Comparative analysis of fine-grained structure formation in an Al-Zn-Mg-Cu alloy during multidirectional isothermal forging and uniaxial compression

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Abstract. A comparative study of the mechanical behavior and microstructural evolution in a cast coarse-grained 7475 Al alloy during uniaxial compression and multidirectional forging at 490°C and 10^{-4} s^{-1} was performed. It was shown that high-temperature deformation of the alloy led to grain refinement accompanied by strain softening. At similar processing conditions, the deformation path provided by multidirectional forging was found to be more favorable for grain refinement and strain softening than that of uniaxial compression.

1. Introduction

Producing fine-grain structures upon plastic working of metals and alloys is an important technical problem, the solution of which may have a high commercial potential due to improved technological and service properties of processed semi-finished products [1,2]. Studies carried out in past decades have shown that methods of severe plastic deformation (SPD), such as high-pressure torsion, equal-channel angular pressing, isothermal multidirectional forging (MDF) etc., which ensure the achievement of high strains, can be very effective for grain refinement [1-6]. Among the above SPD methods, MDF is the versatile and affordable material processing technique, because it assumes the use of universal equipment and tooling and allows processing large-sized billets [3-5].

The principle of MDF is based on free forging operations in several consecutive passes with changing the loading direction at each pass: x → y → z → …, etc. [1,3,5]. Since the billet does not practically change its shape and dimensions, high strains can be accumulated during this processing. At the same time, the use of MDF may be important for grain refinement not only due to achieving high strains, but also ensuring a certain deformation route that may be more favorable for the development of a new fine-grain structure [5] than those in any "monotonic" schemes, such as rolling, extrusion, or compression. Unfortunately, the influence of the MDF processing route on grain refinement is currently not well addressed in the literature and still remains undisclosed. This work was aimed to provide a comparative analysis of the mechanical behavior and structural changes occurring in a high-strength coarse-grained 7475 Al alloy under high-temperature uniaxial compression and MDF. It was found in [5,7] that this alloy demonstrated grain refinement in both processing routes at elevated temperatures. The formation mechanisms of new grains, as well as the effect of the deformation paths on the development of fine-grain structure in this alloy are discussed.
2. Material and methods
The direct-chill cast ingot of the 7475 Al alloy (Al–6.04%Zn–2.46%Mg–1.77%Cu–0.23%Cr–0.16%Zr–0.03%Mn–0.03%Si–0.04%Fe, wt. %) was homogenized at 490°C for 20h. Coarse dendrite-like grains were present after such heat treatment in the initial structure, where some segments of the grain boundaries were alternatively straight and corrugated (figure 1). The sizes of grains were within 1-10 mm in the longitudinal direction and 50-250 µm in the transverse direction. Two types of dispersoids identified as Al₃Zr and Al₃Cr, with the mean sizes of 20 and 100 nm, respectively, were uniformly distributed in the alloy [5,7].

Rectangular samples of about 10×9×6 mm³ (1.8:1.7:1) were machined from the ingot. The first compression axis was aligned with the ingot axis. Uniaxial compression to the true strain of \( e = 1.9 \) and MDF to the total strain of \( e = 3.5 \) were carried out under isothermal conditions at 490°C and a constant strain rate of \( 3 \times 10^{-4} \) s⁻¹. Upon MDF, the samples were deformed with the strain per a pass of 0.7. The testing machine was equipped with a special device enabled to automatically maintain a constant strain rate during compression and a water-quenching apparatus to fix the structural changes occurring during deformation. Microstructural analysis in conventional and polarized light was carried out in the central part of the deformed specimens with an Olympus PME-3 optical microscope. The average size and fraction of strain-induced new grains were evaluated by a line-intercept and a point-count techniques, respectively. Electron backscattering diffraction (EBSD) analysis was performed using a Hitachi-3500A scanning electron microscope with OIM Data Analysis software. In the EBSD maps obtained, different colors corresponded to different orientations, while the low- (\( \Theta \geq 2^\circ \)), medium- (\( \Theta \geq 5^\circ \)) and high-angle (\( \Theta \geq 15^\circ \)) misorientations between neighboring grid points were marked by thin white-, narrow- and bold black lines, respectively. To study the deformation relief, the samples with a pre-polished surface that was perpendicular to the z-axis were used. They were loaded along the x axis with \( e = 0.16 \); and also, sequentially along the x-axis (\( e = 0.16 \)) and after rotating the sample by 90° - along the y-axis (\( e = 0.16 \)) up to the total strain of \( e = 0.32 \).

