Effects of Deformation Processing on the Mechanical Properties of Aluminum Alloy 6063

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Aluminum alloy 6063 was processed by upset forging and cold rolling at ambient temperature. The tensile, ductile, and hardness (HRN) properties of the samples were studied. Upset forging is determined from the processing of this alloy to obtain maximum ultimate tensile strength (UTS) and HRN. At room temperature, the UTS and HRN increase as the range of reduction from processing increases from 0 to 50 pct. However, the ductility decreases correspondingly, which is indicative of a low strain-hardening exponent. The gaseous pores in the as-cast structure spread when forged, while the rolling had no effect on this casting defect. The pore elongation and thinning promoted superior strength, HRN, and ductility in the forged sample, as compared to the cold-rolled sample.

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I. INTRODUCTION

AT room temperature, plastic deformation generally occurs in metals by dislocation motion. The stress required to move a dislocation depends on the characteristics of the atomic bonding and atomic arrangement (*i.e.*, crystal structure), and on obstacles such as solute atoms, the presence and thickness of grain boundaries, and the precipitate particles introduced during casting.

In fcc metals (*e.g.*, Al and Cu), the effective stress is only weakly dependent on temperature. Thus, the dislocation motion remains high even at low temperatures and the material remains relatively ductile.

Over the years, the deformation processing of materials has been of great importance since knowledge of the interrelationship among the process parameters, microstructure, and material properties will enhance the quality of the product.

Deformation processing depends on the microstructure of the starting material, the geometry of the deformation zone, the temperature, the strain rate employed, and the frictional conditions.[1] The microstructure of the material being processed determines the extent of microstructural damage likely to be caused by mechanisms such as cavity formation at hard particles, cracking at grain-boundary triple junctions, and flow localization due to adiabatic cracking.

Deformation forces increase with the flash width-to-thickness ratio, and decrease with increasing billet diameter-to-height ratio and slug temperature, when forging EN3B mild steel slugs (composition in Table I) within the temperature range 1150 °C to 1250 °C.[2]

This work studies the deformation processing of aluminum alloy 6063 with a view toward determining the interrelationship among the process parameters, microstructure, and product properties.

Matrix particles are known to influence cavity formation, while particles at the grain boundaries affect wedge cracking. In this study, upset forging and cold rolling of the material are evaluated, as are the longitudinal tensile properties produced by both processing routes.

II. EXPERIMENTAL METHODOLOGY

A. *Materials and Specimen Preparation*

Test specimens were prepared by melting an extruded scrap of 6063 aluminum alloy with about 98.45 pct Al and 0.45 pct Mg in an oil-fired crucible furnace. The alloy was cast into sand molds to obtain bars $140 \times 25 \times 16$ mm in size. Table II gives the composition of the aluminum alloy evaluated in this study.

The as-cast specimens were either rolled in five passes at ambient temperature (303 K) using a two-high mill or they were forged in a single pass at 303 K using a pneumatic hammer of 56.31 kPa and driven by a 4.5-HP electric motor. The initial specimen thickness was 16 mm.

B. *Mechanical Testing*

Figure 1 shows tensile test specimens that were used to determine the room-temperature (303 K) tensile properties and hardness (HRN) values of the cold-rolled and upset-forged specimens. The tensile tests were conducted in a Hounsfield Tensometer (Tensometer Ltd., Crowdon, UK) at a nominal strain rate of 10^{-3} s^{-1}, while the HRN was measured using a Rockwell Hardness Tester Tru-Blue II model (United Calibration Co., Huntington Beach, LA, USA). The 15N scale was selected and a load Kg was applied with a Brale (Diamond) indenter (United Calibration Co., Huntington Beach, LA, USA), in accordance with ASTM Standard E18-05E1.[3]

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Table I. Chemical Composition of Mild Steel EN3B (Bright BS 970 080 A15)

Element	Fe	Si	Mn	S	P	Ni	Cr	Mo	Cu	Al
Weight percent	bal	0.250	0.820	0.027	0.008	0.080	0.090	0.010	0.120	0.005

Table II. Chemical Composition of Aluminum Alloy 6063

Element	Al	Mg	Fe	Cu	Mn	Zn	Cr	Ti	Sr	Si
Weight percent	bal	0.451	0.430	0.043	0.049	0.048	0.011	0.010	< 0.001	0.503

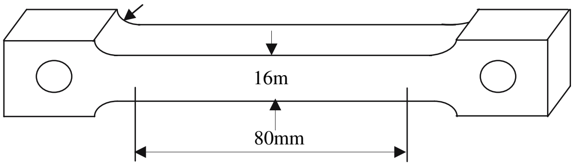

Fig. 1—Tensile test specimen.

