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International Journal of Machine Tools & Manufacture 46 (2006) 1778–1785
INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE
DESIGN, RESEARCH AND APPLICATION
www.elsevier.com/locate/ijmactool

Effect of plastic side flow on surface roughness in micro-turning process

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Received 2 November 2005; accepted 28 November 2005
Available online 18 January 2006

Abstract

Kinematic roughness-based surface finish prediction is known to often under-predict the measured surface roughness in turning process, especially at small (micron level) feed rates. It has also been observed that the surface roughness in micro-turning decreases with feed, reaches a minimum, and then increases with further reduction in feed. This paper presents a model for predicting the surface roughness in micro-turning of Al5083-H116 alloy that takes into account the effects of plastic side flow, tool geometry, and process parameters. The model combines these effects with more accurate estimation of the average flow stress of Al5083-H116 at micron scale of deformation with the help of a previously reported strain gradient-based finite element model. The surface roughness model is evaluated through a series of micro-turning experiments. The results show that the model can predict the surface roughness in micro-turning quite well. It is shown that the commonly observed discrepancy between the theoretical and measured surface roughness in micro-turning is mainly due to surface roughening caused by plastic side flow. Further, it is shown that the increase in roughness at low feed can be attributed to the increased side flow caused by strain gradient-induced strengthening of the material directly ahead of the tool.

Keywords: Surface roughness; Plastic side flow; Micro-cutting; Strain gradient strengthening

1. Introduction

The need for products with very fine surface finish keeps increasing rapidly because of new applications in various fields including optics and die and mold manufacturing. Surface roughness is an important feature of practical engineering surfaces because of its influence on the tribological performance of the surface. Therefore, accurate prediction of surface roughness produced by a mechanical cutting process carried out at the micron/submicron level can contribute to improvement partly in quality and performance.

In conventional single-point turning, the surface roughness of the machined part is known to be affected mainly by the feed and tool nose radius. The geometric contribution of tool nose geometry and tool feed, shown in Fig. 1, is also called kinematic or theoretical surface roughness and is given approximately by the following equation [1]:

$$R_{th} \cong \frac{f^2}{8r_n}, \tag{1}$$

where f is the feed and r_n is the tool nose radius.

The kinematic surface roughness is widely used to estimate the surface roughness in the turning process, but it gives poor estimation of the surface roughness, particularly at small feeds. It can be seen from Fig. 2 that the kinematic surface roughness under-predicts the measured surface roughness in turning, especially at small feeds. It is also observed that surface roughness in micro-turning decreases with feed, reaches a minimum, and then tends to increase with further reduction in feed. This trend can be clearly seen in Fig. 2 for micro-turning of AISI 1045 steel at feeds less than 50 μm/rev.

It has been reported [2–6] that the surface roughness in turning is also affected by the depth of cut, cutting speed, tool wear, presence of built-up edge (BUE), workpiece hardness etc. However, due to lack of understanding of the

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0890-6955/$ - see front matter
doi:10.1016/j.ijmachtools.2005.11.014

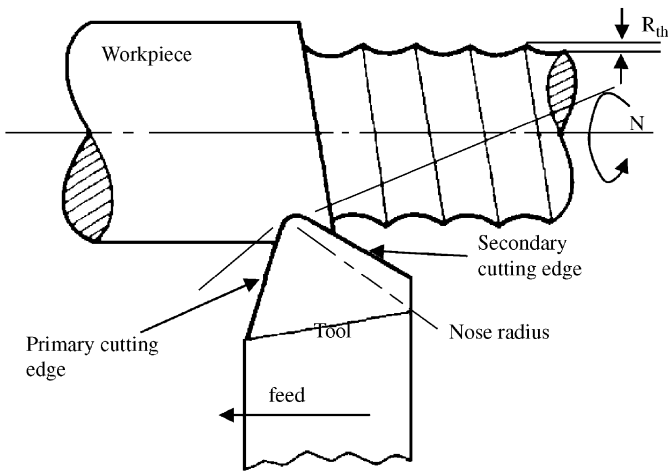

Fig. 1. Illustration of turning operation showing primary and secondary cutting edges and characteristic roughness left on the finished surface [1].

surface-roughening mechanism at the micron/submicron level and lack of physics-based surface roughness models, techniques such as regression analysis, neural network etc., are commonly employed [2–6]. In particular, the contribution of material deformation at the micron scale to surface roughening has not been accounted for in modeling the surface generation mechanism in micro-cutting process.