3. Experimental results
Typical true stress-strain curves derived from uniaxial compression and MDF are shown in figure 2. It is seen that the \( \sigma - e \) curve plotted for uniaxial compression (dotted line in figure 2) demonstrated a peak of flow stresses just after yielding and subsequent significant material softening followed by a steady state of flow stresses at \( e \) of beyond 0.6. On the contrary, the stress-strain curve envelope that was obtained by MDF showed a more significant softening and lower flow stresses achieved at the same effective strains. In this case, the steady state of plastic flow was reached at \( e \) of beyond 3 with a much lower stress level. It is also noteworthy in figure 2 that the flow stresses at the onset of each subsequent MDF pass (i.e. at reloading) were approximately equal to those immediately before

![Figure 1](image1.png) **Figure 1.** The initial structure of the 7475 Al alloy showing layered dendrite-like grains. The ingot axis is vertical.

![Figure 2](image2.png) **Figure 2.** True stress - true strain curves of the 7475 Al alloy plotted for uniaxial compression and MDF.
the material unloading in the preceding compression passes. This suggested that any softening processes associated with static recovery or static recrystallization in the material scarcely occurred upon overheating and soaking the samples at the high temperature between MDF passes. Accordingly, like in the case of uniaxial compression, the structural changes during MDF were mainly affected by plastic deformation (i.e. strain accumulation in each compression pass).

The typical microstructures after (a) uniaxial compression at $e=1.9$; (b) MDF at $e=2.1$; and (c) MDF at $e=3.5$, are shown in figure 3. The dark areas in figure 3 were composed by fine recrystallized grains processed by deformation, while light ones corresponded to the fragments of coarse original grains. It is seen that the deformation under both processing conditions resulted in the development of partially recrystallized bimodal grain structures. In the case of uniaxial compression to the strain of 1.9, new grains with the size of about 6 μm were formed mainly near the original grain boundaries and their volume fraction, $V_{rex}$, did not exceed 20% in the entire sample (figure 3a). Meanwhile, during MDF to the close value of strain $e=2.1$, the regions of new grains of 6-7 μm in size were formed more homogeneously and occupied about 60% of the total material volume (figure 3b). With a further increase in the MDF strain to $e=3.5$, an almost fully recrystallized fine-grained structure evolved (figure 3c). Figure 4 shows strain dependences of $V_{rex}$ for both the material processing routes. It should be noted in figure 4 that changes in the route from uniaxial compression to MDF significantly accelerated the kinetics of grain refinement. At the same time, as noticed above, only a negligibly small effect of the considered change in deformation path on the size of fine recrystallized grains was found, which, apparently, was mainly controlled by the temperature-strain rate conditions [8].

**Figure 3.** Typical microstructure formed in the 7475 Al alloy after (a) uniaxial compression to $e = 1.9$; (b) MDF to $e = 2.1$; and (c) MDF to $e = 3.5$. The last compression axis is vertical.

**Figure 4.** Strain dependences of the volume fractions of fine grains, $V_{rex}$, developed by uniaxial compression and MDF.
4. Discussion

The results obtained show that both the hot compression and MDF resulted in grain refinement of the alloy accompanied by significant strain softening. However, the implementation of these processing schemes led to different microstructural behaviors of the alloy. Namely, at approximately the same effective strain of about 2, the volume fraction of new grains was stabilized at about 20% under uniaxial compression, while with MDF it reached about 60% and continued to increase with increasing strain (figure 4). The effect of the strain path on the evolution of the microstructure can be explained as follows.

Figure 5 shows a typical deformation relief that developed on the polished surface of samples (a, b) under uniaxial compression to $e=0.16$; and (c) under two sequential loadings with the same strains of 0.16, when the compression direction was changed by 90° between passes (i.e., up to the total strain of $e=0.32$). It can be seen that the deformation of the alloy with a coarse-grained layered structure occurred extremely non-uniformly even at the initial stages of the plastic flow due to a high deformation incompatibility of such a structure and caused the intensive formation of arrays of approximately parallel deformation bands that fragmented the original grains. This suggested that the individual regions in each grain bounded by deformation bands were significantly misoriented relative to each other. These bands (the dislocation boundaries with medium-to-high angle misorientation) can also be seen at higher strains on the etched surfaces of samples using polarized optical microscopy [5] and EBSD analysis, as shown in figure 6. Hence, the evolution of deformation bands could play a key role in grain refinement. The process of formation of new grains during high-temperature equal-channel angular pressing and MDF of some Al alloys, related to the development of deformation bands, was discussed in the previous studies [5,9-11]. In particular, it has been pointed out that deformation bands, that were recognized as microshear bands (MSBs) [8,12], subdivided the original grains into separate domains surrounded by medium-angle boundaries. A gradual increase in the number of deformation bands and misorientation angles of their boundaries during deformation led to the transformation of medium-angle boundaries into high-angle ones and the development of a fine-grain structure in accordance to the mechanism of continuous dynamic recrystallization [8].

