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Continuous and ultra-fine grained chip production with large strain machining

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ABSTRACT

In this study, orthogonal cutting technique as a severe plastic deformation (SPD) method for producing chips with an ultra-fine grained microstructure and fair mechanical properties is investigated; further, it has been suggested that by controlling the cutting velocity and contact length between tool and material, it is possible to produce a severely deformed and continuous chip with unrestored microstructure even at high cutting velocities. Solution treated Al-6061 samples in plane strain condition were severely deformed through applying various cutting velocities (from 50 to 2230 mm/s) for three different rake angles (-5°, -10° and -20°) in fixed cutting parameters. Chip thickness, contact length, shear strain, and Vickers microhardness variations were examined for different samples and chip formation mechanism was discussed for different processing conditions. In addition, the microstructure of especial produced chips was studied using transmission electron microscopy (TEM). The results showed that during the dominance of seizure mechanism at the contact surface, microhardness and shear strain (as well as contact length) have inverse dependency upon the variation of the cutting velocity. The results are discussed by considering the heat-time effect contribution in the final microstructure and mechanical properties.

1. Introduction

Recent developments in nanostructured and ultra-fine grained materials (i.e., materials which exhibit significantly enhanced mechanical properties with grain sizes around few hundred nanometers) have renewed attention on the use of large strain plastic deformation for achieving microstructure refinement in metals and alloys. The so-called SPD method, which has been used extensively to realize and study microstructure refinement (Furukawa et al., 2002), has attracted much attention in recent years, most notably from the works done in the area of imposing large strains via equal channel angular pressing (ECAP) by Segal (1995) and Valiev et al. (2000). Typically, the current SPD approaches do have some limitations. First, multiple stages of deformation are needed to create the large plastic strains. Second, high strength metals and alloys are difficult to deform in this manner due to constraints imposed by the forming equipment. Lastly, there are uncertainties pertaining to knowledge and control of deformation field parameters. A potentially attractive route for creating very large plastic strains in a single stage of deformation, while simultaneously overcoming the aforementioned limitations, is the process of chip formation by plane strain (2-D) machining. Brown et al. (2002) demonstrated that large plastic strains imposed in a chip, in a single stage of deformation, results in significant microstructure refinement, including the creation of nanocrystalline and ultra-fine grained materials. This demonstration not only suggests a low-cost method for making nanocrystalline materials but also a novel experimental technique for studying microstructure changes at the micro- and nanoscales by large strain deformation.

In addition, the ultra-fine grained chips produced by the machining process can be utilized as reinforcing component in the composite and two phase materials. About aluminum alloys, some techniques have been developed to create composite structures using aluminum chips dispersed in an aluminum powder matrix. Gronostajski et al. (1998, 2001) mixed the chips of Al and $AlMg_2$ from machining with the ferro-chromium and tungsten powders to produce composite material using compaction and hot extrusion. Kanani et al. (2009) developed a 2D-cutting technique to obtain very small particles with specific dimensions from the large-strained chips. They could produce large strained chips particles

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with 1 mm × 1 mm × 0.5 mm which can be used for creating composite material through powder metallurgy. Sherafat et al. (2009) employed the produced chips particles from this technique and fabricated an Al/Al7075 two-phase material using powder metallurgy route by hot extrusion process.

The formation of nano- and ultra-fine grained materials by machining, and applicability of 2-D machining approach to study microstructure refinement as a function of deformation conditions, was presented for different metals by Shankar et al. (2005b) and Swaminathan et al. (2005). Although there are remarkable studies on the produced chip microstructure analysis by different researchers, in most cases the classical chip formation theory, (as described by Shaw, 1957) has been applied to analyze the microstructure evolution; however, Trent (1988a) showed that this theory does not correctly treat the contact area effects between material and tool. Moreover, to avoid any thermal effect on produced microstructure, very low or medium cutting velocities were applied in most of studies mainly by Shankar et al. (2005a,b) and Swaminathan et al. (2005) which are far away from real machining condition. Trent (1988a) analyzed that in higher velocities, well-known seizure connection might occur due to localization of high strain at contact interface between material and tool rake face; and Astakhov (2006) showed that this can significantly influence the deformation mechanism and subsequently the chip microstructure. Oxley (1980), Trent (1988a,b), and Astakhov and Shvets (1998) have illustrated realistic analyses based on secondary deformation zone (SDZ) at the interface between material and tool's rake face. These studies have shown that while the main deformation occurs in primary deformation zone (PDZ) at tool tip front, the contact area at SDZ (i.e., its type and length) can also affect the whole deformation mechanism and subsequently the final microstructure. Furthermore, when the seizure mechanism at contact area dominates the raised temperature due to SDZ is high enough to be taken into account for microstructure studies, as explained by Trent (1988b).

