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MECHANICAL PROPERTIES AND TEXTURES OF PARTICULATE-REINFORCED ALUMINUM ALLOY MATRIX COMPOSITE UNDER HOT- AND COLD-ROLLING CONDITIONS

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A study has been made on the mechanical properties of an aluminum alloy matrix (Al–3.0 wt% Cu–1.5 wt% Mg–0.4 wt% Mn) composites reinforced with a volume fraction of 15% silicon carbide under hot- and cold-rolling conditions. The preferred crystallite orientation distribution functions (ODFs) of these rolled sheets were measured. The tensile test results showed that the ultimate tensile strength and plasticity of the hot-rolled composite sheet are better than those of the cold-rolled one. However, the cold-rolled sheet specimen exhibits much higher 0.2% offset yield strength than that in the case of hot rolling. The cold-rolling texture of this sheet composite is obtained from the development of hot-rolled texture only by a little rotation about the related axes. It consists of random texture and three weak components, {0 0 1}⟨1 1 0⟩, {1 1 0}⟨1 1 2⟩ and {3 3 14}⟨7 7 3⟩, while the hot rolling texture of the metal-matrix composite (MMC) sheet is almost random under the rolling reduction employed. The preferred grain orientation has effect on the yield strength and no much influence on the ultimate tensile strength of the cold rolled sheet. The decrease in the ultimate tensile strength of the cold-rolled specimen is mainly attributed to the micro-damages in the microstructure produced during cold rolling.

Keywords: MMCs; ODF; Mechanical properties; Texture; Powder metallurgy

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1. INTRODUCTION

Discontinuously reinforced metal-matrix composites (MMCs), especially the particulate-reinforced aluminum-matrix composites, exhibit an improved strength and stiffness. The potential advantages make them suitable for wide applications in aerospace and automotive industries etc. Much attention has been paid to this material on its processing, mechanical properties, fracture behaviors etc (e.g. Davidson, 1991; Singh and Lewandowski, 1993; Doel *et al.*, 1993; Wang *et al.*, 1995; Doel and Bowen, 1996).

There are several routes for producing this kind of material, which can be classified into solid route and molten route according to the ways by which the reinforcement may be introduced. The solid route, such as powder metallurgy (PM) method, offers the most flexibility in blending the powder and has no limitations in the alloy chemistry, volume fraction, size and particle type of the reinforcement etc. So, the PM technique is now accepted as the popular manufacturing route for this kind of materials. One of the prime advantages of the particulate MMCs is that the billets of the composites can be mechanically processed using the conventional technologies developed for monolithic alloys. Although it has improved specific properties, one fatal weakness of this kind of materials is their limited elongations, usually no more than 3% when the content of the reinforcement is added up to 15% as reported (e.g. Davidson, 1991; Lloyd, 1994; Beck *et al.*, 1994; Felli *et al.*, 1997). As important structural materials suitable for advanced engineering, under many circumstances the MMCs are applied in the form of plate or sheets. However, little work was reported on the mechanical properties of the rolled state.

Up till now only limited research has appeared concerning the textures of MMCs under different processing conditions. Humphreys *et al.* (1990) studied the effects of 7 μm SiC particles on the rolling texture of aluminum by the pole figure method and concluded that the addition of 10 vol.% SiC results in a considerable reduction in intensity of the texture. Kaibyshev and Kazyhanov (1997) investigated the grain structure and texture evolution during the different stages of superplastic deformation on the PM2014-20% Al_2O_3 MMC produced via powder technology method.

This paper reports one kind of aluminum alloy reinforced by SiC particles, whose sheet in hot-rolled state shows an elevated elongation.

The crystallite orientation distribution of such an MMC was fully investigated by orientation distribution function (ODF) analysis. Since the exact preferred distribution of the grains within these materials is even not clear and need to be understood in order to elucidate the deformation mechanism of MMCs.

