

Recrystallization Behavior of Rolled Ingots of 6061 and 6069 Aluminum Alloys

X. Li, M.E. Kassner, and S.C. Bergsma

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The purpose of this study was to investigate the recrystallization characteristics of rolled, as-cast, annealed, and homogenized ingots of "Air-Slip"™ Direct Chill (ASDC) 6061 and 6069 aluminum alloys. The % R_x for annealed and homogenized 6061 and 6069 ingots is higher than that of as-cast 6061 and 6069 ingots at a given % CW and heat-treatment temperature. There is no significant difference in % R_x between annealed ingots and homogenized ingots of the same composition at a given % CW and heat-treatment temperature. The % R_x for 6069-AC ingot is higher than that of 6061-AC ingot at a given % CW and heat-treatment temperature, especially at low heat-treatment temperatures. The % R_x of annealed 6069 ingot (6069-A) and homogenized 6069 ingot (6069-H) is slightly higher than that of corresponding 6061 ingots at a given fraction % CW and heat-treatment temperature. The difference in the recrystallization behavior may be related to the increased alloy additions, in excess of the solubility, leading to relatively large second-phase particles, particularly $MgSi_2$. This can lead to particle-stimulated recrystallization.

Keywords alloy 6061, alloy 6069, aluminum alloys, recrystallization, rolling

1. Introduction

The purpose of this study is to investigate the recrystallization characteristics of rolled (1) as-cast, (2) annealed, and (3) homogenized ingots of "Air Slip"™ Direct Chill (ASDC) 6061 and 6069 aluminum alloys. The relationships between the fraction recrystallized (% R_x) and cold reduction (% CW) of 6061 and 6069 aluminum ingots after heat treatments at various temperatures 316 to 538 °C for 1 h were determined. The effect of heat-treatment temperature on the fraction recrystallized, for a fixed rolling reduction, was also investigated. 6069 is a new alloy[1,2] already used industrially. The recrystallization behavior was characterized to better predict 6069 properties subsequent to various thermal and mechanical processing. The recrystallization features of 6069 were placed in the context of the recrystallization behavior of 6061. The latter alloy was also prepared by ASDC for this study. The recrystallization behavior was judged to be best compared to 6061, by performing the recrystallization study of 6061 "identically" cast as that of 6069 rather than relying on approximately identical recrystallization trends of 6061 (usually on conventionally cast) alloy based on the literature.

2. Experimental Procedures

The ingots of 6061 and 6069 aluminum alloys used in this study were provided by Northwest Aluminum Company in three forms.

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- As cast (6061-AC and 6069-AC). These are ASDC ingots with no thermal treatments subsequent to solidification.
- Annealed (6061-A and 6069-A). These are ASDC ingots that were annealed subsequent to solidification.
- Homogenized (6061-H and 6069-H). These are ASDC ingots that were homogenized subsequent to solidification.

Figure 1 shows the annealing and homogenization treatments for 6061 and 6069 aluminum alloys used in this study. The chemical compositions and diameters of the aluminum ingots are listed in Table 1.

The ingots of 6061 and 6069 aluminum alloys were cut randomly and machined into rectangular samples with 18 mm width, 12 mm thickness, and 152 mm length. The rolling was performed at ambient temperature on a New York Loma two-roller rolling machine at Albany Research Center, Department of Energy (Albany, OR). The rolling speed was 8.64 m/min. The initial thickness (T_0) of ingot samples (before rolling) and final thickness (T_F) of ingot samples (after rolling) were measured, and the reduction in thickness (% CW) = (T_0 − T_F) / T_0. Reduction in thickness (% CW) was performed in approximately 10% increments. It was found that edge cracking occurred when % CW reached 60% for both as-cast 6061 and 6069 ingots (6061-AC and 6069-AC) and 80% for annealed and homogenized 6061 and 6069 ingots (6061-A, 6069-A, 6061-H, and 6069-H). This indicates that the rolling properties of 6069 ingots are similar to those of 6061 ingots and annealed and homogenized ingots have better rolling properties than as-cast ingots. The maximum % CW used for the study of recrystallization was selected as 50% for as-cast ingots and 70% for annealed and homogenized ingots. Table 2 lists the various reductions in thickness for rolled 6061 and 6069 ingots.