C. *Microstructural Examination*

The specimens for optical metallography were prepared using standard techniques. A mixture of 1 g of sodium hydroxide (NaOH) in 100 ml of water was used as the etchant. A metallurgical microscope was used to obtain 200× photomicrographs of the processed specimens.

III. RESULTS

A. *Microstructure of Upset-Forged Specimens*

The as-cast structure revealed dendrites with a distribution of Mg_2Si particles in the aluminum matrix (Figure 2). The presence of gas porosity resulting from hydrogen evolution is visible. As the material thickness decreases with cold rolling (0 to 35 pct), the solute (Mg_2Si) particles are visibly absorbed into the solvent, leaving a few well-distributed particles of the second phase in the aluminum matrix (Figures 3(a), 4(a), and 5(a)). However, this rolling process does not eliminate the gas porosity. Above a 35 pct thickness reduction, well-distributed fine solute particles reappear in the aluminum matrix. The solute size grows toward a 50 pct width reduction (Figures 6(a), and 7(a)).

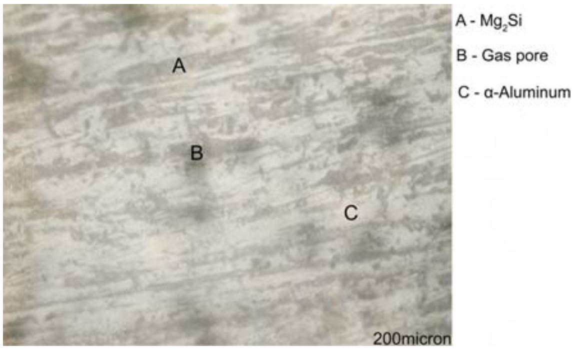

Fig. 2—As-cast sample.

B. *Mechanical Properties of Upset-Forged Specimens*

Table III and Figures 8 through 10 show the mechanical properties measured in this study. The effective (equivalent) stress increases as a result of the absorption of solute particles by the solvent (the aluminum matrix). This agrees with the increasing UTSs obtained with the increasing reduction from 0 to 35 pct during deformation processing. Beyond 35 pct, when the solute precipitates reappear, the elongation decreases without affecting the UTS and the HRN values, which both increase. The authors attribute this behavior to the presence of a large volume of residual stresses that result from the amount of the size reduction performed and the presence of the fine particles of the Mg_2Si precipitates in the aluminum matrix.

C. *Microstructure of Rolled Specimens*

The volume of Mg_2Si precipitates in the aluminum matrix increases with the amount of the size reduction performed on the test specimens during cold rolling. The solute texture changes from a coarse precipitate to a fine one. Grain boundaries were broken up as the size reduction increased (Figures 3(b), 4(b), 5(b), 6(b), and 7(b)).

D. *Mechanical Properties of Rolled Specimens*

The fragmentation of grain boundaries as a result of the size reduction enhances the dislocation generation. The specimen elongation increases as the UTS and HRN values increase (Figures 8 and 9, respectively). However, the elongation of the specimens decreases with the increasing deformation-processing thickness reduction taken, indicating falling ductility (Figure 10). This suggests that rolling generates a large number of immobile dislocations.

IV. DISCUSSION

Comparing the mechanical responses of the specimens to the deformation processes, the tensile strength of the

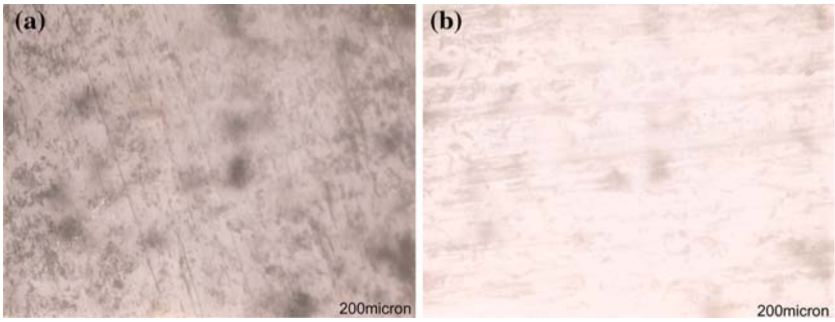

Fig. 3—Sample (*a*) forged and (*b*) rolled with 15 pct thickness reduction.

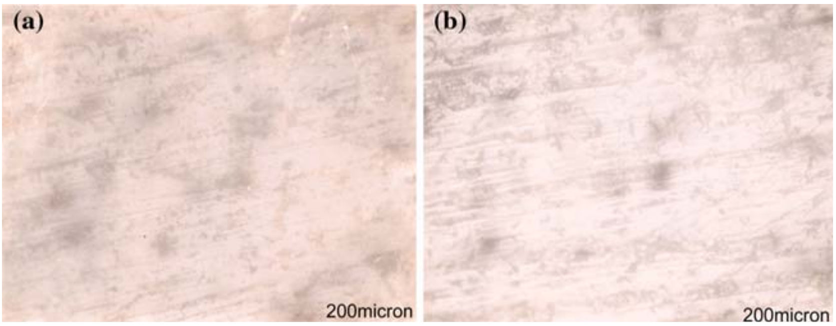

Fig. 4—Sample (*a*) forged and (*b*) rolled with 25 pct thickness reduction.

