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ScienceDirect

Scripta Materialia 60 (2009) 17–20

Scripta MATERIALIA

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Controlling gradation of surface strains and nanostructuring by large-strain machining

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Received 24 July 2008; revised 5 August 2008; accepted 14 August 2008
Available online 7 September 2008

Direct measurement of the deformation field associated with the creation of a machined surface shows that the strains in the surface and chip are large and essentially equal. This is supported by microstructure and hardness data. By interpreting these results in the framework of an upper bound model for the deformation, control of severe plastic deformation parameters on the machined surface is seen to be feasible, suggesting interesting opportunities for nano- and microscale engineering of surface microstructures by machining.

Keywords: Surfaces; Nanostructure; Severe plastic deformation; Machining

The formation of a chip during machining occurs by severe plastic deformation (SPD) in a deformation zone ahead of the advancing tool cutting edge [1]. Controlled, large plastic strains (of the order of 1–15) can be imposed in the chip in a single pass of deformation by design of the tool rake angle and deformation zone geometry [2,3]. This SPD methodology has been exploited as a means for producing bulk and particulate nanostructured materials [3,4]. The deformation zone in machining, while unitary in structure, is still of finite geometry that permeates a zone ahead of the cutting tool and into the surface of the bulk workpiece [5]. An inevitable consequence of this aspect is SPD in the material layer near the machined surface. In general terms, the strains in this layer are quite large (>5) at the surface and decay with depth into the subsurface over a region that is tens of micrometers in extent [6–9]. The structure of the layer on copper surfaces created by abrasive machining has been found to consist of equiaxed grains ~30 nm in size with an orientation texture similar to that of rolling [8,10]. A fine-scale microstructure of ~100 nm grains has been observed on hardened steel surfaces under selected machining conditions [11]. Electron backscatter diffraction (EBSD) analysis of deformation in machined stainless steel indicates that the subsurface microstructure is also ultrafine-grained (UFG) and this UFG region extends tens of micrometers into the depth [12]. These UFG microstructures are a consequence of SPD of the surface occurring in a manner that is perhaps analogous to that on surfaces subjected to sliding, rolling, high-pressure torsion or mechanical attrition [13–17]. Nanoscale microstructures have also been reported on a copper surface produced by "mechanical grinding" with a rotating spherical tool [18]. While the occurrence of an UFG microstructure on machined surfaces created under select conditions has been recognized, what appears not to have been considered is the possibility of systematically controlling the SPD parameters (e.g. strain, strain rate and deformation geometry) during the creation of this surface. Recent studies of machining deformation using particle image velocimetry (PIV) [2,5], although more focused on understanding evolution and control of deformation in the chip, suggest the intriguing possibility of varying in a systematic way the gradation of deformation strains on the surface. In this study, it is shown using direct measurement of strain rate and strain fields, and supported by microstructure and hardness data, that the deformation levels on the machined surface are very

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doi:10.1016/j.scriptamat.2008.08.027

similar to those in the chip. By interpreting these observations in the framework of an upper bound model, control of surface deformation using machining processes is discussed. Since deformation parameters determine the microstructure, this opens up opportunities for realizing controlled nanostructuring and, more generally, of controlling the microstructure of surfaces by machining.

Commercial grade, oxygen-free high-conductivity (OFHC) copper (99.95%, Goodfellow) and brass (70 Cu-30 Zn) were machined at near-ambient temperature (298 K) in a linear, plane strain machining set-up using sharp, high-speed steel tools [2,19]. The samples, in the form of plates 3 mm in width, had initial grain sizes of 35 ± 5 μm (Cu) and 200 μm (brass), and Vickers hardness of 77 ± 3 kg mm^{-2} (Cu) and 80 kg mm^{-2} (brass). The tool was kept stationary and the sample was moved perpendicular to the tool cutting edge. An undeformed chip thickness of 100–200 μm and a machining speed of 10 mm s^{-1} were employed, this somewhat low speed being selected to ensure minimal temperature rise in the deformation zone, as confirmed by infrared thermography [19]. Tools of different rake angles (−30° to +20°) were used to impose different levels of strain in the deformation zone [1,2].