The samples of the rolled ingots of 6061 and 6069 were cut into 12.7 mm lengths along the rolling direction and typically 10 to 15 mm widths and placed into a resistance furnace at 316, 343, 371, 399, 427, 454, 482, 510, and 538 °C maintained within an accuracy of ±1 °C for 1 h (plus 10 min heatup)

Table 1 Chemical composition of 6061 and 6069 Al alloys used in this study, wt.%

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	P	Ga	Sn
6061 as cast ingot 109 mm	0.76	0.20	0.34	···	1.10	0.07	···	0.024	0.01	···	···	···
6069 as cast ingot 89 mm	0.81	0.30	0.60	0.01	1.28	0.22	···	0.052	0.12	···	0.02	···
6061 annealed ingot 109 mm	0.78	0.21	0.35	···	1.08	0.06	···	0.02	0.01	···	···	0.01
6069 annealed ingot 89 mm	0.87	0.30	0.71	0.03	1.36	0.22	0.02	0.048	0.12	···	0.02	···
6061 homogenized ingot 89 mm	0.71	0.26	0.26	0.02	0.95	0.05	···	0.017	0.01	···	0.01	···
6069 annealed ingot 89 mm	0.81	0.30	0.60	0.01	1.28	0.22	···	0.052	0.12	···	0.02	···

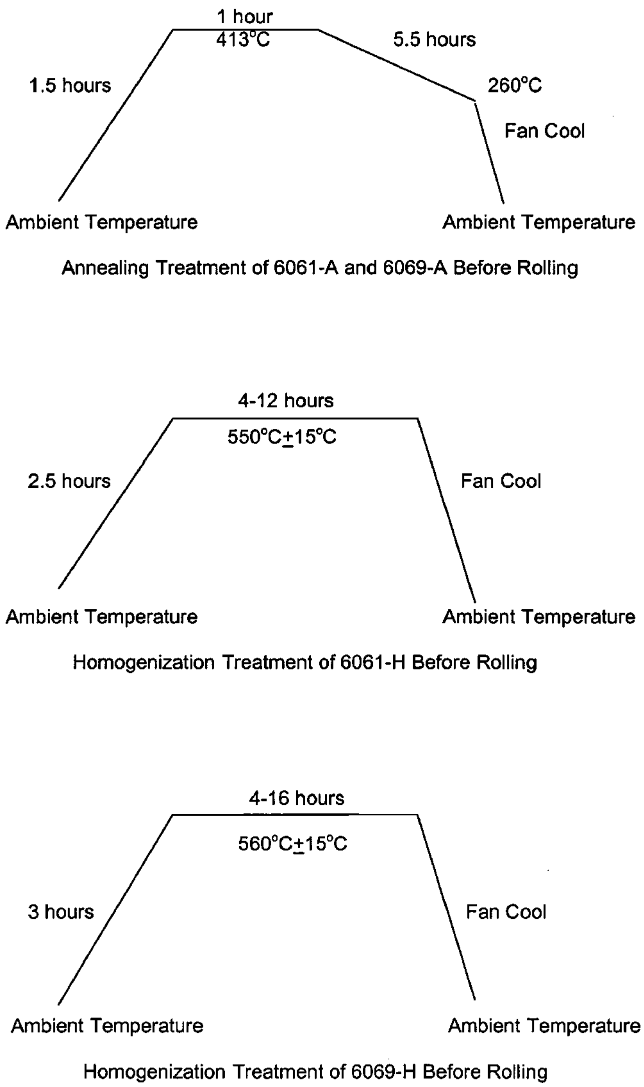


Fig. 1 The annealing treatment and homogenization treatment of 6061 and 6069 ingots before rolling

Table 2 Percent reduction (% CW) of rolled 6061 and 6069 aluminum alloys

Alloy, condition	% CW						
6061 as-cast	9.9	21.0	30.4	39.7	49.8	···	···
6061 annealed	10.6	22.1	32.4	40.4	50.4	60.5	70.4
6061 homogenized	10.4	20.2	31.3	40.2	50.2	60.5	70.3
6069 as-cast	9.8	20.3	29.9	39.7	49.4	···	···
6069 annealed	10.4	20.2	30.4	40.1	50.4	60.5	70.4
6069 homogenized	10.4	20.1	30.3	40.2	50.0	59.8	70.2