2. EXPERIMENTAL AND RESULTS

2.1. Materials Preparation

We used the common PM technique to fabricate the MMCs. The chemical composition of the aluminum alloy powder employed is Al–3.0 wt% Cu–1.5 wt% Mg–0.4 wt% Mn and the particulate reinforcement used in this work is β-SiC with an average size of $\sim$3.5 μm. The volume fraction of the reinforcement is 0.15. After mechanical blending of the mixed powder for over 12 h, the preform of the MMCs was degassed and then hot pressed at 873 K for about 1 h with a vacuum of 10^{-3} bar. The ingot was cooled slowly together with the furnace. The flat sample was obtained after hot-extrusion at 740 K with an extrusion ratio of about 16 to 1. The extruded flat composite was then repeatedly hot rolled on a two-roller mill with multiple pass and reheats between passes. The rolling temperature is about 750 K and the final thickness is $\sim$2.25 mm. Following these, the sample was cold rolled to the required thickness. The total cold-rolling reduction is about 25.3%, and only a very small rolling reduction could be given for each pass due to the low plasticity of the composite.

2.2. Mechanical Properties

The tensile tests were performed at room temperature in Shimadzu DCS-275 Auto Graph electronic tensile machine. The gauge dimension is $16 \times 5 \times 1.68$ mm and $22 \times 5 \times 2.25$ mm for the cold- and hot-rolled composite sheets, respectively. The nominal strain rate applied in the tensile tests of the cold- and hot-rolled specimens is $2.0 \times 10^{-4}\,s^{-1}$. The 0.2% offset yield strength σ_y, the ultimate tensile strength σ_u and the strain to failure δ_f were calculated from the engineering stress vs. engineering strain plots. Each value listed below is an average of two readings. Table I shows the results of the tensile test.

TABLE I The mechanical properties of the hot- and cold-rolled MMCs sheets

Sample status	*Yield strength,* σ_y (MPa)	*Ultimate strength,* σ_u (MPa)	*Elongation,* δ_f (%)
Hot-rolled	300.5	455.5	7.1
Cold-rolled	366.0	391.5	3.2

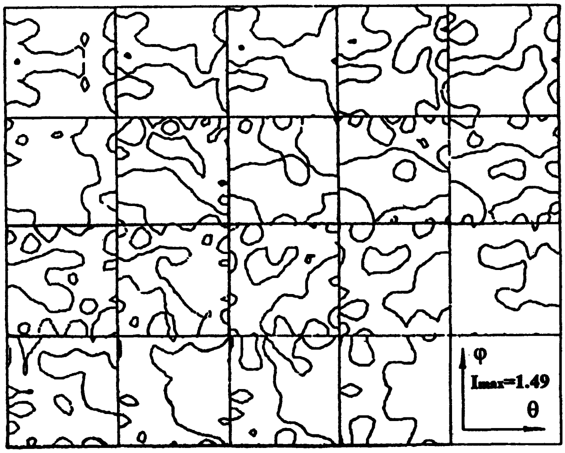
From Table I, we can see that the elongation to failure and the ultimate tensile strength for the hot-rolled sample is much higher than that for the cold-rolled one and also much higher than those of other kinds of MMCs (e.g., see Lloyd, 1994). However, the 0.2% offset yield strength of the cold-rolled sheet was greatly improved as compared with that of the hot-rolled specimen.

Combining the results listed in the Table I, we may deduce that with the same matrix composition the rolling pre-strain plays a significant role in controlling the tensile properties of the present composites.

