Journal of Alloys and Compounds 726 (2017) 367–377

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Surface gradient nanostructures in high speed machined 7055 aluminum alloy

Yanxia Chen [a], Yanqing Yang [a, *], Zongqiang Feng [b], Bin Huang [a], Xian Luo [a]

[a] State Key Laboratory of Solidification Processing, Shaanxi Materials Analysis and Research Centre, Northwestern Polytechnical University, Xi'an 710072, China
[b] College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China

ARTICLE INFO

Article history:
Received 23 December 2016
Received in revised form
18 May 2017
Accepted 2 August 2017
Available online 3 August 2017

Keywords:
Aluminum alloy
High speed machining
Grain refinement
Precipitation
Texture

ABSTRACT

The high speed machining induced surface deformation layer in a 7055 aluminum alloy was investigated by means of transmission electron microscopy (TEM) and precession electron diffraction (PED) assisted nanoscale orientation mapping. The gradient nanostructures were composed of equiaxed and lamellar nanograins and ultrafine grains decorated by coarse grain boundary precipitates (GBPs). The presence of low angle dislocation boundaries, the recrystallized nanograins and ultrafine grains showed direct evidence that dislocation activities and dynamic recrystallization are two dominant grain refinement approaches, while the large size and density differences between GBPs and grain interior precipitates (GIPs) unraveled a prominent precipitate redistribution, which can be accomplished via the thermally and mechanically induced precipitate dissolution, solute diffusion and reprecipitation. The quantitative prediction of solute diffusion in the current machining condition agreed well with the TEM observation results. The crystallographic texture of the surface nanostructured layer was proved to be a mixture of brass, cube and weak rotated cube, the severe but diversified thermomechanical effect of high strain, high strain rate and high temperature shear deformation during high speed machining is responsible for texture development.

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1. Introduction

High speed machining of metallic alloys becomes an increasing demand for advanced manufacturing industry in order to achieve high quality, high productivity and low machining cost. Over the past decades, a great deal of research concern was attracted to reveal the microstructural and crystallographic characteristics of the machining induced surface severe plastic deformation (SSPD) layer [1–5], to improve surface quality and mechanical properties [1,2,5,6], to optimize processing parameters and circumstances [7–9], and to develop novel machining tools, equipments and technologies [1,2,9,10]. Among all these efforts, understanding the microstructural and crystallographic characteristics of SSPD layer and the underlying formation mechanism has been the subject of many previous research literature [3–5], mainly because of their significant effect on fatigue, fracture and many other mechanical properties of the structural components [1,11,12].

As one of the most widely used structural materials in aeronautic industries, the age-hardenable 7000 series (Al-Zn-Mg-Cu) aluminum alloys are known as superior weight-to-strength ratio, good corrosion and wear resistance [13]. Through various artificial aging, they can be greatly strengthened by the uniformly distributed η ($MgZn_2$) precipitate and its nonequilibrium precursors [13,14]. To satisfy the diversified demand for aeronautic structural components, many machining technologies and procedures such as cutting, grinding, turning, milling and drilling, should be separately or cooperatively used. During high speed machining, similar to other surface treatment processes [15,16], a high strain rate plastic deformation usually takes place at the machined surface of aluminum alloy, resulting in a depth-dependent gradient microstructure in which the grain sizes and shapes, precipitate size and density, as well as hardness in different deformation layers can be distinctly different [3–5,15,16]. Preliminary investigations have revealed some aspects about grain refinement and precipitation in the machined 7000 series aluminum alloy [3–5]. However, since grain refinement and precipitation are in fact two simultaneous and dependent processes during high speed machining, a systematic and comprehensive study of the simultaneous precipitation

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[*] Corresponding author.
E-mail addresses: yqyang@nwpu.edu.cn (Y. Yang), qiang733@163.com (Z. Feng).

http://dx.doi.org/10.1016/j.jallcom.2017.08.018
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and grain refinement behaviors is still necessary to fully understand the relationship between grain refinement and precipitation.

Accompanying microstructural changes, the evolution of crystallographic texture may also occur in the machined components [17,18]. Unfortunately, characterization of the texture in the SSPD layer by means of the scanning electron microscope (SEM) based electron backscatter diffraction (EBSD) technique is actually not an easy work since the machining induced deformation layer is usually a few micrometers thick and composed of nanograins with the grain size of dozens of nanometers and with fairly large residual strains [19–22]. A novel orientation mapping technique with higher spatial resolution but lower sensitivity to residual strains thus needs to be developed to fill such scientific and technological gap. To date, several crystal orientation analysis techniques, such as the SEM-based transmission Kikuchi diffraction [23,24], transmission electron microscope (TEM) based precession electron diffraction (PED) [21,22,25] and the three-dimensional orientation mapping in the TEM (3D-OMiTEM) [26], have been developed to push the nanoscale orientation mapping forward to a smaller grain size regime and to three dimensions. Particularly, the TEM based PED method shows good capability in orientation mapping of nanocrystals with grain sizes as small as 5 nm [21]. While reducing typical dynamic effects in TEM, this technique can remarkably improve the orientation sensitivity and pattern indexing rates [21,22,25]. The PED technique has been widely used for orientation mapping of many kinds of nanocrystalline materials [22,25].

