On the Structure and Strength of Severe Strained Metal Matrix Composite Al-30%SiC$_w$

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ABSTRACT

The effect of the SiC whiskers on the microstructure developed during severe plastic deformation and subsequent annealing is examined. Particular attention was paid to the role of the SiCw on the recrystallization behavior and grain size in Al-30%SiCw composite. The heavily deformed structure and microstructural evolution during annealing at different temperatures of the composite was compared with that of the bulk aluminum. It was shown that the microstructure of as-deformed monolithic aluminum is quite different from that of the composite matrix. Accordingly, there is a gap between recrystallization processes of the composite and the bulk pure aluminum. The reasons for influence of reinforcing elements on structure and strength of the composite are discussed.

1. INTRODUCTION.

In recent studies [1-5] the recrystallization behavior of metal matrix composites (MMCs) was examined after conventional amounts of cold work (9-90% reductions). At the same time the investigation of microstructural development in the composite during annealing after severe plastic deformation is still absent. It is known [6] that extensive deformation is an effective method to produce ultrafine microstructure in different materials. Recrystallization behavior of a material subjected to severe strain is characterized by a number of specific features [6-9]. The mechanisms of structure formation during annealing at elevated temperatures of materials with such structure are not yet understood well. Moreover, the presence of reinforcing elements can modify various aspects of recrystallization, such as the kinetics and the characteristics of formed microstructure.

Thus the aim of this study is to provide an information on recrystallization behavior of MMCs and to examine a role of reinforcing elements in the microstructural evolution during severe plastic deformation and following annealing.

2. EXPERIMENTAL PROCEDURES.

Two materials were used in the present study. The aluminum was of 99.5 pst. The Al-30vol.% SiC$_W$ composite was fabricated via a squeeze casting method.

To achieve a highly strained state, both the composite and the monolithic aluminum were subjected to severe plastic deformation at room temperature by torsion straining under high pressure (about 7GPa). A special set of a Bridgeman anvil type was used [9]. Specimens of 8 mm diameter and 0.3 mm thick were cut out from rods. The logarithmic strain e was approximately equal to 7. After that the specimens were annealed in a furnace for 1 h at temperatures ranging from 100 to 500°C. All samples were cooled in air. The room temperature measurements of microhardness (HV) were performed on a PMT-3 microhardness tester, using a Vickers diamond pyramidal indenter with a load of 0.05 kg applied for 20s.

The microstructure was examined using optical and transmission (TEM) electron microscopies. Specimens for optical microscopy were prepared using a standard technique. The grain size was determined by a linear intercept method using a structural analyzer Epiquant and a dark field TEM method. Thin foils for TEM were jet polished for perforation using a Struers Tenupol polishing system. The polishing solution used was 20% nitric acid in methanol, cooled to a temperature of -30°C, under a potential of 30V. Subsequent ion milling techniques were used to obtain great thin areas from the composite discs. The ion milling time was about 1-2h per sample and the beam angle used is 15°. The TEM studies were performed on a JEM-2000EX electron microscope.

The X-ray diffraction analysis was used through the Williamson-Hall method to determine physical line broadening, coherent domain size and internal elastic strain [7].

3. RESULTS.

3.1 Starting microstructure.

Severe plastic deformation leads to formation of different structural states in the composite and the bulk aluminum (Fig. 1 and 2).