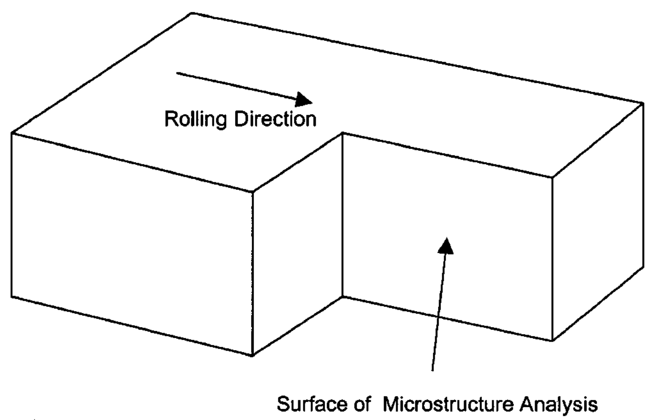


Fig. 2 Position of the surface used for microstructure analysis of rolled ingots of 6061 and 6069 aluminum alloys

followed by a water quench at 21 °C. After heat treatment, the samples were polished and etched for microstructural analysis. Figure 2 shows the position of the surface used for the microstructural analysis of rolled ingots. Keller's reagent [2 mL HF (48%), 3 mL HCl (conc.), 5 mL HNO_3 (conc.), and 190 mL H_2O] was used as the etchant. Each (200×) micrograph was marked to indicate recrystallized grains. The micrographs were scanned into a computer using an HP ScanJet 3P scanner (Hewlett-Packard Company, Colorado Springs, CO) for image analysis to determine the fraction recrystallized (% R_x) measured as an area of recrystallized grains calculated by using NIH Image 1.60 software.

3. Results and Discussion

As expected, it was observed that the % R_x at a given heat-treatment temperature increases as the thickness reduction (% CW) increases for all rolled 6061 and 6069 ingots. Also, for a given % CW, the fraction recrystallized increases as the heat-treatment temperature increases for all rolled 6061 and 6069 specimens. The results are listed in Tables 3 to 8 and in Fig. 3 to 9. The effects of heat-treatment temperature on fraction

Table 3 The fraction (%) recrystallized of rolled 6061 as-cast ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness reduction (%)	Annealing temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
9.9	0.0	0.0	0.0	1.2	3.1	4.4	5.2	6.3	6.5
21.0	0.0	0.0	1.3	3.1	6.0	10.2	12.7	19.7	24.2
30.4	0.0	0.0	3.4	5.2	10.1	21.7	26.3	35.7	48.9
39.7	0.0	1.2	6.9	11.0	21.5	36.5	50.9	70.7	83.2
49.8	1.3	3.2	8.5	19.4	33.0	51.3	68.1	84.5	91.2

Table 4 The fraction (%) recrystallized of rolled 6069 as-cast ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness reduction (%)	Annealing temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
9.8	0.0	0.0	0.0	3.0	5.2	6.2	6.8	7.4	7.9
20.3	0.0	1.1	4.2	11.5	18.9	24.0	26.1	28.2	28.7
29.9	0.0	8.8	17.2	29.5	38.8	42.2	60.2	71.1	80.5
39.7	1.0	11.6	34.9	49.5	56.8	67.8	82.7	90.3	94.3
49.4	2.3	26.3	41.7	52.2	72.3	79.6	90.1	95.6	98.7

Table 5 The fraction (%) recrystallized of rolled 6061 annealed ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness Reduction (%)	Annealing Temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
10.6	0.0	0.0	0.0	2.9	4.3	6.1	6.8	7.6	8.1
22.5	0.0	0.9	6.9	12.8	14.3	19.8	24.3	30.5	39.5
32.4	0.0	3.7	11.4	24.9	32.8	43.8	50.0	62.4	80.7
40.4	11.0	14.0	29.4	36.0	57.9	59.3	71.0	89.8	98.1
50.4	22.3	36.2	40.2	49.3	70.1	73.2	89.2	98.1	100
60.5	40.3	50.3	64.3	75.3	83.4	91.2	95.3	100	100
70.4	61.0	70.3	78.2	82.4	91.4	96.1	99.1	100	100

Table 6 The fraction (%) recrystallized of rolled 6069 annealed ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness Reduction (%)	Annealing Temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
10.4	0.0	0.0	0.0	2.7	4.0	5.8	6.9	7.2	8.6
20.2	0.0	2.2	3.9	11.3	15.9	21.2	25.3	30.2	34.2
30.4	1.3	8.1	18.7	33.7	38.2	47.5	54.1	60.2	76.3
40.1	10.9	18.1	34.8	43.9	71.2	85.1	91.2	92.3	98.9
50.4	26.4	41.3	6.9	85.2	90.1	95.2	96.1	99.1	100
60.5	45.7	57.2	80.4	93.2	95.9	98.8	99.9	100	100
70.4	66.0	74.1	88.7	95.8	97.7	100	100	100	100

recrystallized for fixed values of % CW are illustrated in Fig. 9 to 14 based on the earlier figures.