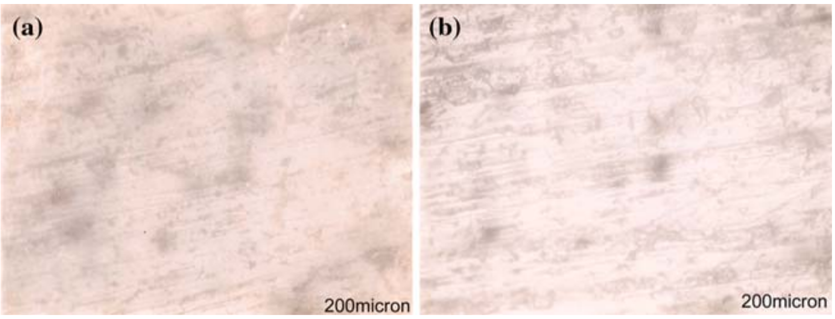

Fig. 5—Sample (*a*) forged and (*b*) rolled with 35 pct thickness reduction.

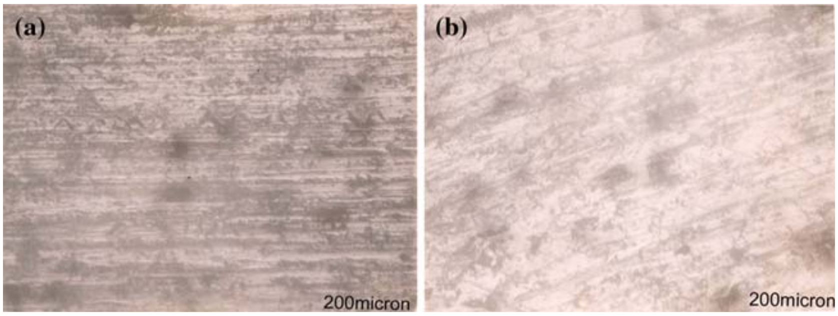

Fig. 6—Sample (*a*) forged and (*b*) rolled with 45 pct thickness reduction.

specimens is more significantly improved with forging than with cold rolling, even at the same thickness reduction (Table III). The rate of fall in the specimen elongation during forging is lower than during cold rolling. This implies that the strain-hardening exponent in forging is low, with low uniform elongation. In

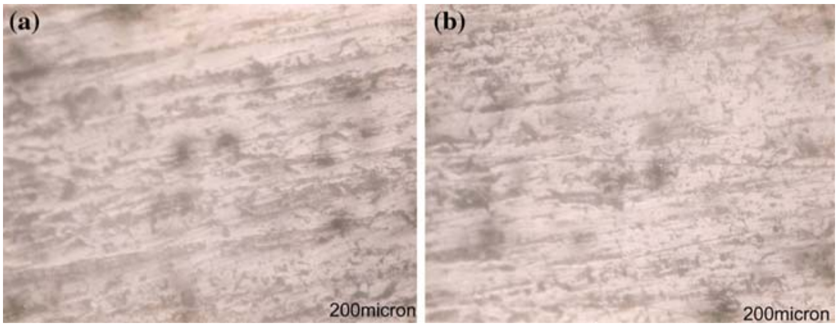

Fig. 7—Sample (*a*) forged and (*b*) rolled with 50 pct thickness reduction.

Table III. Mechanical Properties of Forged and Rolled Specimens at Room Temperature

	Percentage Elongation		Ultimate Tensile Strength, in MN/m^2		Hardness (HR15N)	
Percentage Reduction	Rolled	Forged	Rolled	Forged	Rolled	Forged
0	1.67	1.50	133	136	25.20	21.85
15	1.17	1.30	151	164	50.12	52.37
25	0.83	1.10	164	192	50.89	53.70
35	0.64	0.90	185	213	54.76	55.22
45	0.44	0.70	208	241	56.53	57.71
50	0.33	0.60	231	252	58.66	58.05

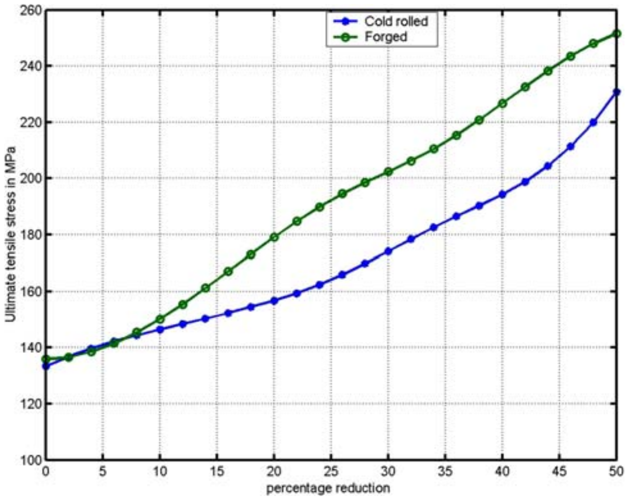

Fig. 8—Graph of ultimate tensile strength and percentage reduction.