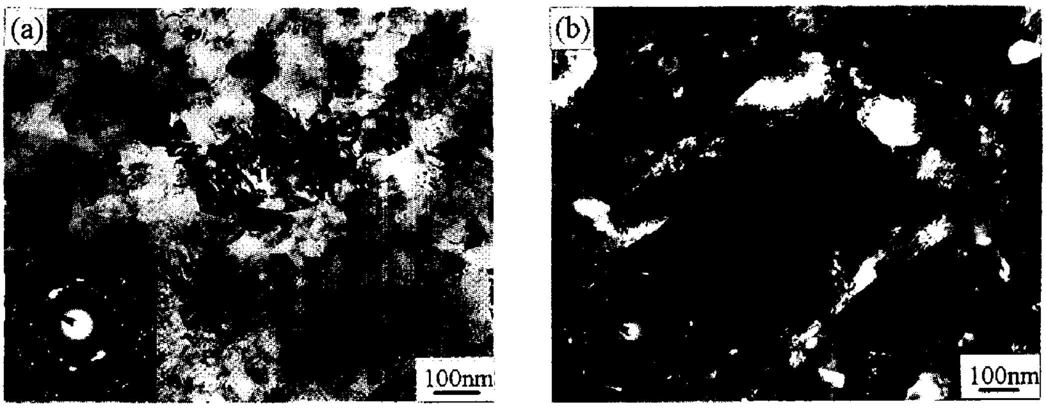

Figure 1. Microstructure of the as-deformed composite Al–30%SiCw with corresponding electron diffraction pattern (a). Dark field image taken from (220_{SiC}) the whiskers end.

The structure of the composite matrix is typical for conventional alloys and a intermetallic compound subjected to severe deformation [6-9]. It consists of equiaxed grains with an average diameter of about 120 nm. As seen from a selected area of electron diffraction patterns (SAD) (Fig.1a), this structure is of a granular type. The pattern was taken from an area of 0.4 μm^2 and contained numerous diffraction spots randomly arranged in rings. This indicates that grain boundaries are mainly of a high-angle misorientation. Three features of matrix structure indicate to the presence of high internal stresses in the aluminum matrix [6, 7]. Diffraction spots have significant elongation toward the azimuthal direction. A special kind of extinction contours and a local distortion of contrast within some matrix grains is observed. The sources of these stresses are into grain boundaries [10], those are highly non-equilibrium (NEGB). Another important feature of the deformed state of the composite is the presence of large elastic bending of the whiskers. Certain of the large whiskers demonstrate an azimuthal angle misorientation of about 10 deg as evidenced by diffraction patterns from the whiskers end. [Fig. 1(b)].

The microstructure of monolithic aluminum is quite different from that of the composite matrix (Fig. 2). This is a recrystallized type of structure.

Figure 2. Microstructure of the as-deformed bulk aluminum:

Conventional extinction contours are observed in small (≈ 0.3 μm) grains of 99.5 Al. Grain boundary dislocations and lattice dislocations are rarely encountered. A diffraction contrast inside separate grains is uniform that testifies to the absence of significant internal stress fields. Notice that grains with equilibrium grain boundaries (EGBs) [11] constitute about 75%. Such a microstructure is formed as a result of DRX occurrence at ambient temperatures after severe deformation [9, 12, 13].

3.2 Structural evolution during annealing.

3.2.1 Microhardness behavior.

The gap between microstructures of the as-deformed composite matrix and monolithic material is responsible for a strong difference in material hardness (Fig. 3).

It is seen that this difference is much greater than the usual effect caused by introduction of reinforcing elements into aluminum alloy. The microhardness of the composite is two and half times greater than that of the bulk aluminum at room temperature.

The microhardness is shown as a function of temperature for the composite and monolithic aluminum in Fig.3. The isochronal annealing curve for the composite does not have a definable recrystallization step till 500^{o}C. A smooth microhardness decrease takes place with increasing annealing temperatures up to 300^{o}C. This temperature corresponds to a 20 pct HV drop for the composite. Further temperature increase does not lead to a significant change of microhardness.

Monolithic aluminum exhibits a conventional evolution of hardness as temperature increases. The significant reduction in hardness takes place at following annealing in the temperature interval 100-200^{o}C. A 50pct hardness drop occurs at these temperatures. Subsequent temperature increase leads to a gradual hardness reduction. The microhardness after annealing at T=500^{o}C of the bulk aluminum is less than that of the composite by more than a factor of 4.