It is observed from Tables 3 to 8 that the % R_x of annealed and homogenized 6061 and 6069 ingots (6061-A, 6061-H, 6069-A, and 6069-H) is higher than that of as-cast 6061 and 6069 ingots (6061-AC and 6069-AC) at a given % CW and heat-treatment temperature. There is no significant difference in % R_x between annealed ingots and homogenized ingots for a given compaction

Table 7 The fraction (%) recrystallized of rolled 6061 homogenized ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness Reduction (%)	Annealing Temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
10.4	0.0	0.0	0.0	1.1	2.4	6.0	7.2	8.2	8.6
20.2	0.0	0.0	4.3	8.7	11.8	18.4	20.6	24.6	28.7
30.4	0.0	3.6	10.3	21.4	28.3	40.0	41.3	56.8	81.2
40.1	1.5	13.3	20.5	29.9	47.8	52.9	74.2	85.6	92.3
50.4	13.4	25.1	30.6	45.4	64.8	71.6	80.2	91.4	96.0
60.5	30.2	48.3	50.2	66.9	79.4	84.2	89.1	95.0	100
70.4	52.3	60.4	67.6	72.4	86.3	90.0	94.0	100	100

Table 8 The fraction (%) recrystallized of rolled 6069 homogenized ingot (thickness reduction 10 to 50%) after 1 h heat treatment at various temperatures (316 to 538 °C)

Thickness Reduction (%)	Annealing Temperature								
	316 °C	343 °C	371 °C	399 °C	427 °C	454 °C	482 °C	510 °C	538 °C
10.4	0.0	0.0	1.2	3.8	4.2	5.9	6.9	7.6	8.7
20.1	0.0	6.8	8.0	12.8	15.8	18.9	22.4	25.7	29.6
30.3	1.3	7.4	24.2	32.7	38.1	47.4	58.0	64.9	70.1
40.2	3.0	19.1	39.9	50.1	70.1	84.1	88.0	90.2	92.7
50.0	24.1	37.1	64.2	87.5	90.1	91.2	94.5	97.6	98.8
59.8	43.9	54.2	79.2	90.2	95.3	96.1	99.1	100	100
70.2	61.5	72.2	92.3	92.4	98.1	100	100	100	100

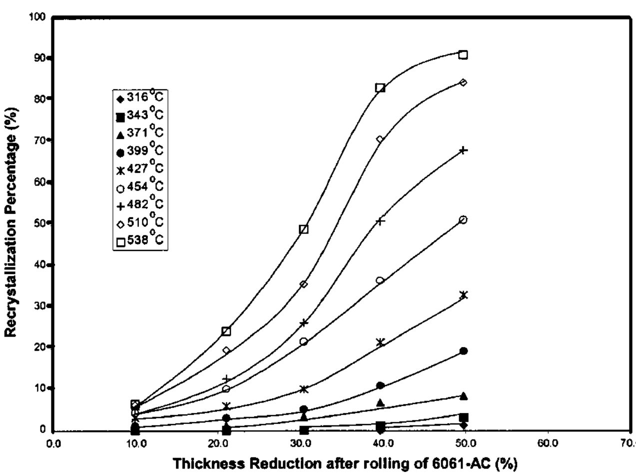


Fig. 3 The relationship between % CW of rolled 6061 as-cast ingot and % R_x after heat treatment at various temperatures for 1 h

