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ScienceDirect

Procedia CIRP 87 (2020) 137–141

www.elsevier.com/locate/procedia

5th CIRP CSI 2020

Influence of built up edge on the surface topography of Ti-15Mo

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Abstract

Titanium alloys have been increasingly used in biomedical applications due to their mechanical and corrosion resistance, non-toxicity, and low modulus of elasticity. This latter property leads to intense material deformation during cutting and contributes to the formation of built up edge, which changes tool geometry and chip formation, altering workpiece surface quality. Its instability should also be taken into account, as it contributes to a high dispersion of roughness results. Considering the relevance of such effects in machining of a beta titanium alloy, this paper proposes a characterization of the built up edge formed during turning of Ti-15Mo and the correlation of its geometry with different surface roughness parameters. Obtained results show that the effective rake angle generated by the built up edge changes within a narrow range but its increase contributes to lower reduced peak height values obtained from the Abbott-Firestone curve.

Keywords: Built up edge; Surface roughness; Beta titanium alloy

1. Introduction

Despite their high manufacturing cost, in the last few decades, titanium alloys have been extensively applied in medical devices because of their biocompatibility [1]. However, aluminium and vanadium, present in Ti-6Al-4V, the most common among all titanium alloys, are toxic elements and may be associated to several diseases [2].

Another important feature to be considered on the production of implants is the elastic modulus (or Young modulus), which shall be as low as the bone's. This is necessary to avoid the stress shielding phenomenon, related to the inhomogeneous distribution of mechanical stresses, which may promote the loosening of the implant or even new bone fractures [3].

Beta titanium alloys usually present significant contents of niobium, tantalum and molybdenum, elements which are absolutely harmless to human health and help to decrease the phase transition temperature and stabilize the body-centered cubic structure (BCC) of titanium. These alloys have high mechanical strength and resistance to corrosion, good conformability and considerably lower elastic modulus than alfa (with hexagonal close packed structure, HCP) or alfa-beta (HCP+BCC) titanium alloys [4].

Due to the chemical affinity with commonly used tool materials, machining of titanium alloys is usually associated with diffusion wear. Moreover, in reason of their low thermal conductivity, which increases the temperature of the tool and promotes thermoplastic instability, cutting force fluctuations and vibration, which damage surface integrity, can occur. These features, added to their outstanding mechanical

10.1016/j.procir.2020.02.098

properties even at high temperatures, severely impair their machinability [5].

In order to face all these difficulties, cutting tools must present considerably high hot hardness, wear resistance, fracture toughness and chemical stability. Uncoated cemented tungsten carbide is the main tool material employed in the machining of titanium alloys, as it shows out to be more advantageous than other materials such as ceramic, cubic boron nitride (CBN) or polycrystalline diamond (PCD) [6]. The use of cutting fluids and low cutting speeds (compared to those usually employed on the machining of stainless steels, for example) is also recommended [7].

Arrazola et al. [8] have compared the machinability of Ti-6Al-4V alfa-beta titanium alloy against Ti-5553 near-beta titanium alloy (5 wt% Mo). They concluded that the latter presents a poorer machinability, as a lower cutting speed was necessary to achieve the same tool life. Besides the considerable molybdenum content, its higher ultimate tensile strength may explain the obtained results. Hatt et al. [9] have compared tool wear in the machining of Ti-54M (alfa-beta alloy) and Ti-6246 (beta alloy). They have observed for the first alloy both flank and crater wear caused by abrasion, whilst for the latter, a combination of different mechanisms which led to plastic deformation and breakage was noted. Tool wear has also a significant influence on surface integrity. Che-Haron [10] have observed that surface roughness increases with higher values of cutting speed when machining Ti-6Al-2Sn-4Zr-6Mo alfa-beta alloy, probably as a consequence of the modification of the cutting edge as an effect of flank and crater wear, as well as edge chipping, caused by abrasion, adhesion and diffusion mechanisms.

Regarding tool geometry, Wang and Liu [11] recommended the use of chamfered edges for better results in machining of titanium and nickel-based alloys, because it has proved to strengthen the cutting edge, avoiding edge chipping.

Although built up edge plays an important role in machining of beta titanium alloys because of their low elastic modulus and high hardening coefficient, it is not often reported and its effect on surface quality is not discussed. Considering this, an analysis of the correlation between built up edge characteristics and surface roughness parameters is proposed in this work, which should contribute to explain the variability of roughness results when built up edge is present.

