Microstructures of Cutting Chips of SUS430 and SUS304 Steels, and NCF 750 and 6061-T6 Alloys

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Microstructures of chip specimens of high-strength materials produced by machining were examined by FE-SEM/EBSP method (an orientation imaging microscopy, OIM). In the ferritic SUS430 (16Cr) steel, the chip specimen with shear strain (γ) of ~7.5 was principally composed of equiaxed submicron grains which were for the most part surrounded by large angle grain boundaries (misorientation, θ≥15°). A similar microstructure was observed in the chip specimen with γ≈22 of the Inconel X-750 (NCF 750) nickel-base alloy. However, the chip specimen of the austenitic SUS304 (18Cr–8Ni) steel (γ≈14) and that of the 6061-T6 (aluminum) alloy (γ≈10) exhibited principally a deformed microstructure with elongated grains and subgrains separated by small angle (2°≤θ<5°) or medium angle grain boundaries (5°≤θ<15°), although equiaxed submicron grains were partly observed. The chip specimens exhibited very high hardness compared to the original materials except 6061-T6 alloy. The maximum hardness value (609 Hv) was observed in the chip specimen with γ≈22 of the Inconel X-750 alloy. Strong particles with equiaxed submicron grain structure, which can be easily produced by milling of cutting chips of commercial alloys, will be potential strengthening for metal matrix composites.

KEY WORDS: chip specimen; submicron grains; FE-SEM/EBSP method; machining.

1. Introduction

Nano-structured materials have recently drawn considerable attention, because these materials sometimes show very high strength without serious loss of ductility compared to the materials with deformed microstructure formed by usual processing.1−2 It is also known that nano-structured materials have large internal friction.3−4 Interesting properties of these materials are related to the largely increased density of lattice defects such as large angle grain boundaries and dislocations.3,5−8 Severe plastic deformation techniques such as equal channel angular pressing (ECAP),9−11 high pressure torsion (HPT)12 and accumulative roll-bonding (ARB)13 have been developed for production of nano-structured materials. However, application of these techniques is limited to relatively low-strength materials.

T. L. Brown et al.14 and S. Swaminathan et al.15 proposed a low-cost cutting process for production of nanostructured metals and alloys with very high hardness. A large shear strain (γ) up to ~20 can be imposed on chips by a single cutting process. This method is also applicable to the high-strength materials. Using the selected area electron diffraction patterns of thin films with a transmission electron microscope (TEM), S. Swaminathan et al.15 found that the change from elongated sub grain structure to nano-scale equiaxed grain structure occurs at a shear strain of ~13 in the chip specimens of the OFHC Cu. Based on the similar analysis using a TEM, M. Ravi Shankar et al.16 concluded qualitatively that there exists a small region containing high angle boundaries in the chip specimens of the 6061-T6 alloy deformed to a shear strain (γ) up to 3.2 or 5.2. However, the analysis by the FE-SEM/EBSP method (an orientation imaging microscopy, OIM)17,18 revealed that most of grain boundaries (~70%) are small angle grain boundaries (θ<15°), although equiaxed submicron grains were partly observed. The chip specimens exhibited very high hardness compared to the original materials except 6061-T6 alloy. The maximum hardness value (609 Hv) was observed in the chip specimen with γ≈22 of the Inconel X-750 alloy. Strong particles with equiaxed submicron grain structure, which can be easily produced by milling of cutting chips of commercial alloys, will be potential strengthening for metal matrix composites.

Severe plastic deformation process using machining can produce a large amount of nano-structured materials in a relatively short time without using special devices. Strong particles are easily produced by milling of chips, because the chips involve many cracks. These strong particles may constitute the strengthening phase in the metal matrix composites. This paper reports the basic research for developing the multi-functional metal matrix composites with high strength, high toughness and large internal friction. Chip specimens with shear strain (γ) up to ~22 were produced by machining of SUS430 and SUS304 steels, and Inconel X-750 (NCF 750) and 6061-T6 alloys. Microstructures of the chip specimens were examined by the FE-SEM/EBSP method. The hardness of chip specimen was also examined in these alloys. Then, possibility of production of nano-grained materials with high strength (high hardness) were discussed on the basis of the experimental results.
2. Experimental Procedure