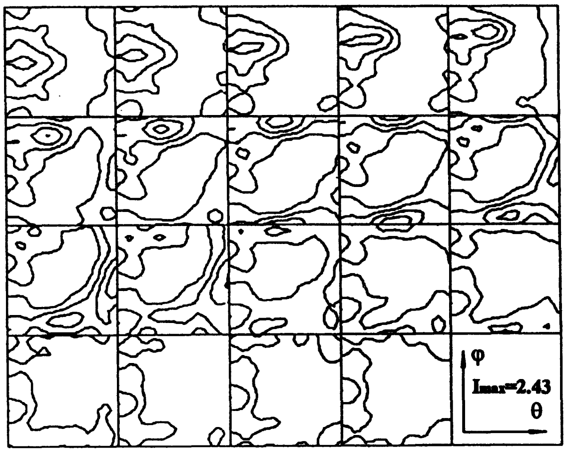
2.3. Hot- and Cold-rolling Textures

As we know, the grains in metals or alloys have a tendency to rotate and form certain microstructures with preferred grain orientations under rolling conditions, so do the MMC sheets to some extent. The textures of the MMC sheets were described by ODF analysis. For the aluminum matrix composite sheets used in this study, we measured three pole figures {1 1 1}, {2 0 0}, {2 2 0} as usual on RIGAKU (Japan) D/MAX-3A X-ray diffractometer with CuK_α radiation by reflection method. The maximum polar angle is $\chi_f = 70°$. The ODFs were generated from these pole figures by the series expansion method of Roe (1965), in which the coefficients W_{lmn} were computed by two-step method (Liang *et al.*, 1981). In this work, the series was expanded up to $L_{max} = 16$ and the calculating results are presented in constant ψ sections in the Euler space. Figure 1(a) and (b) shows the constant ψ sections of the ODF for the hot-rolled and cold-rolled composite sheets, respectively.

We can observe from Fig. 1 that the textures developed during hot- and cold-rolling are not very sharp, especially that in Fig. 1(a) for hot-rolled sheet is nearly random. For such light rolling reduction, the textures were not fully developed.



(a)



(b)

FIGURE 1 Textures of the hot rolled and cold rolled MMCs sheets; Constant ψ sections of the ODF: (a) hot-rolled sheet and (b) cold-rolled sheet; (level intensities: $1.0, 1.4, 1.8, \ldots, \times$ random).

3. DISCUSSIONS

The difference between particulate-reinforced aluminum composites and the monolithic aluminum alloys is that the volume fraction of large nondeformable particles (0.1–0.2) contained in the former is significantly greater than that in the conventional alloys (0–0.02). For the composites in which the particles have sizes of at least a few microns, the dislocations cannot cut through the nondeformable particles during deformation. They can only pass the particles by Orowan mechanism and leave Orowan loops around the particles. This is one kind of strengthening mechanism existing in the MMC, but it is not vigorous (Nardone and Prewo, 1986). It can only lead to the minor hardening of the composite during cold rolling.

During cold rolling, due to the incompatibility between the deforming matrix and the nondeformable particles, there will be a lot of dislocations generated. Besides, the difference in the coefficients of thermal expansion between the SiC_p and the matrix will result in considerable generation of higher dislocation density within the matrix (Arsenault and Shi, 1986). These are the most important strengthening mechanisms for the MMC.

At the higher temperature of hot rolling, the softer matrix and the particulate can accommodate the plastic deformation, there will be no recrystallization process and only recovery exists in the microstructures. However, the situation in cold rolling is not the same as that for the hot rolling. The direct effect of the strengthening of the matrix during cold rolling in MMC sheet is to increase the 0.2% offset yield strength. From Table I, we may observe that the 0.2% offset yield strength of the cold-rolled MMC sheet is enhanced by 20 percent as compared with that of hot-rolled MMC sheet and reaches 366 MPa. The increase in yield strength for engineering structural materials is significant in that they are able to serve under more seriously strained conditions.

From the fractography of the hot- and cold-rolled tensile specimens shown in Fig. 2, we may notice that they are quite different in fracture modes. The fracture surface is much smoother in the cold-rolled sample than that of the hot-rolled one. The dimples are obviously smaller and shallower in the case of the cold-rolled condition. From the point of microscopic scale, the fracture surface for the hot-rolled specimen shows more ductile characteristics comparing to that of the cold-rolled sample, as can be observed in Fig. 2(b) and (d). This results from the soft matrix of the MMCs under hot-rolled condition.