2. Material and methods

In order to investigate the influence of built up edge geometry on surface roughness, turning tests in the titanium alloy Ti-15Mo were carried out with the application of flood coolant (10% emulsion) and an uncoated cemented tungsten carbide insert DNMG110408, ISO grade S20. The insert was mounted in a tool holder DDNNN 2020K 11, which provides a cutting edge angle of 62.5°, a rake angle of -7° (due to the presence of chip breaker, the effective rake angle corresponds to +13°) and a relief angle of +7°. The tool holder was placed in a lathe Imor PRN-320, with maximum rotation speed of 1500 min^{-1}. Cutting speed was varied in two levels (v_c = 54 m/min and 104 m/min), while feed rate f = 0.1 mm/rev and depth of cut a_p = 0.5 mm were kept constant.

Cutting tests were performed in workpieces with diameter of 35 mm and four sections, so that images of the cutting edge could be acquired and surface roughness could be evaluated after a cutting pass of 30 mm. For each level of cutting speed, a new insert was applied in a total axial length of 360 mm, which means that three workpieces (12 sections) were used for each cutting speed. The characterization of the built up edge formed during cutting through the measurement of effective rake angle and edge radius (Fig. 1b), as well as the assessment of the respective turned surface through the measurement of skewness, kurtosis and parameters of the Abbott-Firestone curve, like reduced peak height and reduced valley depth, were performed in a microscope Alicona InfiniteFocus SL.

It is well known that built up edge is unstable, but considering that no tool wear was observed during cutting, it was assumed that its shape has approximately the same characteristics during each pass (axial length of 30 mm). In an attempt to correlate its geometry with surface characteristics, roughness parameters were measured at the end of each section in two distinct regions of the turned surface and the average value was used to construct the graphs. To analyze the geometric characteristics of the built up edge, average values of 20 profiles positioned perpendicular to the main cutting edge (edge radius and cutting edge angle should be considered) were obtained (Fig. 1a). It is important to highlight that irregular formed or broken built up edges were not considered in the analysis, so that less than 12 points were used in the graphs. Examples of the cutting edges after the first cutting pass with different cutting speeds are demonstrated in Fig. 1c.

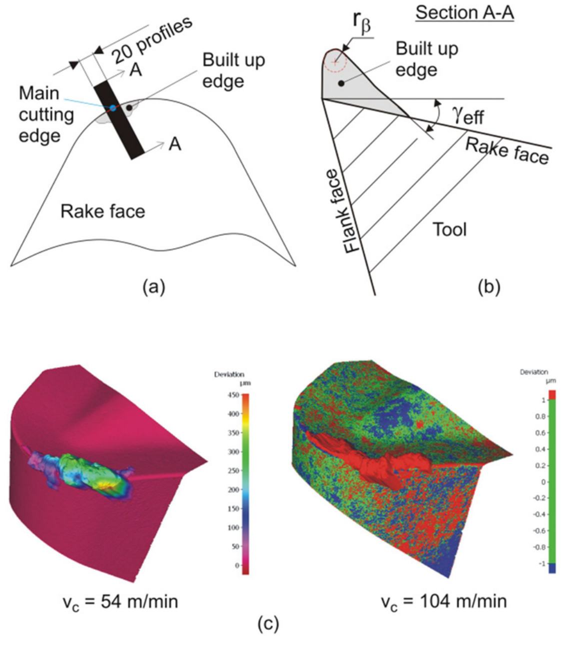

Fig. 1. Geometry of built up edge: (a) extracted profiles, (b) geometric parameters, and (c) examples of cutting edges after the first cutting pass (axial length of 30 mm) with v_c = 54 m/min and 104 m/min.

3. Results and discussion

Built up edge is formed due to the adhesion and work hardening of chips on the tool rake face and is commonly related to low cutting speeds. In the case of titanium alloys, low values of elastic modulus contribute to the deformation of the material and favor built up edge formation. During cutting, such structure corresponds to the actual cutting edge and substitutes the original tool geometry, altering material removal characteristics, because of changes in the effective rake angle and edge radius.

Although built up edge is usually unstable and can break during cutting, its geometry is responsible for chip formation, influencing surface roughness. Positive rake angles and large edge radii were the main characteristics observed during turning of Ti-15Mo with uncoated cemented tungsten carbide inserts.