2.1. Materials and Production of Chip Specimens

Table 1 lists the chemical composition of alloys used in this study. Ferritic SUS340 (16Cr) steel with body-centered cubic (bcc) structure, austenitic SUS304 (18Cr–8Ni) steel and 6061-T6 (aluminum-base) alloy with face-centered cubic (fcc) structure were received in the form of round bars of 30 mm diameter. Hot-forged bars of 20 mm diameter of the Inconel X-750 (nickel-base) alloy with fcc structure were solution-heated for 7.2 ks (2 h) at 1 423 K (1 150°C) and then water-quenched. The grain size of original material was 13 μm for SUS340 steel, 40 μm for SUS304 steel, 80 μm for 6061-T6 alloy and 108 μm for Inconel X-750 alloy.

The chip specimens of the steels were produced by dry cutting with carbon steel cutting tools with a rake angle (α) of 4.8° using a lathe. Those of the 6061-T6 alloy and the Inconel X-750 alloy were produced by machining with carbon steel tools or cemented carbide (WC) tools with a rake angle of –30° to 20° using a lathe with cutting fluid. Table 2 reports the cutting conditions and geometry of resulting chip specimens in machining. Relatively low cutting speed (Vc) of ~0.24 to 0.36 m/s was chosen to avoid excessive heating of chip specimens during machining. The cutting depth (a0) and feed (b0) in machining, and the thickness (a) and width (b) of the chip specimens are also listed in the table. Two dimensional cutting was adopted for producing chip specimens in this study. The approximate shear strain (γ) in the central part of the chip specimens was calculated by the following equation.20)

\[ \gamma = \tan(\Phi - \alpha) \] \[ = \cot(\Phi) + \tan(\Phi - \alpha) \] .............. (1)

where Φ is the shear plane angle, and

\[ \tan(\Phi - \alpha) = \left( \frac{a_0}{a} \right) \cos \theta \left[ 1 - \left( \frac{a_0}{a} \right) \sin \theta \right] \] .............. (2)

Swaminathan et al.15) confirmed that for two-dimensional cutting the shear strain calculated by the above equation was close to the value experimentally obtained by the high-speed image analysis on the chip of OFHC copper. A rough estimation of shear strain was also made using the above equations for a chip specimen of the Inconel X-750 alloy (γ ≈ 3) produced under the non two-dimensional cutting condition in the previous study.19)

In order to produce chip specimens with the same microstructure by machining, it is necessary to control the cutting conditions with or without usage of cutting fluid. The works should be machined using cutting tools of the same material, and the rake angle, the cutting depth, the feed and the cutting speed should be kept constant during cutting process. The geometry of cross section in the chip should be maintained during machining, because wear of cutting tools may affect the geometry of the chip specimen. In this study, machining was repeated several times to produce continuous chips of at least 20 mm in length.

2.2. Analysis of Microstructures and Measurement of Hardness

Misorientation (rotation angle, θ°) between neighboring grains in the chip specimens was examined by the electron backscatter diffraction pattern (EBSP) method using a field emission scanning electron microscope (FE-SEM) (or simply, FE-SEM/EBSP method), which is an orientation imaging microscopy (OIM).17,18) Each chip specimen was thinned by ion milling and the representative microstructure was examined by the FE-SEM/EBSP method. The variation of microstructure in the thickness direction of the chip was also examined by this method on the chip specimen with γ ≈ 7.5 of the SUS430 steel produced by separate cutting process under the same cutting condition. Two chip specimens with γ ≈ 22 of the Inconel X-750 alloy were examined to confirm that the same microstructure was observed in the chips produced by separate cutting process under the same cutting condition.19)}
condition. The analyzed area was in the range from 10 μm × 10 μm to 100 μm × 100 μm. Geometry and size distribution of more than 150 grains were also examined in the chip specimen using the inverse pole figure map (the color-coded map) obtained by the FE-SEM/EBSP method. In this study, boundaries between two domains, which have the misorientation (θ) equal to or larger than 2°, are defined as “grain boundaries”. According to the misorientation (θ), grain boundaries are conventionally classified into three categories, namely, small angle grain boundaries (2°≤θ<5°), medium angle boundaries (5°≤θ<15°) and large angle grain boundaries (θ≥15°). Fractions of large, medium, and small angle grain boundaries were examined in chip specimens. Microstructures of original materials and chip specimens were observed using an optical microscope or a scanning electron microscope. The specimens for metallographic observation were prepared by embedding chip specimens in resin mold. The specimens were mechanically polished using diamond paste (the grain size is 3 to 0.25 μm) and were electrolytically etched using 10% chromium acid – water solution. The hardness of original materials and chip specimens was measured using a Micro Vickers Hardness Tester at the load of 0.98 N. The hardness was obtained as an averaged value over eight out of ten indentations by excluding the maximum and minimum values for each measurement.