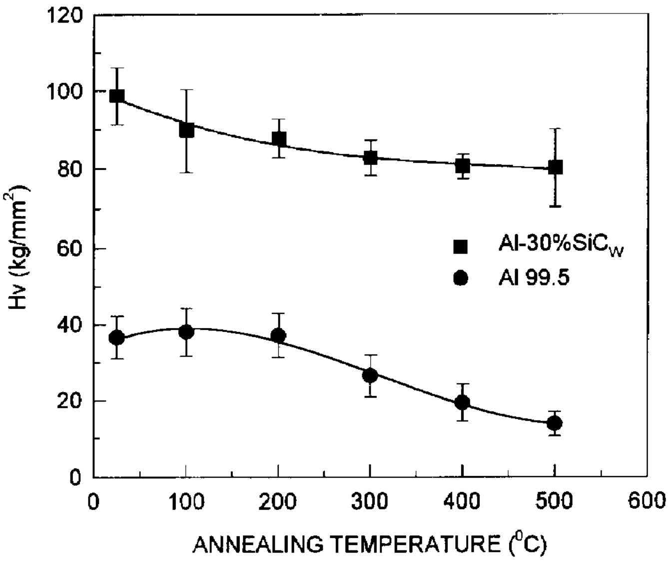

Figure 3. Curves of hardness (load 0.05 kg) plotted against temperatures at which the specimens were annealed for 1h after deformation.

3.2.2 Microstructural evolution.

The influence of temperature on grain size for the composite and monolithic metal is shown in Fig. 4. It is seen that grain size *vs* temperature dependence for the composite differs from that for bulk aluminum.

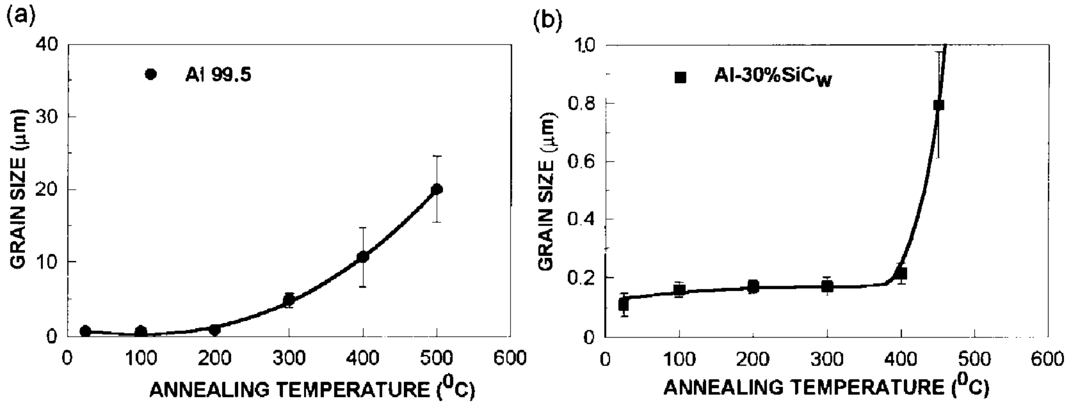

Figure 4. Grain size as a function of annealing temperature: (a) for bulk aluminum, (b) for composite.

TEM studies revealed that a grain growth by a factor of 1.5-1.7 was observed at T=100°C in the composite matrix [Fig. 4(b) and 5(a)]. The microstructure following annealing at 100°C consists mainly of equiaxed grains with NEGBs. The specific features of this structure and the granular microstructure in the as-deformed state of the composite are similar. The size of grains with NEGBs slightly increases. Temperature increase up to 450-500°C results in relaxation of long-range internal stress fields originated from the bent whiskers. The almost uniform contrast from the whiskers is observed. This results in an extensive growth of grains with equilibrium boundaries [Fig. 4 and 5(c)]. Their boundaries exhibit a usual banded contrast and the presence of grain boundary dislocations are not detected. At T=450°C recrystallized grain size increases by a factor of seven. After annealing at temperatures 450-500°C some grains are almost free of dislocations. At the same time in other grains the enhanced density of lattice dislocation is observed [Fig. 5(d)] after isochronal annealing. The recrystallized grains are generally equiaxed and uniform. Notice that annealing at 500°C results in a dramatic grain growth in the aluminum matrix.

Figure 5. Microstructural evolution of composite Al–30%SiCw following isochronal annealing at various temperatures: (a) 100°C, (b) 300°C, (c) 450°C, (d) 500°C.