As built up edge formation is unstable, even with the same cutting conditions the same geometry cannot be guaranteed after cutting each section (axial length of 30 mm) because of release of particles, changes in tool-workpiece contact characteristics, entry and exit of the tool. It is assumed, however, that, mainly at the final part of each section, an approximate geometry is maintained.

Besides some vibration occurred during the process, two factors contribute to an irregular workpiece surface (Fig. 2): fragmented particles of built up edge, which adhere to the surface; and a blunt cutting edge, which makes it more difficult to the tool to penetrate and shear the material, causing intense plastic deformation and chip side flow, verified by the presence of protuberances near the grooves.

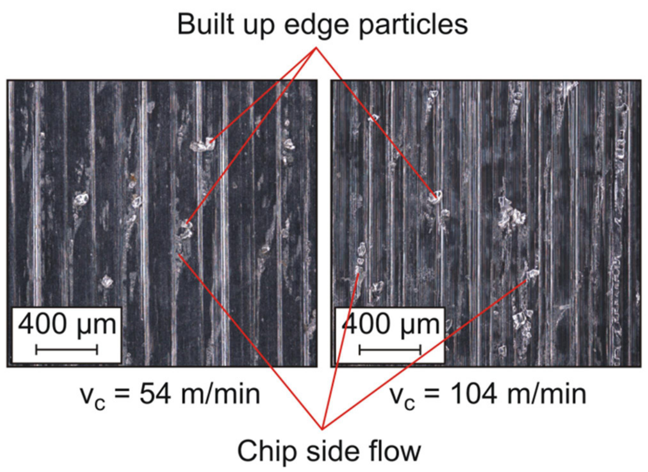

Fig. 2. Surface obtained after turning with f = 0.1 mm/rev, a_p = 0.5 mm and different cutting speeds.

Due to the random positioning of the irregularities, the turned workpieces were characterized by means of surface (not profile) roughness parameters. Figs. 3a and 3b show the values of skewness (Ssk), while Figs. 4a and 4b demonstrate the values obtained for kurtosis (Sku), both dependent on effective rake angle and edge radius of the built up edge. No clear trend could be noted for the variation of edge geometry or cutting speed, but Ssk is always positive and Sku is always higher than 3, which characterizes steep peaks and valleys.

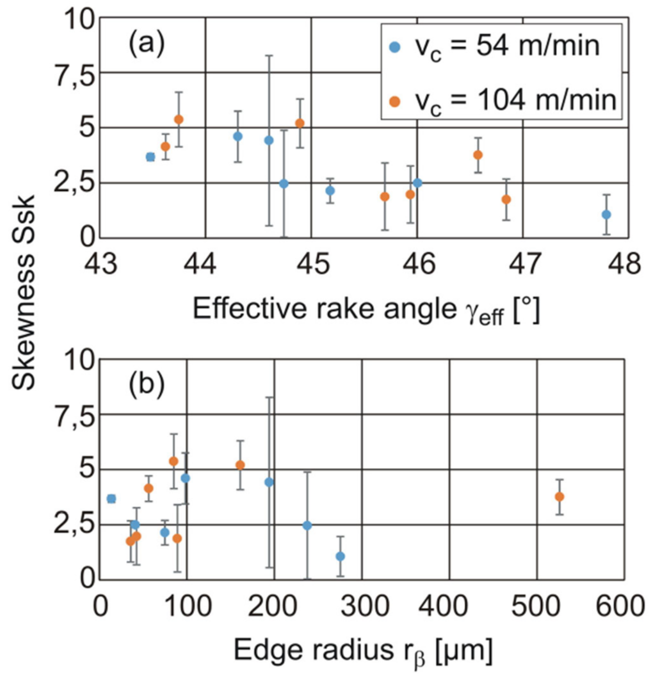

Fig. 3. Variation of skewness with different (a) effective rake angles and (b) edge radii (f = 0.1 mm/rev, a_p = 0.5 mm).