3. Results

3.1. Microstructures of Chip Specimens

3.1.1. Ferritic SUS430 (16Cr) Steel
The analysis by the FE-SEM/EBSP method revealed that the chip specimen with shear strain (γ) of ~7.5 was principally composed of equiaxed submicron grains in the ferritic SUS430 steel. Figure 1 shows the image quality map, inverse pole figure map showing the crystal orientations parallel to ND (normal direction to specimen surface), boundary misorientation map and fraction of grain boundaries with different misorientations (θ) in the chip specimen with γ = 7.5 of the SUS430 steel. The analyzed area is 20 μm × 20 μm. The length direction of the chip specimen (the direction of chip formation) is vertical. Grain boundaries exhibit dark contrast in the image quality map (Fig. 1(a)). The chip specimen is principally composed of equiaxed ultra-fine grains which are smaller than ~1 μm in size (Fig. 1(a)). Some black particles are considered to be precipitates of Cr77C6 carbide. There is a large misorientation (θ) between neighboring grains in this chip specimen (the inverse pole figure map, Fig. 1(b)). The boundary misorientation map shows the spatial distribution of small angle grain boundaries (2°≤θ<5°) (indicated by green lines), medium angle grain boundaries (5°≤θ<15°) (shown by red lines) and large angle grain boundaries (θ≥15°) (indicated by blue lines) in the specimen (Fig. 1(c)). Equiaxed submicron grains are for the most part separated by large angle grain boundaries, although some submicron grains may be Cr77C6 precipitates. Figure 1(d) shows the fraction of grain boundaries with different misorientations (θ) in the same chip specimen. The fraction of large angle grain boundaries (θ≥15°) is ~59% and that of medium angle grain boundaries (5°≤θ<15°) is ~28%, while the fraction of small angle grain boundaries (2°≤θ<5°) is ~13%. Uniform distribution of submicron grains was also confirmed in the wider analyzed area (100 μm × 100 μm) of the same chip specimen. Figure 2 shows the geometry and size distribution of grains in the chip specimen with γ = 7.5 of the SUS430 steel. The average aspect ratio (the ratio of length to width) of grains is ~1.28 and the average length of the grains is ~0.502 μm (Fig. 2(a)). More than 60% of the grains are smaller than 0.5 μm in length (Fig. 2(b)). Thus, the chip specimen with γ = 7.5 of SUS430 steel is principally composed of uniformly distributed equiaxed submicron grains which are for the most part separated by large angle grain boundaries (θ≥15°).

Figure 3 shows the change in the microstructure (image quality map) in the thickness direction of the chip specimen with γ = 7.5 of the SUS430 steel. Very small grains are visible in the secondary deformation zone with the larger plastic strain near the surface contacting with cutting tool (Fig. 3(a)). The fraction of large angle grain boundaries (θ≥15°) was ~88% and that of medium angle grain boundaries (5°≤θ<15°) was ~10%, while the fraction of small angle grain boundaries (2°≤θ<5°) was only ~2%. According to microstructural observation using an optical microscope, the width of this zone was ~50 μm and only ~7% of the thickness of the chip. Figure 3(b) represents the typical microstructure observed in the central part of the chip specimen. The microstructure consists of equiaxed submicron grains which are similar to those observed in another chip specimen (Fig. 1). The fraction of large angle grain boundaries was ~63% and that of medium angle grain boundaries was ~26%, while the fraction of small angle grain boundaries was ~11%. Similar microstructure is observed in the region near free surface where many cracks were found, although a little larger grains are partly involved (Fig. 3(c)). The fraction of large angle grain boundaries was ~38% and comparable to that of medium angle grain boundaries, ~43%. The fraction of small angle grain boundaries was ~19%. Thus, equiaxed submicron grain structure shown in Figs. 1 and 3(b) is considered to occupy ~90% in volume of the chip specimen with γ = 7.5 of the SUS430 steel.

