Material removal mechanism and cutting energy analysis at tool cutting edge scale in end milling

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Abstract

Downsized machining scale influences on the material removal mechanism and impacts upon chip formation, cutting energy and consequently, surface formation. This paper aims at establishing a relationship between machining scaling and microstructure scale, i.e., by adjusting the grain size to the mean chip cross section formed under end milling cutting condition. Specific cutting energy, maximum cutting forces and friction coefficient were evaluated in end milling operation of low carbon steel (mean grain size = 11 µm) using end mills with carbide inserts coated with TiNAl (edge radius = 25 µm) under different feed per tooth (5, 11 (similar to mean grain size), 25 (similar to the cutting edge radius) and 70 µm/z). The results showed that machining scale cannot be defined based upon the feed per tooth / cutting edge radius ratio, once the mean grain size will also play a fundamental role on the scale effect. Specific cutting energy values and friction coefficient on the tool rake face were assessed when feed per tooth is smaller than the grain size.

1 Introduction

The microscale machining is defined when the uncut chip thickness is smaller than 999 µm [1]. However this definition does not identify the characteristics that separate micromachining from conventional macroscale cutting. The microstructure of the workpiece material, cutting tool material and geometry, and cutting parameters affect the mechanics of the material removal as the cutting scale decreases [2]. A major difference between macro- and micromachining is the significant increase in the workpiece material's shear flow stress as the size of the cutting zone decreases, commonly referred as the "size effect" in machining. At the same time, inhomogeneities such as grain boundaries, crystal defects, and impurities play a major role in the slip process while the shear strength of the workpiece material approaches its theoretical shear strength. Thus, a decrease in the uncut chip thickness results in an increase in the specific cutting energy [3]. Liu [4] showed in the cutting of ferrous materials that the tool may be in contact with only ferrite or pearlite, which significantly changes the cutting mechanisms and the response of the associated process, such as the cutting forces and the surface roughness. This paper aims at establishing a relationship between machining scaling and microstructure scale by adjusting the grain size to the mean chip cross section formed under end milling.

2 Experimental procedure

The end milling was carried out in a Hermle C800U CNC machining centre by considering down-milling and dry condition. The cutting parameters adopted were 700 m/min cutting speed, 500 μm depth of cut, 2 mm width of cut, and 5, 11, 25 and 70 μm/tooth feed (f_z). A carbide endmill tool coated with PVD-TiNAl layer (code R390-11 T308-PL 1030) and 24.404 ± 0.848 μm edge radius was used in machining. The cutting edge radius (r_e) was measured by Olympus OLS4000 3D Laser Microscope. A 0.16%C steel with 216.0 ± 4.0 HV hardness and 10.8 ± 0.1 μm grain size (GS) (ASTM E112-96) was used as workpiece. The cutting force was measured by a Kistler 9257BA piezoelectric 3-component dynamometer and 5233A signal conditioner. To calculate the specific cutting energy (SCE) [J/mm^3] the cutting force was integrated numerically by the trapeze method during the cutting time and multiplied by the ratio between cutting speed and removed workpiece volume. The surface images were made by Wyko NT1100 optic profiler.

3 Results and discussion

Figure 1 presents the transition points captured by signals of specific cutting energy as a function of the ratio f_z / r_e and f_z / GS. Thus, the graph shows three intervals: In (I) the ploughing is the main mechanism observed from tool/material interaction where the specific cutting energy increased 1531% for $f_z <$ GS, while friction coefficient on tool rake face decreased 39% and cutting force increased 25% because of an unbalance of force generated from the occurrence of ploughing and shearing of material at the cutting edge. The interval (II) between f_z / r_e = 1 and f_z / GS =1 is indicative of the transition from a ploughing-dominated to a shearing-dominated regime, commonly known as the minimum chip thickness (MCT). The transition from a ploughing-dominated region (below the MCT) to a shearing-dominated region (above the MCT) can be interpreted in terms of the effective rake face angle which was estimated by Oliveira [5] to be in the range of -48° for micromilling of AISI 1045 steel. According to Vogler et al. [6], the relationship between the MCT and cutting edge radius is in the range of 20 up to 30% for pearlitic and ferritic carbon steels. Finally, the shearing can be considered majority when $f_z / r_e > 1$ given the decrement of cutting force and specific cutting force.

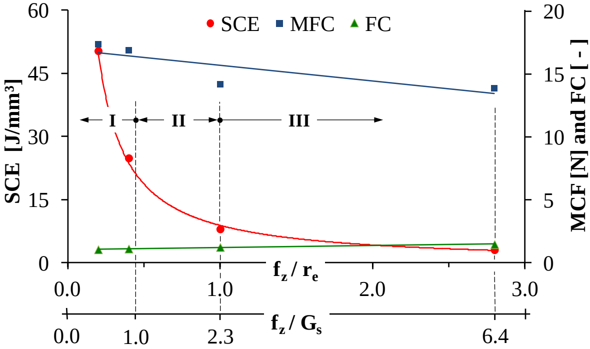

Figure 1: Variation of SCE, maximum cutting force (MCF) and friction coefficient (FC) as a function of the ratio f_z / r_e and f_z / GS.

Figure 2 illustrates the topography of surface finish with 2 different grains. For f_z = GS, the surface finish presented a topography with different grain height, due to difference in elastic modulus in each grain. Thus, when $f_z \leq$ GS, anisotropic response from polycrystalline materials takes place. It was also observed by Assis et al. [7] that the surface roughness is affected in the same way, i.e. at $f_z / r_e < 1$ the roughness increases and at $f_z / r_e \geq 1$ starts to increase with an inflection point at $f_z/r_e = 1$.

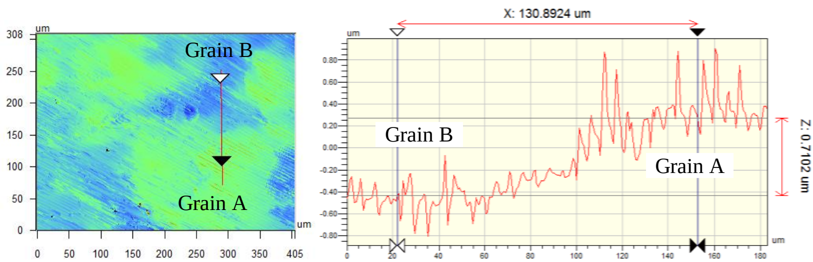

Figure 2. Surface finish for f_z = GS.

4 Conclusions

In summary, the specific cutting energy increased by 1531% while friction decreased of 39%, when $f_z < r_e$. In this case, ploughing is the main mechanism observed from tool/material interaction. The cutting force for values of $f_z <$ GS increased 25% when compared to the values achieved when $f_z > r_e$, due to an unbalance of force generated from the occurrence of ploughing and shearing of material at the cutting edge. When $f_z =$ GS, the surface finish presented a topography with different grain height, due to difference in elastic modulus in each grain. This shows that, when $f_z \leq$ GS, anisotropic response from polycrystalline materials takes place. By using the ratio f_z / GS it is possible to assert that when this relation is smaller than 1, the main material removal mechanism is ploughing. Within the interval between 1 and r_e / GS it is considered to be the transition from ploughing and shearing to ratios greater than r_e / GS. Finally, the machining scale does not depend only upon the ratio f_z / r_e, but upon the microstructure as well.

Acknowledgements:

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