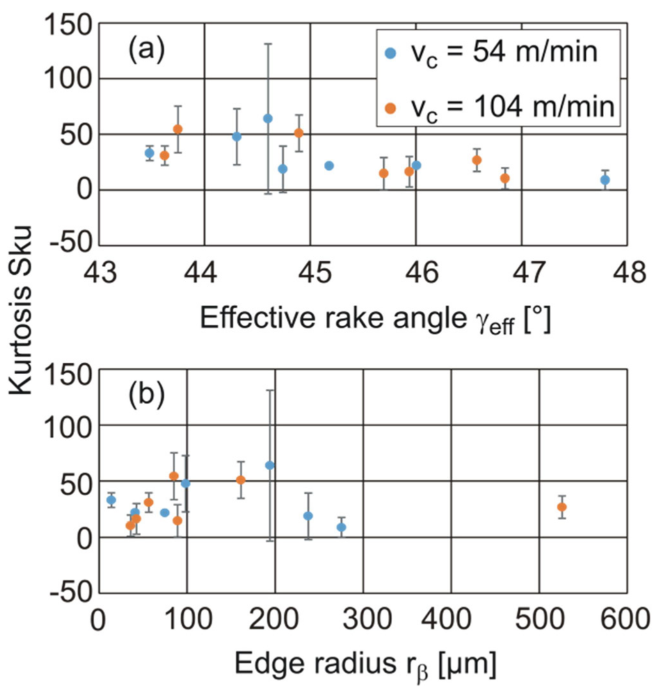

Fig. 4. Variation of kurtosis with different (a) effective rake angles and (b) edge radii (f = 0.1 mm/rev, a_p = 0.5 mm).

Due to the presence of adhered and deformed material on the surface and the occurrence of some vibration during the process because of high elongation of the material before shearing, parameters of the Abbott-Firestone curve were chosen to measure peaks and valleys beyond the core surface roughness. Thus, an additional assessment was performed through the reduced peak height (Spk) and the reduced valley depth (Svk), demonstrated in Figs. 5 and 6, respectively. Both parameters are shown in function of the effective rake angle and the edge radius after built up edge formation.

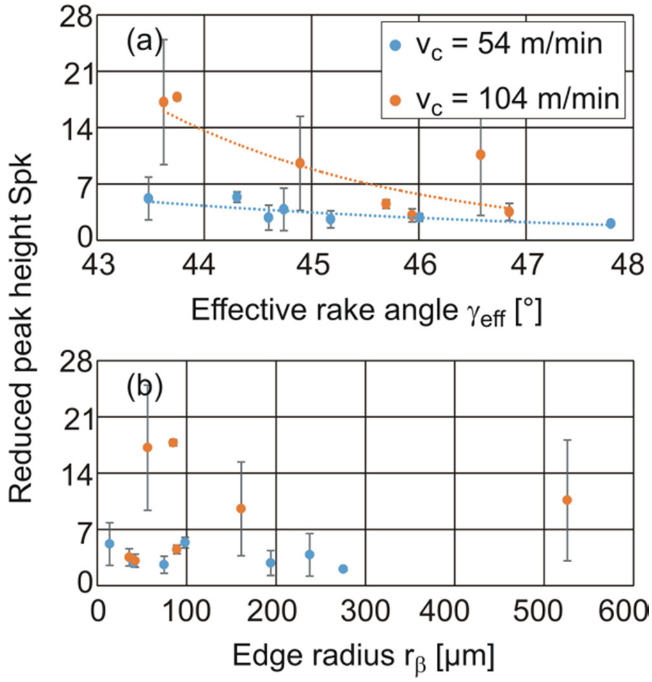

Fig. 5. Variation of reduced peak height with (a) different effective rake angles and (b) edge radii (f = 0.1 mm/rev, a_p = 0.5 mm).

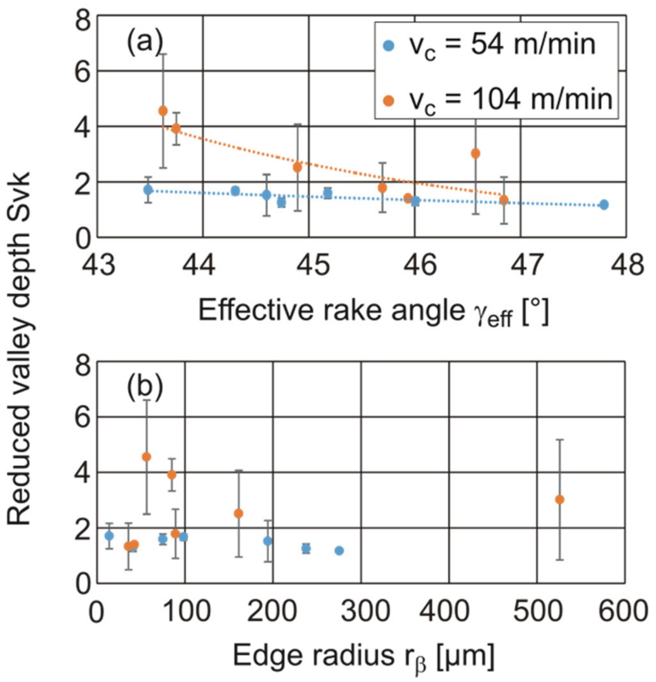

Fig. 6. Variation of reduced valley depth with (a) different effective rake angles and (b) edge radii (f = 0.1 mm/rev, a_p = 0.5 mm).