The average length of submicron grains was almost unchanged with increasing shear strain up to ~15, while the average aspect ratio of the grains increased to ~2.25 owing to the decrease of the width. However, submicron grains were surrounded for the most part by large angle grain boundaries as in the chip specimen with γ = 7.5.

3.1.2. Austenitic SUS304 (18Cr–8Ni) Steel

Figure 4 shows the inverse pole figure map showing the crystal orientations parallel to ND (normal direction to specimen surface), boundary misorientation map and fraction of grain boundaries with different misorientations (θ) in the chip specimen with γ = 14 of the SUS304 (18Cr–8Ni) steel. The analyzed area is 20 μm × 20 μm. The length direction of the chip specimen (the direction of chip formation) is vertical. This specimen exhibits a typical deformation structure with many elongated grains which occupy most of the analyzed area (Fig. 4(a)), although equiaxed submicron grains with the size smaller than ~1 μm are partly observed. In the boundary misorientation map (Fig. 4(b)), elongated grains surrounded by large angle (θ≥15°) or medium angle (5°≤θ<15°) grain boundaries are observed in a wide area, although equiaxed submicron grains separated by large
angle grain boundaries ($\theta \geq 15^\circ$) are partly observed. It is expected that severe plastic deformation during machining induces the phase transformation of austenite to martensite in the SUS304 steel. However, the effect of the phase transformation is negligible in the grain refinement of this chip specimen, because the area fraction of bcc phase (martensite) was only ~0.003. The orientation of black areas in Fig. 4(a) is not identified by the FE-SEM/EBSP method because of large local distortion of the specimen. These areas were not included in the estimation of fractions of grain boundaries with different misorientations ($\theta$).

Fig. 4. Inverse pole figure map showing the crystal orientations parallel to ND (normal direction to specimen surface), boundary misorientation map and fraction of grain boundaries with different misorientations ($\theta$) in the chip specimen with $\gamma \approx 14$ of the SUS304 steel. (a) inverse pole figure map (color coded map), (b) boundary misorientation map, (c) fraction of grain boundaries with different misorientations ($\theta$), ($\gamma$: shear strain of chip specimen).
um angle grain boundaries ($5^\circ \leq \theta < 15^\circ$) is ~35%, while that of large angle grain boundaries ($\theta \geq 15^\circ$) is only ~28% (Fig. 4(c)). Thus, the chip specimen with $\gamma = 14$ of the SUS304 steel has principally a deformed microstructure with subgrains surrounded by small angle or medium angle grain boundaries. According to the observation using an optical microscope, the thickness of secondary deformation zone was ~30 $\mu$m and was only ~5% of the chip thickness in the chip specimen with $\gamma = 14$ of SUS304 steel. Thus, most of the chip specimen (~95% in volume) principally consists of a deformation structure with elongated grains (Fig. 4). Similar result was obtained by the FE-SEM/EBSP method in the chip specimen with $\gamma = 14$ of the austenitic SUS316 steel.