Analysis of the data [5,7] showed that the above-described structural mechanism associated with the development of MSBs may be responsible for the development of new grains in the present 7475 Al alloy both under uniaxial compression and MDF. However, it is clearly seen using polarized microscopy (figure 6) that during uniaxial compression, the interiors of non-recrystallized grains contained a large number of bands, the boundaries of which remained approximately parallel to each other at all strains and gradually rotated toward the material flow direction. Thus, we can imagine [13] that if the deformation/microshear bands are formed parallel to each other inside a grain (figure 5a,b), their evolution can lead to the formation of mainly two-dimensional flat structures, as schematically shown in figure 7a. With increasing strain under conditions of the constant strain path in the uniaxial
Figure 6. Microstructures formed in the alloy under uniaxial compression to (a) $e=0.3$; (b, c) $e=0.7$; (d) $e=1.9$ and (e, f) MDF to $e=2.1$: (a, b, d, e) polarized optical microscopy; (c, f) EBSD analysis.

Figure 7. Schematic representation for the formation of the microstructure during deformation: (a) uniaxial compression; (b) two-axial compression; (c) MDF [13].

Compression, these structures could tend to orient perpendicular to the compression axis, and their spacing should decrease with increasing the strain. Note that such structures can also be observed at high strains in cold rolling, as well as torsion under high pressure [e.g. 12,14,15]. Therewith, when the present 7475 Al alloy was compressed to $e=1.9$, the boundaries of MSBs with medium-to-high misorientations remained mostly extended and were interspersed with many low-angle ones. Fragmentation of the initial grains and subsequent formation of the equiaxed fine-grained structures were feasible only near the initial grain boundaries (figure 6c), where the increased stress level and associated local lattice distortions [16] facilitated the development of MSBs in different directions.

On the contrary, the change in the deformation path in MDF, caused by a sequential change in the direction of the loading axis, ensured the development of MSBs in various directions (figure 5c). This is schematically illustrated in figure 7b,c [13]. An increase in the density of the bands and their mutual crossing during deformation led to a continuous fragmentation of initial grains (figure 6e,f). Concurrently, new crystallites were formed in the places fragmented by the boundaries of the bands. Moreover, as can be seen in figure 3b,c, new fine grains were extensively formed not only near the initial high-angle boundaries, but also inside the grains. This provided a more uniform development of the fine-grained structure and significantly increased the volume fraction of new grains at high strains (figure 4). Thus, the change in the deformation path during high-temperature MDF could control structural changes and play a role in grain refinement in the alloy.
5. Conclusions

1. Under hot uniaxial compression conditions, the $\sigma$–$\varepsilon$ curve of the 7475 Al alloy demonstrated a peak of flow stresses just after yielding with subsequent alloy softening. A steady state of plastic flow was reached after a strain of about 0.6. MDF at the same temperature and strain rate led to a more significant decrease in flow stresses, followed by their stabilization at higher strains of beyond 3.

2. Both uniaxial compression and MDF led to the development of a fine-grained structure. New grains of 6-7 $\mu$m in size evolved as a result of fragmentation of the original grains upon the formation of deformation bands, followed by transformation of their boundaries to high-angle grain boundaries.

3. The implementation of the above processing methods led to different microstructural behaviors of the alloy. During uniaxial compression, deformation/microshear bands developed mainly parallel to each other within each grain and, with an increase in the strain, were oriented in the direction perpendicular to the applied load. In this case, fragmentation of the original grains followed by grain refinement took place only near the original high-angle boundaries, where development of deformation/microshear bands in various directions was facilitated by higher stress concentrations and larger lattice distortions.

4. Changing the deformation path during MDF ensured the development of the deformation / microshear bands in various directions and led to the continuous fragmentation of original grains. At approximately the same strain of about $\varepsilon=2$, the volume fraction of new grains processed by uniaxial compression stabilized at the value of about 20%, while upon MDF, it reached about 60% and proceeded to increase continuously to about 85% with further alloy straining to $\varepsilon=3.5$. This suggests that the deformation path provided by MDF controls the structural changes and plays an important role in the grain refinement.

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