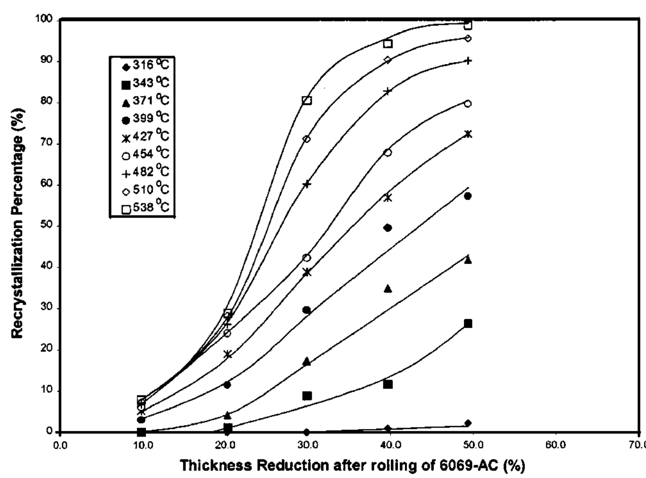


Fig. 4 The relationship between % CW of rolled 6069 as-cast ingot and % R_x after heat treatment at various temperatures for 1 h

at a fixed reduction in thickness and heat-treatment temperature. It is also observed from Tables 3 and 4 that the % R_x of 6069-AC is higher than that of 6061-AC ingot at a given % CW and heat-treatment temperature, especially at low heat-treatment temperatures. The % R_x of annealed 6069 ingot (6069-A) and homogenized 6069 ingot (6069-H) is higher than that of corresponding 6061 ingots at a given thickness reduction and heat-treatment temperature, but the difference may not be as substantial as that of as-cast ingots.

Figure 15 to 17 are micrographs that illustrate 6061 and

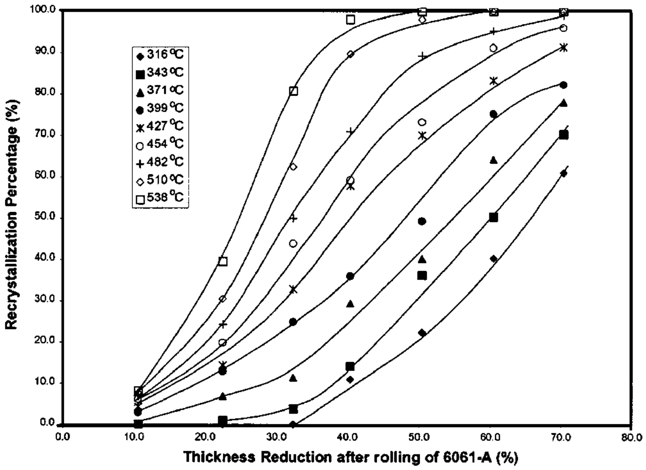


Fig. 5 The relationship between % CW of rolled 6061 annealed ingot and % R_x after heat treatment at various temperatures for 1 h

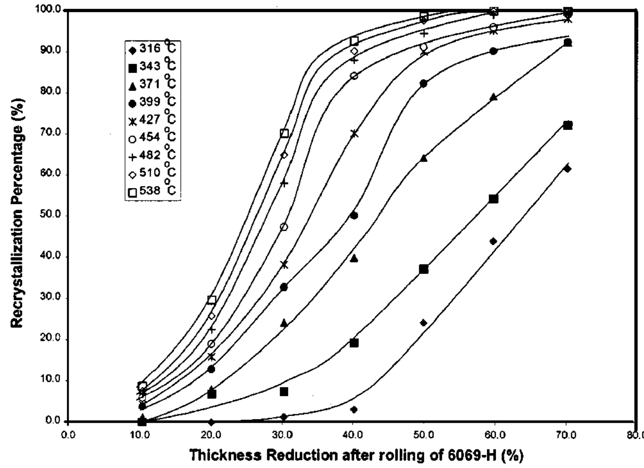


Fig. 8 The relationship between % CW of rolled 6069 homogenized ingot and % R_x after heat treatment at various temperatures for 1 h

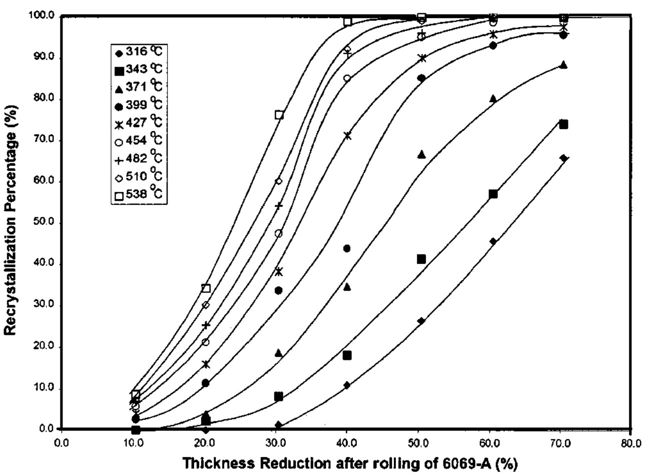


Fig. 6 The relationship between % CW of rolled 6069 annealed ingot and % R_x after heat treatment at various temperatures for 1 h