3.1.3. Inconel X-750 Alloy

In Inconel X-750 (Ni-base) alloy with fcc structure, the chip specimens with shear strain ($\gamma$) of ~3 to ~5 exhibited a deformed microstructure with elongated grains and subgrains in addition to equiaxed submicron grains. Figure 5 summarizes the result of crystallographic analysis on the chip specimens with $\gamma \approx 10$ and $\gamma \approx 22$ of the Inconel X-750 alloy. The analyzed area is 20 $\mu$m $\times$ 20 $\mu$m (Fig. 5(a)). The length direction of the chip specimen is vertical also in the figure. Many equiaxed submicron grains can be observed between elongated grains in this chip specimen (Fig. 5(a)). Equiaxed submicron grains as well as elongated grains are surrounded by large angle grain boundaries ($\theta \geq 15^\circ$) or medium angle grain boundaries ($5^\circ \leq \theta < 15^\circ$) (Fig. 5(b)). The fraction of large angle grain boundaries ($\theta \geq 15^\circ$) is ~55% and that of medium grain boundaries ($5^\circ \leq \theta < 15^\circ$) is ~24%, while the fraction of small angle grain boundaries ($2^\circ \leq \theta < 5^\circ$) is ~21% (Fig. 5(c)). The amount of equiaxed submicron grains increases and the submicron grains become uniformly distributed with increasing shear strain of chip specimens. Figure 5(d) shows the inverse pole figure maps of the chip specimens with $\gamma = 22$. This specimen shows almost uniform distribution of equiaxed submicron grains similar to the submicron grain structure in the chip specimen with $\gamma = 7.5$ of the SUS430 steel (Fig. 1), although a few elongated grains (~1 $\mu$m) can also be seen. Such a microstructure was observed in another chip specimen with $\gamma = 22$ of the Inconel X-750 alloy produced by separate cutting process under the same cutting condition. According to microscopic observation using an optical microscope, the thickness of secondary deformation zone was ~30 $\mu$m and was smaller than ~6% of the chip thickness in the chip specimens of the Inconel X-750 alloy. Therefore, such an equiaxed submicron grain structure may occupy more than ~90% in volume of the chip specimen with $\gamma = 22$. Unfortunately, the fractions of grain boundaries with different misorientations ($\theta$) could not be obtained by the present
analysis in this chip specimen because of very large distortion of the specimen. Figure 6 shows the relationship between the fraction of grain boundaries with different misorientations (θ) and the shear strain of chip specimen in the Inconel X-750 alloy. The fraction of large angle grain boundaries (θ≥15°) is ~15% in the chip specimen with γ = 3 and increases with increasing shear strain to ~55% (γ = 10), while both fractions of small angle grain boundaries and of medium angle grain boundaries decrease with increasing shear strain. Swaminathan et al.15) reported that a switch-over from elongated sub grain to nano-scale equiaxed grain structures occurred at a shear strain of ~13 in the chip specimens of OFHC Cu. However, the amount of equiaxed submicron grains increases and a deformed microstructure with elongated grains and sub grains gradually changes to almost uniformly distributed, equiaxed submicron grain structure with increasing shear strain in the Inconel X-750 alloy. The present results are different from those reported in OFHC Cu.15)

3.1.4. 6061-T6 Alloy

According to the selected area electron diffraction patterns of thin films of the 6061-T6 alloy using a transmission electron microscope, M. Ravi Shankar et al.16) concluded qualitatively that there exists a small region containing high angle boundaries in the chip specimens deformed to a shear strain up to 3.2 or 5.2. However, the results of crystallographic analysis revealed that the chip specimen with γ = 4 of 6061-T6 alloy showed a deformed microstructure with elongated grains of a few μm to a few tens μm in length (~1 μm to 10 μm in width) surrounded not only by large angle (θ≥15°) grain boundaries but also small angle (2°≤θ<5°) and medium angle (5°≤θ<15°) grain boundaries. Figure 7 shows the inverse pole figure map showing the crystal orientations parallel to ND (normal direction to specimen surface), boundary misorientation map and fraction of grain boundaries with different misorientations (θ) in the chip specimen with γ = 10 of the 6061-T6 alloy. The chip specimen exhibits principally a deformed microstructure with elongated grains and sub grains with various sizes, while the aggregates of equiaxed submicron grains are partly observed (Fig. 7(a)). These grains are mostly separated by small angle grain boundaries (2°≤θ<5°) and medium angle grain boundaries (5°≤θ<15°) (Fig. 7(b)). The fraction of large angle grain boundaries is only ~24%, while the fraction of small angle grain boundaries (2°≤θ<5°) is ~51% and that of medium angle grain boundaries (5°≤θ<15°) is ~25% (Fig. 7(c)). Microscopic observation using an optical microscope revealed that the thickness of secondary deformation zone was ~50 μm and was ~10% of the chip thickness in the chip specimen with γ = 10 of the 6061-T6 alloy. A deformation structure with elongated grains (Fig. 7) that occupies ~90% in volume represents the microstructure in this chip specimen. Similar deformed microstructure was detected by the FE-SEM/EBSP method in the chip specimen with γ = 7 of a pure aluminum. Considering the results of crystallographic analysis on the chip specimens of the Inconel X-750 alloy, much larger shear strain is required to obtain the chip specimen principally composed of equiaxed submicron grains in the 6061-T6 alloy. It seems also necessary for production of nano structured materials to accomplish a uniform distribution of large angle grain boundaries.