A few studies on roughening of free surfaces of metallic materials due to plastic deformation have been reported in sheet metal forming [7–9]. Plastic deformation roughens a free surface by producing slip bands within grains along with relative rotation and sliding among the grains.

The effect of material swelling in ultra-precision diamond turning has been investigated [10] and a good correlation between the surface roughness and the amount of elastic recovery has been shown. Influences of vibration [11–13] and crystallographic orientation [14] on surface roughness in diamond turning have also been investigated.

Sokolowski [15] suggested that there is a minimum uncut chip thickness, below which a chip will not form. When this occurs, rubbing takes place instead. Applying this idea to the secondary cutting edge of a turning tool, it is suggested that a small triangular portion of the material is left behind. The portion left behind has been analyzed by Brammertz [16] who called it a Spanzipfel. An additional purely geometric term (see Eq. (2)) was proposed by Brammertz to supplement the kinematic surface roughness to account for the contribution of the Spanzipfel to the surface roughness in turning.

$$R'_{th} = \frac{f^2}{8r} + \frac{f_m}{2}\left(1 + \frac{rf_m}{2}\right). \quad (2)$$

Grzesik [17] proposed a revised model based on Brammertz's work to account for the increasing trend in surface roughness below a certain feed by introducing the minimum uncut chip thickness as a function of the tool feed.

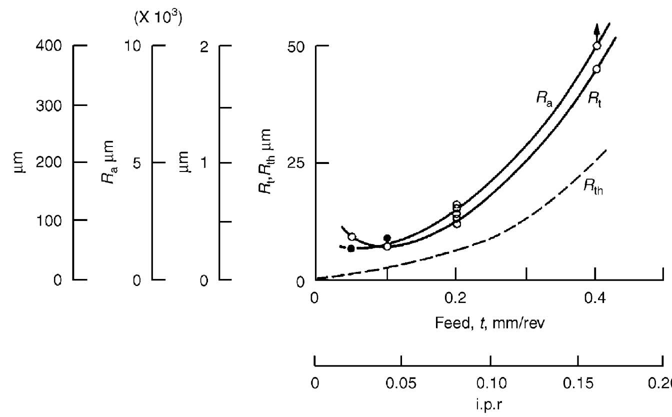

Fig. 2. Comparison of measured and theoretical values of surface roughness (workpiece: AISI 1045 steel; tool: tungsten carbide) [1].

However, as pointed out by Shaw [1, pp. 519], the Spanzipfel will be plastically deformed and made smaller as it comes into contact with the clearance surface of the tool. Consequently, it is not likely to completely account for the observed trend at small feeds.

Sata [18] has studied the influence of material side flow on surface finish and has found that this component of roughness is zero for a brittle material such as brass, but may contribute up to 6 μm to the roughness when alloy steel is machined.

Shaw [1] also indicated that plastic side flow is most significant at very small feeds and could be partly responsible for the rise in surface roughness after reaching a minimum for feeds less than a certain value. According to Shaw, this is due in part to the fact that the specific cutting energy, and hence the mean stress on the tool face, increases rapidly as the feed decreases. This in turn will cause more plastic side flow along the secondary cutting edge. The furrow or ridge that is formed because of material side flow will add to the discrepancy between the measured and theoretical surface roughness. Although Shaw [1, pp. 516] forwarded this as a likely explanation, he did not demonstrate its validity through modeling and analysis. The present paper attempts to do this explicitly.

Therefore, the purpose of this paper is to study surface roughening due to plastic deformation in turning at micron-level feed rates, i.e. micro-turning. In particular, the surface roughness associated with material plastic side flow is analyzed and modeled quantitatively.

2. Plastic side flow-induced surface roughness

In turning, the material around the cutting edge is subjected to sufficiently high pressure to cause the material to flow to the side (see Fig. 3). As shown schematically in Fig. 4, the solid curve shows the ideal surface profile left behind in the absence of side flow while the dotted curve shows the surface profile with side flow. It is evident from Fig. 4 that the peak-to-valley roughness is larger when side flow is present.