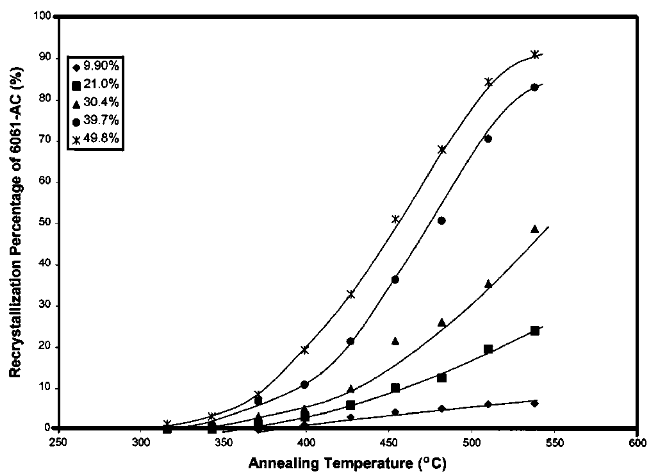


Fig. 9 The relationship between heat-treatment temperature and % R_x of rolled 6061 as-cast ingot for various % CW for a heat treatment time of 1 h

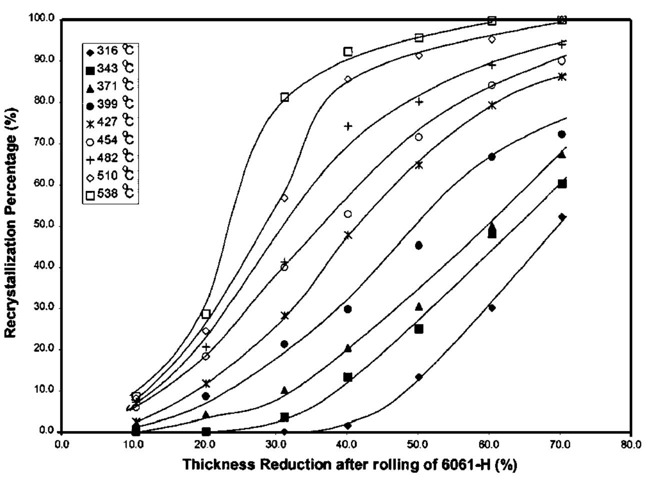


Fig. 7 The relationship between % CW of rolled 6061 homogenized ingot and % R_x after heat treatment at various temperatures for 1 h

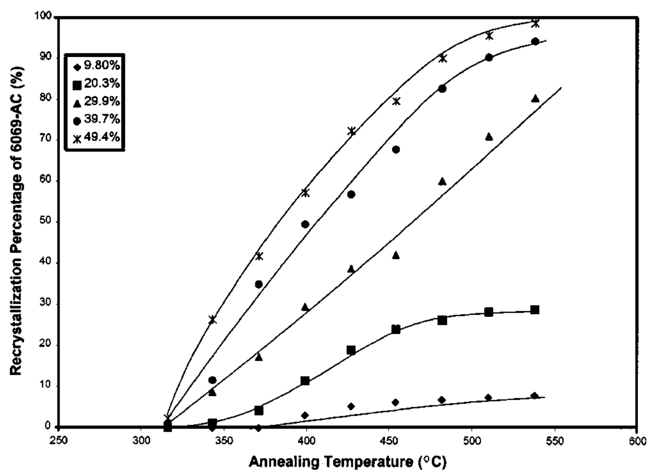


Fig. 10 The relationship between heat-treatment temperature and % R_x of rolled 6069 as-cast ingot for various % CW for a heat treatment time of 1 h