3.2. Hardness of Chip Specimens

Table 3 summarizes the hardness of the chip specimens and the original materials. The hardness of the chip specimens with γ = 7.5 is 417 Hv and very high compared to that of the original material (161 Hv for the specimen with γ = 0) in the SUS430 steel. The hardness of the chip specimen does not increase so much even if the shear strain is doubled (443 Hv for the chip specimen with γ = 15). Similar results are obtained on the chip specimens of Inconel X-750 alloy. The maximum hardness, 609 Hv, is that about three times as much as the hardness of the original material (207 Hv for the specimen with γ = 7.5), is attained in the chip specimen with γ = 22 of the Inconel X-750 alloy in this study. The chip specimen with γ = 14 of the SUS304 steel also shows a high hardness value (448 Hv) compared to the original material (197 Hv for the specimen with γ = 0). Very high hardness of these chip specimens may be attributed to the generation of equiaxed submicron grains and the introduction of lattice defects such as dislocations during machining. However, the hardness of chip specimen with γ = 10, 137 Hv, is not so high compared to that of the original material (112 Hv for the specimen with γ = 0).

The chip specimens of the alloys except 6061-T6 alloy exhibited very high hardness compared to their original materials. Chips cannot be used engineering materials in their original form, because they generally involve many cracks introduced during machining, which are suppressed by other method such as ECAP, HPT and ARB. However, as indicated by the hardness values of chip specimens, each segment separated by cracks may have high strength. Strong particles with equiaxed submicron grain structure can be easily produced from cutting chips of commercial alloys using a high-energy ball mill. These particles will constitute the strengthening phase of metal matrix composites when incorporated in ductile metals.

4. Discussion

The microstructure of chip specimens which were produced by machining of various alloys may be affected by

| Materials Properties | SUS430 steel | SUS304 steel | 6061-T6 alloy | Inconel X-750 alloy |
|----------------------|-------------|--------------|---------------|-------------------|
| Hardness (Hv)        | 161 (γ = 0) | 197 (γ = 0)  | 112 (γ = 0)   | 207 (γ = 0)       |
| (shear strain, γ)    | 417 (γ = 7.5) | 448 (γ = 14) | 137 (γ = 10)  | 533 (γ = 10)      |
| 443 (γ = 15)         | 609 (γ = 22) |

* Vickers hardness number (kgf/mm²) (load: 0.98 N); original material is indicated by γ = 0.
crystal structure, shear strain and stacking fault energy. Figure 8 summarizes the results of crystallographic analysis of chip specimens with different shear strains of some alloys by the FE-SEM/EBSP method. Open symbols show the chip specimen mostly composed of submicron grains, and closed symbols indicate the chip specimen having principally deformed microstructure with elongated grains and sub grains. The stacking fault energy of the SUS304 steel used in this study could not be calculated using Pickering’s equation, because the nitrogen content is unknown. Therefore, the approximate value of ~0.011 J/m² was estimated from the experimental study on the Fe–Cr–Ni alloys by Bredris. The stacking fault energy of the SUS430 steel is considered to be similar to the value for pure iron and Fe–Si alloy with bcc structure of 0.20 J/m², although the effect of Cr content on ferrite is not known. The stacking fault energy of Cu is 0.050 J/m² and is lower than that of pure aluminum, 0.20 J/m² because of its low contents of alloying elements. The stacking fault energy, 0.09 J/m², of the Inconel X-750 alloy in the solution-treated condition was cited from Mulford’s paper. As shown in Fig. 1, the chip specimen with the shear strain (γ) of ~7.5 was principally composed of equiaxed submicron grains surrounded by large angle grain boundaries (misorientation, θ ≥ 15°) in the ferritic SUS430 (16Cr) steel with bcc structure. A similar submicron grain structure was observed in the chip specimen with much larger shear strain (γ = 22) of the Inconel X-750 (Ni–Cr) alloy with the lower stacking fault energy (Fig. 5). However, a deformed microstructure with sub grains prevailed in the chip specimens with shear strains smaller than ~14 in the chip specimens of the 6061-T6 (Al) alloy (Fig. 7), Inconel X-750 alloy (Fig. 5) and austenitic SUS304 (18Cr–8Ni) steel (Fig. 4) with fcc structure, irrespective of the values of stacking fault energy.

