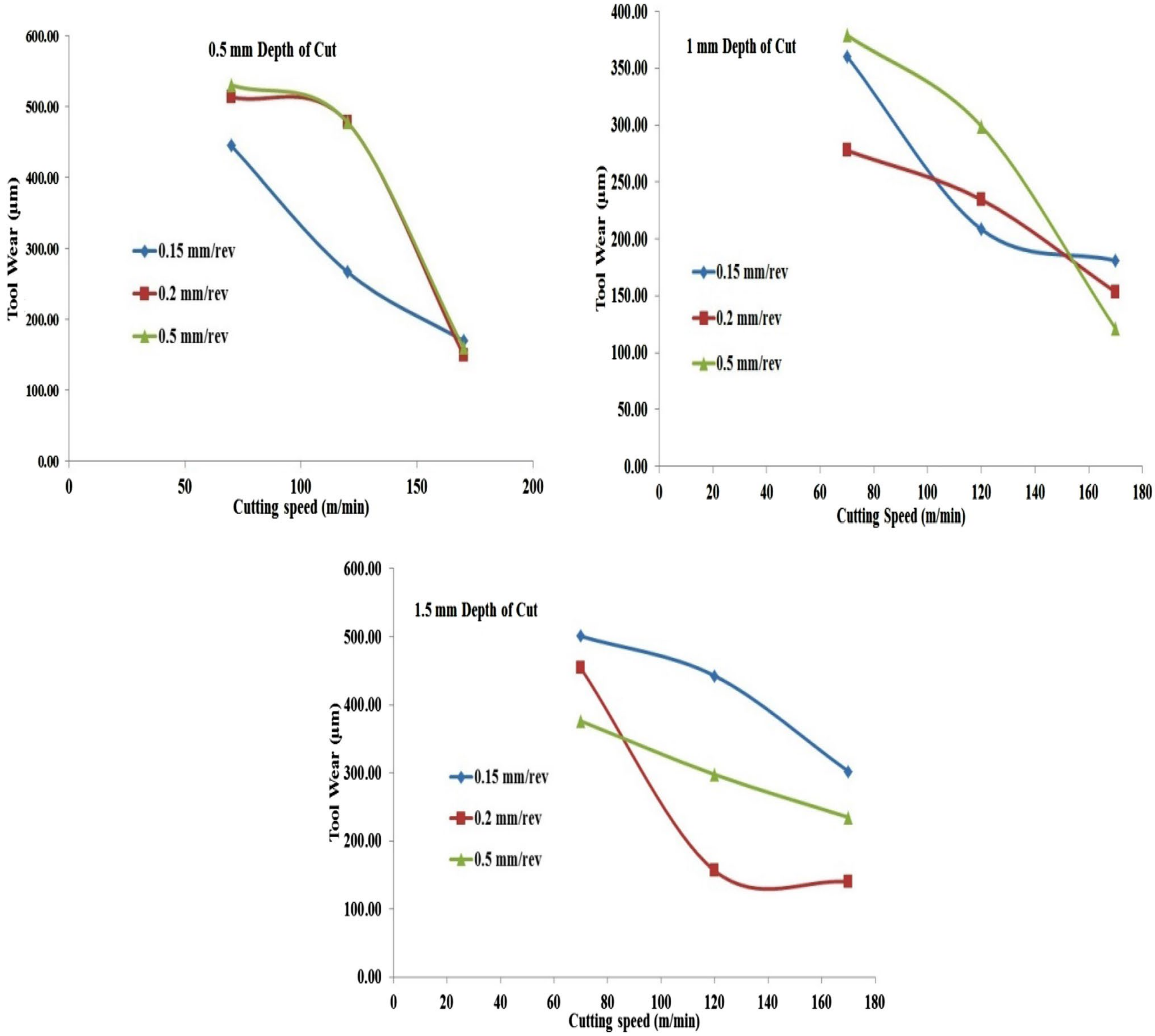

Fig. 6 Effects of process parameters on chip thickness ratio

- Finally, it is recommended to machine austenitic stainless steel at 0.2 mm/rev feed rate and 0.1 mm depth of cut on high-speed machining to attain longer tool life and improved machinability.

It is hoped that the results of the present work will facilitate materials engineer and machinists to go for tool texturing to obtain better machinability. It will also encourage researchers to conduct research to establish the field further.