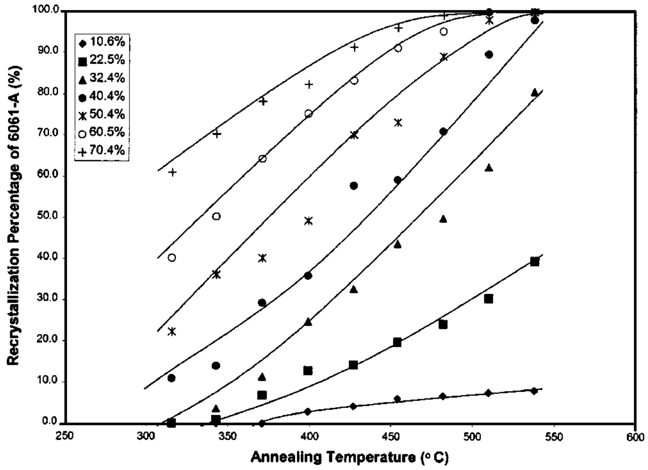


Fig. 11 The relationship between heat-treatment temperature and % R_x of rolled 6061 annealed ingot for various % CW for a heat treatment time of 1 h

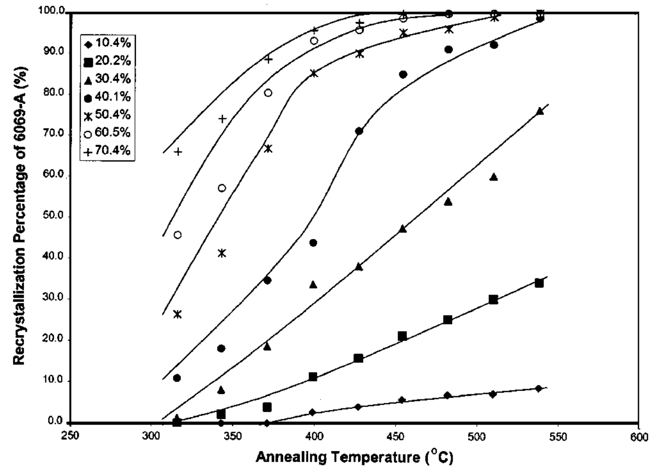


Fig. 12 The relationship between heat-treatment temperature and % R_x of rolled 6069 annealed ingot for various % CW for a heat-treatment time of 1 h

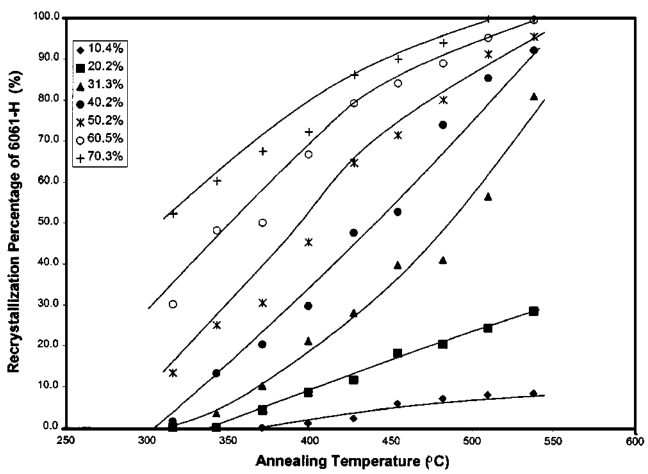


Fig. 13 The relationship between heat-treatment temperature and % R_x of rolled 6061 homogenized ingot for various % CW for a heat-treatment time of 1 h