The major reason for the decrease in the ultimate tensile strength is that there exist a lot of micro-damages, of about 20–100 μm in length

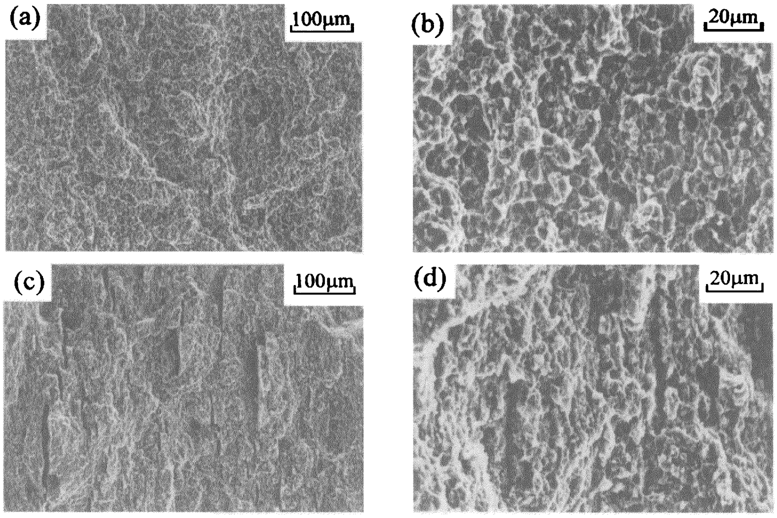


FIGURE 2 Fractography of the tensile test for MMC sheet: (a) and (b), hot-rolled; (c) and (d), cold-rolled.

produced during cold rolling in the microstructures. These can evidently be observed in Fig. 2(c). During plastic tensile deformation, these pre-existed microcavities will coalesce and form perilous crack sources that lead to the final failure of the MMCs.

The mechanical properties, or more exactly, the elastic and plastic anisotropy of the materials are greatly influenced by the textures of the materials. The initial texture for the cold-rolling process is nearly random, as can be observed in the constant ψ sections of the ODF for the hot-rolled sheet as shown in Fig. 1(a). The maximum intensity level is only 1.49. It may be deduced that the mechanical properties or the texture related properties are almost isotropic for the hot-rolled sheet of the MMCs. On the other hand a weak fcc cold rolling texture was clearly developing in the cold-rolled sample, which can be fully revealed by ODF of Fig. 1(b). Besides the strengthening mechanisms mentioned above, the existence of the textured microstructures also has an effect on the increase of the 0.2% offset yield strength of the cold-rolled MMC sheet.

With the aid of ODF analysis, the textures in the cold-rolled composite sheet could be ascertained. Besides the random texture, there are three moderate strong texture components, these are $\{0\,0\,1\}\langle 1\,1\,0\rangle$ ($\psi = 45°$, $\theta = 90°$, $\varphi = 0°$ and $90°$), $\{1\,1\,0\}\langle 1\,1\,2\rangle$ ($\psi = 35°$, $\theta = 45°$, $\varphi = 0°$ and $90°$) and $\{3\,3\,14\}\langle 7\,7\,3\rangle$ ($\psi = 0°$, $\theta = 17°$, $\varphi = 45°$). Due to the addition of large-sized nondeformable particles the texture formation in MMCs was restricted to some extent, i.e., the grain rotation in MMCs would be further limited and some of the slip systems were prevented from operating. Such case is wholly different from that in the unreinforced aluminum alloys. The deformation textures were not fully developed under such small rolling reduction employed.