The present work was concerned with the microstructural, chemical and crystallographic features in the SSPD layer of a high speed machined 7055 aluminum alloy, with particular emphasis on the effect of high speed machining on grain refinement, precipitation and texture evolution. Especially, the newly-developed PED assisted TEM orientation mapping method was used to unravel the crystallographic characteristics of the surface nanostructured layer in the machined aluminum alloy.

2. Experimental

2.1. Materials and the high speed machining

An AA7055-T77 aluminum alloy (with nominal composition of Al-8.2Zn-2.0Mg-2.3Cu-0.12Zr-0.08Fe-0.04Si (wt.%)) plate ($100 \times 100 \times 30$ mm^3 in size) was chosen in the present investigation. Before machining, the plate surfaces were polished with silicon carbide papers. The high speed milling was accomplished at ambient temperature on a high speed machining center Mikron HSM800 under dry condition. The Sandvik cutting tools GC1620, with a diameter of 10 mm, helix angle of 30°, rake angle of 13.5° and flute number of 4, was used. The machining parameters were employed as follows: cutting speed $v_c = 1100$ m/min, feed rate $f_z = 0.04$ mm/z and depth of cut $a_p = 0.5$ mm. The feed direction was kept parallel to the rolling direction of the as-received plate, and here was defined as SD, while the direction perpendicular to the machined surface was defined as ND.

2.2. Microstructure characterization and texture analysis

The microstructural features of the high speed milled 7055 aluminum alloy sample were characterized using optical microscope (OM), a field emission gun SEM Zeiss Supra 55 and a 300 kV TEM Tecnai F30 G^2 equipped with a high angle angular dark field (HAADF) detector and an energy dispersive spectroscopy (EDS). The OM and SEM samples were prepared through grinding, polishing and chemical etching, while the cross-sectional TEM samples were prepared via an improved transverse TEM sample preparation method to continuously show microstructural evolution along the depth direction.

The crystallographic texture of the machined surface was analyzed by using the PED assisted TEM orientation mapping method, which was accomplished in the Tecnai F30 G^2 TEM equipped with a PED system NanoMEGAS ASTAR [22,25]. The detailed process includes continuous scanning of the fast precessed electron beam on an area of interest with a precession angle of 0.6°, beam size of 5 nm and step size of 4 nm, simultaneously fast acquisition of PED patterns and off-line ultrafast matching of these obtained PED patterns with the precalculated kinematical diffraction patterns. Further orientation mapping analysis and visualization were carried out using ASTAR MapViewer as well as the Channel 5 software package. For comparison, EBSD analyses of the as-received 7055 aluminum alloy was performed on the Zeiss Supra 55 SEM equipped with an Oxford EBSD system, the step size for scanning is 100 nm.

3. Results

3.1. The starting material

Prior to machining, the surface-adjacent region of the as-received 7055-T77 aluminum alloy shows a typical rolled microstructure characterized by lamellar grains with a large boundary spacing range (Fig. 1a). In the EBSD orientation map (Fig. 1b), the grain morphology seems more clearly, both high angle grain boundaries (HAGBs, >15°, see coarse lines) and low angle grain boundaries (LAGBs) can be well distinguished. Specifically, the grain boundaries parallel or nearly parallel to rolling direction are more often with large misorientations, while those intersected with rolling direction are usually with small misorientations. Based on crystal orientation analysis, a strong orientation {110}<112> can be observed in {111} pole figure (Fig. 1c), indicating a brass texture in the surface-adjacent layer of the as-received materials.

Close TEM observation was performed to reveal the detailed microstructure of the as-received 7055-T77 aluminum alloy (Fig. 2a and b). High density of nanoscale grain interior precipitates (GIPs) within a large size range of 10–20 nm can be observed throughout the Al matrix, while the grain boundary precipitates (GBPs) show ellipsoidal shapes and seem much larger than GIPs. In the corresponding selected area diffraction pattern (SAED) as shown in Fig. 2c, extra sharp diffraction spots at $\{010\}_{Al}$ and $\{011\}_{Al}$ can be attributed to the coherent Al_3Zr particles with a $L1_2$ superlattice structure, whereas pairs of weak diffraction spots at 1/3 and 2/3 $\{022\}_{Al}$ are emblematic of the main strengthening phase η ($MgZn_2$) in the Al matrix [14].

3.2. The machining induced SSPD layer

3.2.1. Microstructural analysis

After high speed machining along the original rolling direction, a very thin but distinct white layer can be clearly observed adjacent to the topmost surface (see dashed line, Fig. 3a). Cross-sectional TEM observation of the white layer further revealed a 0.8–1.3 μm thick SSPD layer characterized by a hybrid grain structures (Fig. 3b and inset). To be specific, such SSPD layer can be divided into two sublayers, i.e. a 150–200 nm thick topmost surface layer composed of equiaxed nanograins and ultrafine grains (see red dashed line, also refer to Figs. 4a and 6a), and an 850–1000 nm thick subsurface layer composed of lamellar nanograins and ultrafine grains with a large range of aspect ratios (see layer between red and yellow dashed line, also refer to Figs. 4a and 6a). The grain size and shape, as well as the size, shape and density of GIPs and GBPs, show close relationships with the depth from the machined surface. The crystallographic feature of grains and the precipitation behavior of

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