PIV, a correlation-based image analysis method, was used to directly map the strain rate and strain fields with particular attention being paid to evolution of deformation in the material constituting the machined surface [2,5]. For mapping the deformation, one side of the plate sample was constrained along its entire length by a transparent glass block, ~6 mm thick, to ensure minimal side flow of the material during the machining while enabling direct observation of material flow through the deformation zone and into the machined surface region. A high-speed charge-coupled device (CCD) camera (Kodak Motion Corder Analyzer Sr-Ultra, maximum frame rate 10^4 s^{-1}), positioned stationary with respect to the cutting edge, was used to image the deformation zone from the side of the sample constrained by the glass block. A sequence of images, in time steps (Δt) corresponding to the framing rate of the camera (250 s^{-1}) was collected to characterize the deformation field parameters. By following the motion and relative displacement of "asperities" specifically introduced onto the side face of the sample and applying the PIV technique, the displacement and velocity fields in the deformation zone and adjoining machined surface were obtained [2,5]. The strain rate field was estimated by spatial differentiation of the velocity field, and the strain field, by integration of the strain rate field along particle trajectories.

The microstructure of the machined surface and chips in copper was analyzed using transmission electron microscopy (TEM). Electron-transparent specimens representative of the surface and chip were prepared using a combination of mechanical polishing and electrolytic jet-thinning. The specimens were then studied in a JEOL 2000FX microscope operating at 200 kV. Hardness values for the surface and chip were obtained using Vickers indentation (100 g load) and nanoindentation (Nanoindenter XP, MTS Nano Instruments). To estimate the variation of hardness with depth into the subsurface, indentations were made on tapered sections of the samples (with the edge integrity protected by a nickel layer) so as to obtain a high depth resolution of the hardness.

Figure 1a and b show the shear strain rate determined using PIV for copper (+20°) and brass (−30°), respectively. The region of high strain rate characterizes the deformation zone in these figures. A narrow region of severe deformation with strain rate of about 50–100 s^{-1} extends across the chip width and, more importantly for the present discussion, permeates some distance into the subsurface underneath the tool as well, as shown by the arrows in Figure 1. The extent of this permeation is much greater in the copper even when using a positive rake angle tool than in the brass with the negative rake angle tool. As with the chip [2,5], most of the strain resulting on the machined surface is imposed in this severe deformation region when the material constituting the surface generated in the wake of the tool traverses it (Fig. 1). The spatial contiguity of the chip and the machined surface suggests that the level of strain on the machined surface is probably the same as that prevailing in the chip. The permeation of the severe deformation region into the subsurface for a given material increases with decreasing rake angle such that the more negative

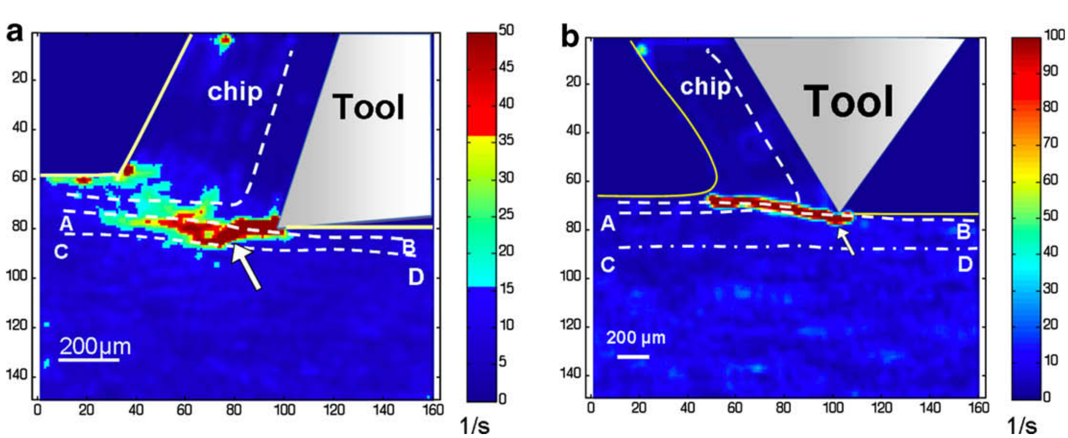

Figure 1. Shear strain rate fields obtained using the PIV for (a) copper, +20° rake and (b) brass, −30° rake. AB and CD are two particle trajectories along which the strain rate field was integrated to obtain subsurface strains. Particle trajectories into the chip were used to estimate chip strains.