The cold-rolling texture development in the present MMC sheet could be explained by the detailed theoretical analysis of Dillamore *et al.* (1968). Since the initial or hot-rolling texture exhibits no strong preferred orientation, the orientations with $\langle 1\,1\,0\rangle$ and $\langle 1\,1\,1\rangle$ transverse directions are present in the microstructures of the hot-rolled sheet. During the cold-rolling process, the usual shear component $\{0\,0\,1\}\langle 1\,1\,0\rangle$ has zero $\mathrm{d}\theta/\mathrm{d}E$ and a positive slope of the curve of $\mathrm{d}\theta/\mathrm{d}E$ vs. rotation angle θ. The $\mathrm{d}\theta/\mathrm{d}E$ represents the instantaneous rate of rotation in radians per unit natural longitudinal strain. So it is just a metastable orientation. If the deformation proceeds, it will change to an other more stable orientation. In the case of particulate-constrained deformation, however, this orientation should be more stable.

The shear component $\{0\,0\,1\}\langle 1\,0\,0\rangle$ was usually formed with inhomogeneous rolling deformation and rolling temperature (Lee and Duggan, 1991; Choi *et al.*, 1997). The former is often due to the friction effect existing in the rolling deformation or the rolling geometry. The particulate-reinforced metal-matrix composite has lower plasticity and the small rolling reduction per pass make the deformation inhomogeneous through the thickness of the specimen. So there is inevitably a shear strain near the sample surface and there will be no large plane strain during the plastic deformation. This is a major factor that controlling the development of the shear component $\{0\,0\,1\}\langle 1\,1\,0\rangle$.

Obviously, the component $\{3\,3\,14\}\langle 7\,7\,3\rangle$ is very near to the texture component D of $\{4\,4\,11\}\langle 11\,11\,8\rangle$ ($\psi = 0°$, $\theta = 27°$, $\varphi = 45°$), which was first predicted by Dillamore *et al.* (1968). In Euler space, only 10° rotation of θ in D component is needed, to obtain the component $\{3\,3\,14\}\langle 7\,7\,3\rangle$. During rolling deformation, only 10° rotation of θ for D component about transverse direction $\langle 1\,1\,0\rangle$ is required to obtain the component of $\{3\,3\,14\}\langle 7\,7\,3\rangle$. Concerning the development of the component $\{1\,1\,0\}\langle 1\,1\,2\rangle$, it is a more stable orientation in fcc metals as predicted by Dillamore *et al.* (1968). It has zero $d\theta/dE$ and a negative slope of the curve of $d\theta/dE$ vs. θ. In fact, it is also a typical texture component for rolled fcc alloys. Another possible way for the development of the component $\{0\,0\,1\}\langle 1\,1\,0\rangle$ is by a little rotation of cube $\{0\,0\,1\}\langle 1\,0\,0\rangle$. The texture characteristics of the MMC sheet employed in this work are similar to that of the typical fcc alloys.

As for the usual classification of the texture types by stacking-fault energy (SFE) in fcc metals, we may notice that the components S and C do not substantially appear in the MMC sheet. This is most probably due to the alternation of the slip plane operative for the aluminum alloy under the condition of reinforcement by nondeformable particles.

4. CONCLUSIONS

(1) For aluminium alloy matrix composite Al–3.0 wt% Cu–1.5 wt% Mg–0.4 wt% Mn reinforced by 15 vol. % of SiC_p, the hot rolled sheet exhibits good ductility up to $\sim 7\%$, while the strain to failure of the cold rolled sheet reaches 3%.
(2) The cold-rolled MMC sheet shows elevated 0.2% offset yield strength compared with that of hot rolling state. The ultimate tensile strength of the cold rolled sheet is lower than that of the hot-rolled MMC sheet. The reason for this is that there exist a lot of micro-cavities produced during cold rolling.
(3) The rolling process has a prominent effect on the distribution of the grains of the MMC sheet, especially at the lower rolling temperature, which can influence the mechanical properties. The deformation texture of the MMC sheet developed during the cold rolling consists mainly of three weak components, $\{0\,0\,1\}\langle 1\,1\,0\rangle$, $\{1\,1\,0\}\langle 1\,1\,2\rangle$ and $\{3\,3\,14\}\langle 7\,3\,3\rangle$. The hot rolling deformation texture is even weaker and nearly random.

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