The number of slip systems in metals and alloys with bcc structure is 48, and is larger than that in the materials with fcc structure (12). Frequent cross-slip of dislocations in more slip systems may increase the opportunity of interactions between dislocations in the SUS430 steel with bcc structure, which may lead to the enhanced tangle of many dislocations in different slip systems introduced by machining. About ECAP for production of ultra-fine grained microstructure in high-purity aluminum, the route B_c seems to be favorable for operating many slip systems to produce high misorientation boundaries as a result of accumulation and dynamic recovery of dislocations during ECAP. The number of slip systems may be restricted in comparison with ECAP with route B_c, when materials are subjected to a simple shear deformation process in the chip formation during machining. Accumulation of slip dislocations may occur more easily in metals and alloys with bcc structure, which have more slip systems than those with face-centered cubic (fcc) or close-packed hexagonal (cph) structure. This is why the chip specimen principally composed of equiaxed submicron grains was produced at relatively small shear strain (~7.5) by dry cutting of the SUS430 steel. In the Inconel X-750 alloy, the fraction of large angle grain boundaries (misorientation, θ ≥ 15°) increased with increasing shear strain of chip specimens (Fig. 5). The amount of equiaxed submicron grains increased and a deformed microstructure principally composed of elongated grains and sub grains gradually changed to a uniformly distributed, equiaxed submicron grain structure with increasing shear strain (γ) up to ~22 (Fig. 5). Swaminathan et al. reported that in an OFHC Cu a switch-over from elongated sub grain to nano-scale equiaxed grain structures with a significant fraction of high-angle grain boundaries was a consequence of the onset of dynamic recrystallization at a strain of ~13. The stacking fault energy of Cu is 0.050 J/m² and is lower than that of the Inconel X-750 alloy (0.09 J/m²).

McQueen reported that the degree of dynamic recovery observed in metals at a certain value of strain rate and homologous temperature depends on the relative abilities of dislocations to leave the slip planes. This has been found to be limited in metals of low stacking fault energy because the dislocations are extended on the slip plane and require thermal activation to constrict in order to cross-slip or climb. Therefore, equiaxed submicron grains may be formed by dynamic recovery in the ferritic SUS430 steel and 6061-T6 (aluminum-base) alloy with relatively high stacking fault energy.

Temperature measurements of chips were not made in this study. However, the maximum temperature of chips during machining can be deduced to some extent from the maximum tool temperature in the published data. According to the literature, the contact length between chip and cutting tool during machining is usually in the range from ~0.2 mm to ~2 mm. Therefore, chips may be heated to a high temperature in a very short time (shorter than ~0.2 s). For cutting depth of 0.2 mm with cemented carbide tools, the averaged tool temperature is ~833 K for 18Cr–8Ni steel and ~873 K for Inconel X-750 alloy (~0.15 mm with high speed steel cutting tools with a rake angle (~α) of 6° and the cutting speed of 0.43 m/s). The maximum temperature of chip specimen may be close to 833 K in the SUS304 steels and the SUS430 steels in the dry cutting process in this study, although the cutting depth is smaller (0.05 to 0.10 mm in this study). The averaged tool temperature is ~873 K for Inconel X-750 alloy (with a rake angle (~α) of 0° and the cutting speed of 0.24 m/s) when the cutting depth is 0.2 mm. For cutting depth of 0.15 mm with high speed steel cutting tools with a rake angle (~α) of 6° and the cutting speed of 0.43 m/s, the averaged tool temperature is ~413 K for pure aluminum. In addition to a small cutting depth (0.05 mm), a cutting fluid was used in the machining of the Inconel X-750 alloy and the
6061-T6 alloy in this study. Heating of chip specimens to tool temperature may occur in a shorter time in these alloys.