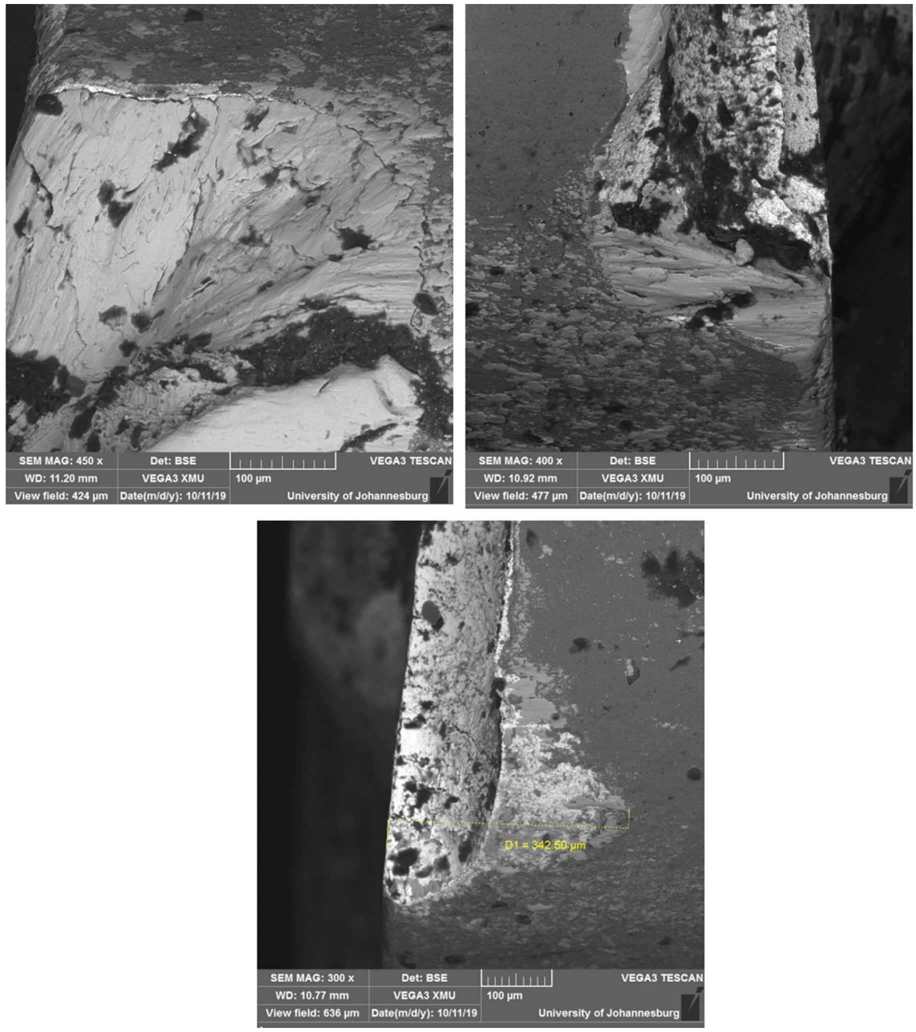

Fig. 7 Tool edges with wear morphology

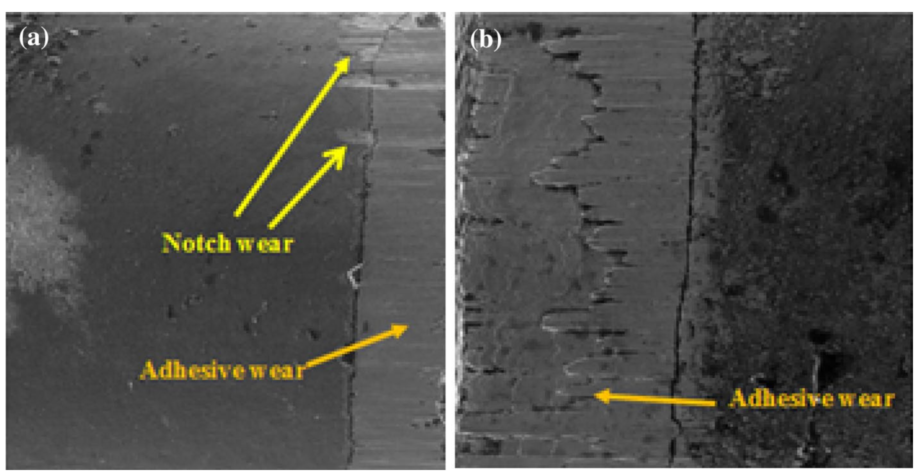

Fig. 8 Tool wear at cutting speed **a** 120 m/min, and **b** 170 m/min

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