Although the variation of the effective rake angle after the formation of built up edge occurred in a narrow range and the correlation coefficients present relative low values ($R^2 \sim 0.63$), an increase in this parameter produced a decreasing trend of Spk and Svk values for both cutting speeds. A more positive geometry and a consequent increase of shearing angle lead to a reduction of chip deformation and explain the lower values of the measured roughness parameters. The tests carried out with a higher cutting speed produced a worse surface, with higher values of Spk and Svk, what can be associated with higher temperatures involved in the process, which favors material deformation and reduces the strength of the built up edge.

Differently, a broad range of edge radii was observed after the tests, but no evident influence of such characteristic on the measured roughness parameters could be noted, even though an intense material deformation and chip side flow were expected with larger radii. Apparently, the edge tip was not consistent during cutting, which can have constantly altered the built up edge-workpiece contact geometry.

4. Conclusions

Based on the obtained results it can be concluded that built up edge affects surface roughness irregularly. Large built up edge radii are not stable and consequently do not demonstrate any trend with the measured roughness parameters. Contrarily, an increase in the resultant effective rake angle after built up edge formation causes a reduction of reduced peak height and reduced valley depth. Additionally, a higher value of cutting speed leads to a reduced surface quality.

The observations are valid for the range of tested conditions and cannot be generalized. More experiments should be carried out in order to better understand the effects of cutting parameters on surface properties.

Acknowledgements

The authors would like to thank the Brazilian Federal Agency for the Support and Evaluation of Graduate Education (CAPES).

This work was supported by the São Paulo Research Foundation (FAPESP) (grant numbers 2015/15622-2, 2017/12309-7 and 2017/12304-5).

References

[1] Kaur M, Singh K. Review on titanium and titanium based alloys as biomaterials for orthopaedic applications. Mater Sci Eng C 2019;102:844-862.
[2] Niinomi M, Nakai M, Hieda J. Development of new metallic alloys for biomedical applications. Acta Biomater 2012, 8:3888-3903.
[3] Niinomi M. Mechanical biocompatibilities of titanium alloys for biomedical applications. J Mech Behav Biomed 2008, 1:30-42.
[4] Terlinde G, Fischer G. Beta Titanium Alloys. In: Leyens C, Peters M, editors. Titanium and Titanium Alloys: Fundamentals and Applications. Weinheim: Wiley-VCH; 2003. p. 37-57.
[5] Rahman M, Wang Z-G, Wong Y-S. A Review on High-Speed Machining of Titanium Alloys. JSME Int J C-Mech Sy 2006, 49:11-20.
[6] Ezugwu EO, Silva RB, Sales WF, Machado AR. Overview of the Machining of Titanium Alloys. In: Abraham MA, editor. Encyclopedia of Sustainable Technologies. Elsevier; 2017. p. 487-506.

[7] Ribeiro MV, Moreira MRV, Ferreira JR. Optimization of titanium alloy (6Al–4V) machining. J Mater Process Tech 2003, 143-144:458-463.
[8] Arrazola P-J, Garay A, Iriarte L-M, Armendia M, Marya S, Le Maître F. Machinability of titanium alloys (Ti6Al4V and Ti555.3). J Mater Process Tech 2009, 209:2223-2230.
[9] Hatt O, Crawforth P, Jackson M. On the mechanism of tool crater wear during titanium alloy machining. Wear 2017, 374-375:15-20.
[10] Che-Haron CH. Tool life and surface integrity in turning titanium alloy. J Mater Process Tech 2001, 118:231-237.
[11] Wang B, Liu Z. Influences of tool structure, tool material and tool wear on machined surface integrity during turning and milling of titanium and nickel alloys: a review. Int J Adv Manuf Tech 2018, 98:1925-1975.