The melting point (T_m) is in the range from 1 673 K (1 400°C) to 1 728 K (1 455°C) for SUS304 (18Cr–8Ni) steel and ~1 783 K (~1 510°C) for SUS430 (16Cr) steel. The melting point of the Inconel X-750 alloy is in the range from 1 666 K (1 393°C) to 1 700 K (1 427°C). The melting point of the 6061-T6 alloy may be close to that of pure aluminum 933 K (660°C). The maximum chip temperature seems to be in the range from ~0.4 T_m to ~0.5 T_m in these alloys. Considering the temperature increase during machining, machining process essentially belongs to hot deformation. Thus, in the SUS430 steel and the 6061-T6 alloy with relatively high stacking fault energy, dynamic recovery is expected to occur in chips which contact with tools heated at high temperatures during machining, although the heating time for chips may be very short (shorter than ~0.2 s). The chip specimen with γ = 7.5 of the SUS430 steel (bcc) that has equiaxed submicron grain structure is considered to have almost the same stacking fault energy (~0.20 J/m^2) as that of SUS304 (16Cr) steel.

The melting point of the Inconel X-750 alloy (fcc) (~0.47 T_m for SUS430 steel and ~0.44 T_m for 6061-T6 alloy) that has principally deformed microstructure. This suggests that crystal structure which is related to the number of slip systems exerts a large influence on the evolution of equiaxed submicron grain structure during cutting. Swaminathan et al. reported that equiaxed submicron grain structure in an OFHC Cu (stacking fault energy is 0.050 J/m^2) was caused by dynamic recrystallization. However, dynamic recovery may also lead to the formation of equiaxed submicron grains even in the Inconel X-750 (nickel-base) alloy and austenitic SUS304 steel with relatively low stacking fault energy, because migration of atoms in a large scale by grain-boundary diffusion or short-circuit diffusion through dislocation cores may be unrealistic for nucleation of equiaxed submicron grains in a very short period of cutting.

Second-phase particles may also affect the rearrangement and annihilation of dislocations introduced during severe plastic deformation. As described in the chapter 2, the SUS430 steel involves Cr_23C_6 carbide particles with the average particle spacing of ~2.1 μm and the average particle diameter of ~0.23 μm. However, the effect of Cr_23C_6 carbide particles on the generation of equiaxed submicron grains may be small in this steel, because the average particle spacing is much larger than the average length of ultra-fine equiaxed grains (~0.50 μm) and the volume fraction of the carbide particles is very small (smaller than 0.001).

5. Conclusions

The microstructure and hardness of chip specimens produced by machining of high-strength materials were examined in this study. The results obtained are summarized as follows.

1. The chip specimen with γ = 7.5 of the ferritic SUS430 (16Cr) steel with bcc structure was principally composed of equiaxed submicron grains which were for the most part separated by large angle grain boundaries (misorientation, θ ≥ 215°). However, the chip specimen with shear strain (γ) = 14 of the austenitic SUS304 (18Cr–8Ni) steel with fcc structure had a deformed microstructure with elongated grains and sub grains, while equiaxed submicron grains were also observed. A similar deformed microstructure was observed in chip specimens with shear strain up to ~10 of the aluminum-base (6061-T6) alloy (fcc) with relatively high stacking fault energy.

2. For chip specimens of the nickel-base (Inconel X-750) alloy (fcc), the fraction of large angle grain boundaries (θ ≥ 15°) increased from ~15% to 56% with increasing shear strain (γ) in the range from ~3 to ~10. The change from deformed microstructure to equiaxed submicron grain structure occurred gradually with increasing shear strain. The chip specimen with γ = 22 showed almost uniform distribution of equiaxed submicron grains, although very small fraction of elongated grains (~1 μm) existed.

3. The hardness of the chip specimens is generally very high compared to the original material except 6061-T6 alloy. The maximum hardness, 609 HV, that is about three times as much as the hardness of the original material (207 HV), was attained in the chip specimen with γ = 22 of the Inconel X-750 alloy in this study. Strong particles with equiaxed submicron grain structure can be easily produced by milling of cutting chips of commercial alloys. These particles will be potential strengtheners for metal matrix composites when incorporated in ductile metals.

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