The microstructural evolution of bulk aluminum in the temperature range 100-500°C is quite different from that of the composite [Fig. 4(a) and 6]. Two stages of recrystallization process of heavily deformed aluminum are distinguishable.

In the temperature interval T=100-200°C isochronal annealing leads to insignificant grain growth. The process of grain boundary structure recovery is a main process of the first stage of recrystallization. The contrast from grain boundary dislocations and NEGBs gradually disappears with increasing temperature in the interval T=100-200°C. Recrystallized grains become more equiaxed.

The inflection point at T=200°C is apparently distinguished for the bulk aluminum. Isochronal annealing at this temperature leads to disappearance of grain boundary dislocations in the aluminum.

Further temperature increase results in the dramatic growth of grains with equilibrium boundaries. This is main process of second stage of recrystallization. Formation of conventional recrystallization structure occurs. After isochronal annealing in the temperature range 300-500°C all grain boundaries exhibit conventional extinction contours.

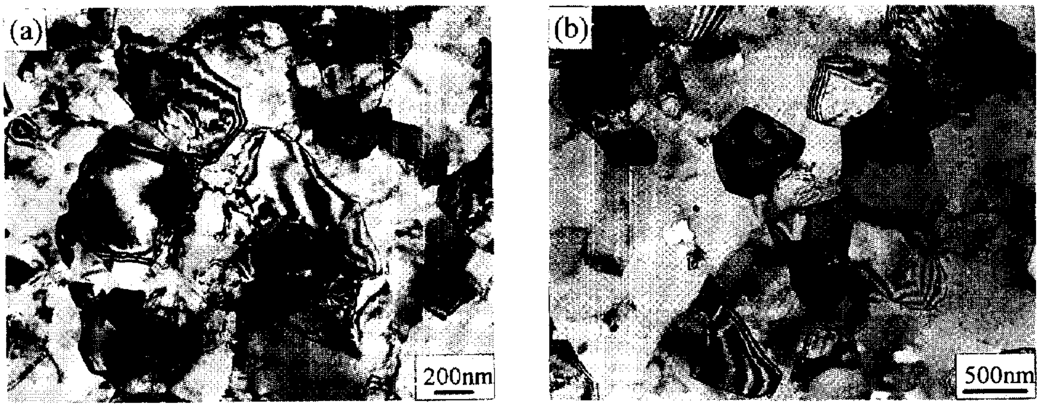

Figure 6. Microstructure of the bulk aluminum after isochronal annealing at 100°C (a) and at 200°C (b).

3.2.3 X-ray Structural Analysis.

The data of the X-ray physical line broadening analysis presented in terms of coherent domain size and internal elastic strain are displayed in Fig. 7. It is seen that the effect of severe deformation and following annealing at temperatures less than 500°C on structure parameters of the composite matrix and monolithic aluminum is quite different. In the as-deformed state the lattice strain of the composite matrix is much higher and the crystallite size is nearly three times less than respective structure parameters of the monolithic aluminum.

The X-ray line broadening in the composite in the temperature range 100-200°C decreases. Two reasons are responsible for this. Firstly, the internal elastic strain decreases. However, this reduction is not too high [7, 8] and does not exceed 30 pct. Secondly, the crystallite size slight increases. The insignificant growth of the elastic strain was observed at higher temperatures. Whereas the coherent domain size is stable in the temperature interval 200-400°C. At T=500°C the contribution of the crystallite size to the total X-ray line broadening is negligible. Consequently, it is rather difficult to determine the coherent domain size with appropriate accuracy.

The structural parameters of monolithic aluminum can be determined by X-ray diffraction only in a temperature range of 100-200°C. A strong decrease in the internal strain and a sharp increase in the crystallite size is observed.