In the present study, we show the capability of 2D-machining not only for imposing the large strains but also the simultaneous high strain rates. Furthermore, the possibility of obtaining stable ultra-fine grained chips from this technique is discussed according to the obtained experimental results. The results are interpreted on the basis of the microstructure evolution according to the correlated impacts of the imposed strain, the strain rate and the generated heat. Different cutting conditions in a variety of cutting velocities are applied on an age-hardened aluminum 6061 alloy in as-solution annealed state. By taking into account the contact length variation, we have made an attempt to characterize a special condition in which a continuous chip could be issued with undergoing a severe deformation and consequently having a stable nano- and ultra-fine grained structure with a steady state production rate even at high cutting velocities. Chip formation mechanism and mechanical properties as well as the microstructure of different cases are discussed here, including the effect of contact length parameter. In the followings, basic theory of the orthogonal cutting as well as thermal analysis of the deformation zone will be explained in Section 2.

2. Theory

2.1. Orthogonal cutting

The plane-strain machining is characterized by a sharp, wedge-shaped tool that removes a preset depth of the material (t_1) by moving in a direction perpendicular to its cutting edge. In the orthogonal cutting process, material is severely deformed at a very narrow zone in front of the tool tip. Merchant (1945) suggested that the whole shear strain is imposed on a certain plane and this plane is classically called a "shear plane". The shear plane position and general deformation model for orthogonal cutting is shown in Fig. 1.

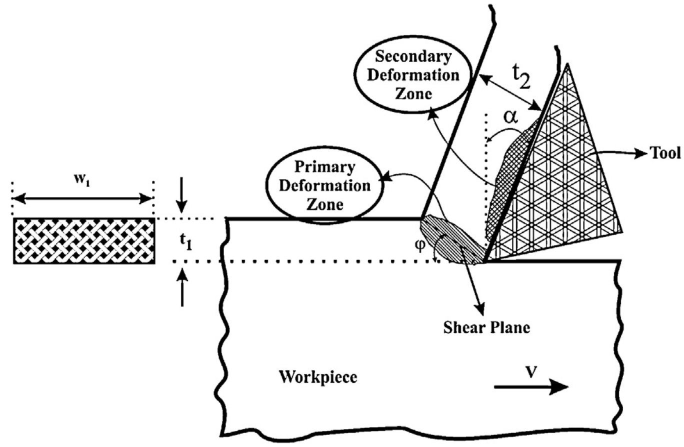

Fig. 1. Machining parameters and deformation zones during orthogonal cutting.

Generally, the principal machining parameters are the tool rake angle, cutting velocity and the friction at the tool–chip interface, while the deformation field parameters are strain, strain rate and temperature, as discussed by Trent and Wright (2000). Finally, the geometry of the deformation zone and the associated shear strain are determined by the shear plane angle (φ) and the rake angle (α). The shear strain (γ) imposed on the chip during the chip formation is given by (according to Merchant, 1945):

$$\gamma = \frac{\cos\alpha}{\sin\varphi\cos(\varphi-\alpha)} \tag{1}$$

where φ is calculated from a measurement of the produced chip's thickness (t_2) and t_1 (Fig. 1), as:

$$\tan\varphi = \frac{(t_1/t_2)\cos\alpha}{1-(t_1/t_2)\sin\alpha} \tag{2}$$

Trent (1988a) and Astakhov et al. (2001) have shown that while the main deformation occurs in front of the tool tip zone, the secondary deformation zone has considerable effects on the deformation regime and the chip microstructure. Seizure connection between chip back surface and tool rake face was illustrated by Trent (1988a) for the first time. The contact length between tool and chip under seizure connection can be calculated by Astakhov and Osman (1996) experimental equation as follow:

$$C = t_1\xi^{1.5}, \quad \xi = \frac{t_1}{t_2} \tag{3}$$

where C is the contact length between chip back surface and tool rake face and ξ is called as chip comparison ratio.

2.2. Thermal considerations

It should be noted that by increasing the cutting speed, nearly all of the work done in both the PDZ and SDZ converts into heat because of the very large amount of plastic strain and likely high strain rate; consequently, this generated heat causes the chip, the tool and the work material to warm up, as explained by Boothroyd (1975). Further, Trent and Wright (2000) and Childs et al. (2000) have discussed that the main source of generated heat during chip formation process is due to high shear strain at PDZ, which converts to heat by ~95%. In addition, Trent (1988b) and Astakhov (2006) have analyzed that, at SDZ where the seizure connection can occur between the chip and tool rake face, the next heat source