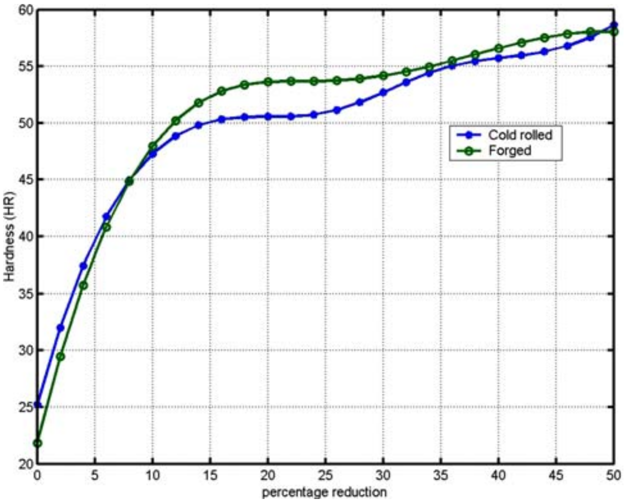

Fig. 9—Graph of HRN and percentage reduction.

contrast, this could be attributed to the second-phase particles and other precipitates in the aluminum matrix (Figures 3(a), 4(a), 5(a), 6(a), and 7(a)) becoming evenly distributed during rolling. However, there is no significant difference in the specimen HRN with the varying deformation processes. The likelihood of damage to the second-phase particle size is higher in forging than in rolling. Thus, the high concentration of formed cavities at hard second-phase particles during deformation in rolled specimens leads to reduced UTS in comparison to forged specimens.

Another reason for the observed difference in the UTS is flow localization, which is more feasible in cold-rolled specimens than in forged specimens. The authors observed that spherical gaseous pores characterize the forged matrix in the photomicrographs. During deformation, the reduction in volume and the changes in the configuration of individual gaseous pores may cause an increase in the tensile strength of the matrix.

The mechanical properties of the samples depend, to a large extent, on the microstructure of the starting material, because it is the starting material that controls the structural damage caused during deformation processing. The following damage mechanisms have been

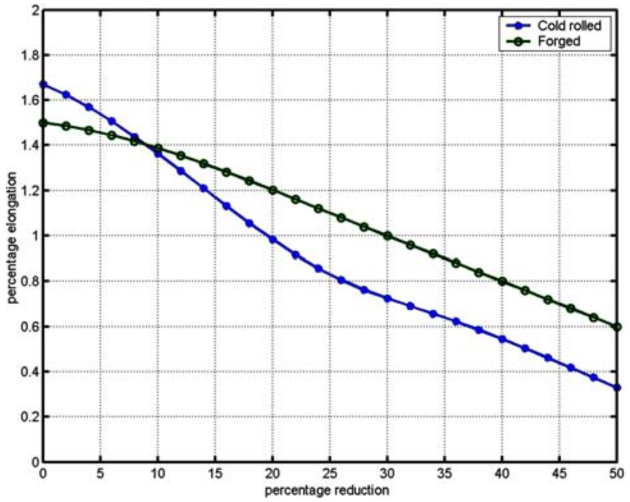

Fig. 10—Graph of percentage elongation and percentage reduction.

identified[4] as being important in materials containing hard particles.

(a) Cavity formation at particles. This is important at ambient temperatures and high strain rates.
(b) Cracking at grain-boundary triple junctions. This is important at low strain rates and high (recrystallization) temperatures.
(c) Flow localization that results from adiabatic heating. This is important at very high strain rates.

Reduced ductility in specimens is traceable to structural damage resulting from any of these mechanisms. The current study is at ambient temperature. Although the matrix undergoes plastic deformation and strain hardening, the hard particles in the matrix do not deform and cavity formation occurs at such sites.

V. CONCLUSIONS

This work has shown that size reduction through both forging and rolling at room temperature could be used to increase dislocation motion while still improving the UTS and HRN characteristics of the material. Forging is more effective in this regard. The forging process destroys grain boundaries much more than does rolling, and it also causes the gaseous pores to move by spreading them along the forging direction, thus reducing the rate of crack growth and damage.

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