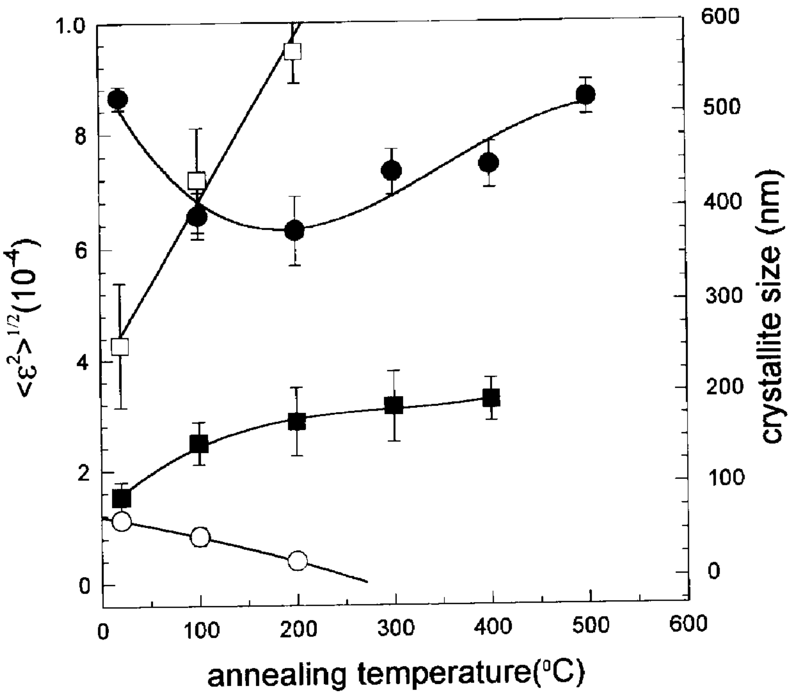

Figure7. Dependence of the microstrain (circles) and crystallite size (squares) *vs* annealing temperatures. Closed symbols correspond to the composite Al–30%SiCw and open symbols to the monolithic aluminum.

4. DISCUSSION.

4.1 Heavily deformed structure

The specific type of matrix microstructure in the heavily deformed Al-30%SiCw composite indicates that there is a strong effect of silicon carbide whiskers on the as-deformed structure of the aluminum composite. Severe plastic deformation of the composite leads to formation of the ultrafine grain structure in the aluminum matrix. To the contrary, recrystallized grain form in the bulk aluminum after severe deformation. The microstructure of the composite matrix is characterized by two main features. Firstly, the grain size of the composite matrix is smaller at least by a factor of 3 compared with the bulk aluminum. Secondly, in the composite matrix the internal elastic strain is eight times greater than in its matrix alloy. As a result, the hardness of the composite is much higher than that of the bulk aluminum. Incorporation of the SiCw into aluminum has the effect due to strong bending of the whiskers after moderate strains [14]. The incompatibility of plastic deformation between soft matrix and hard ceramic whiskers cause the appearance of long-range internal stresses originated from the bent SiCw [14, 15]. This retards diffusion processes into the aluminum matrix and provides the formation of NEGBs [16].

4.2 Recrystallization behavior

During following annealing the deformation induced defects and related elastic stress fields remain in the composite [14] and influence recrystallization behavior. The recrystallization process of the severe strained Al-30%SiCw composite consists of three stages as the temperature increases. The microstructure of the composite is extremely stable at heating up to 400°C. Adsorption of dislocation networks by grain boundaries occurs at the first stage. This step of grain boundary structure recovery takes place in the temperature interval 100-200°C. At the second stage NEGBs gradually transform into equilibrium ones. This process occurs in the temperature interval 200-400°C. At the third stage at temperatures more than 450°C an extensive growth of nuclei with equilibrium boundaries takes place just after relaxation of long-range stress fields originated from the bent whiskers. The high stability of as-deformed composite microstructure and, consequently, the slight influence of annealing temperature on the composite hardness is caused by the presence of these stress fields and their interaction with stress fields originated from the NEGBs.

In the severely strained monolithic aluminum static recrystallization occurs in two steps. The first stage of recrystallization is a recovery of grain boundary structure in the temperature interval 100-200°C. This is a reason for hardness reduction in this temperature interval. Disappearance of grain boundary dislocations causes a lattice strain fall and yields an extensive grain growth at higher temperatures.

Thus, severe plastic deformation is an effective method to produce a high strength state in the metal matrix composite. This state is stable under heating up to high temperatures and may be attractive for some special applications.

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