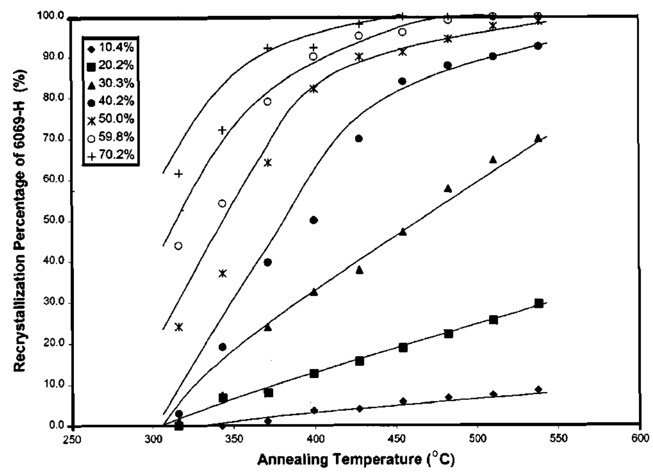
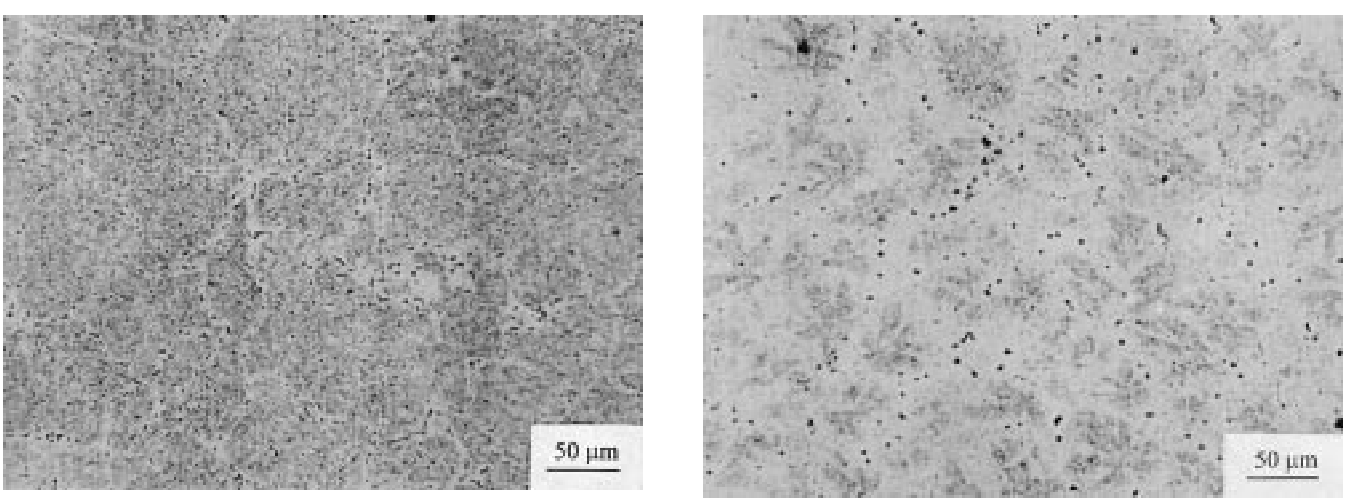
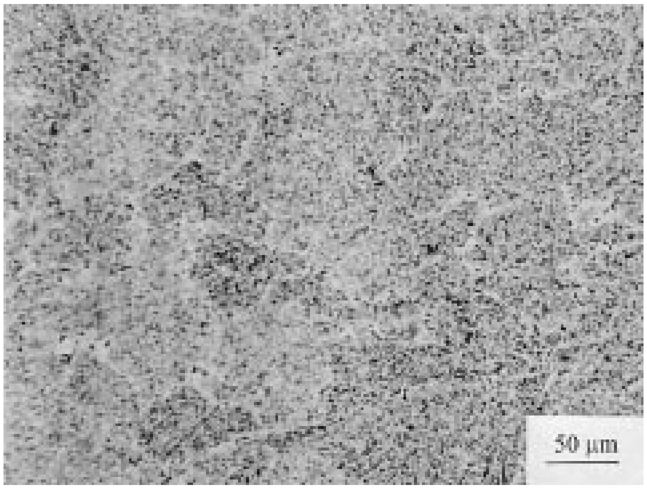


Fig. 14 The relationship between heat-treatment temperature and % R_x of rolled 6069 homogenized ingot for various % CW for a heat-treatment time of 1 h

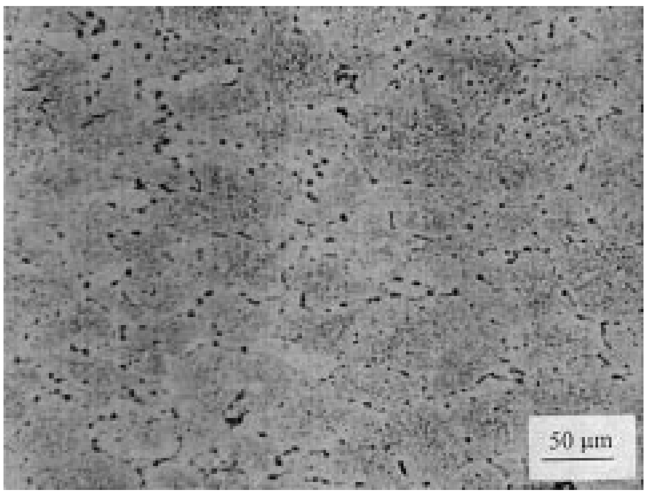


(**a**) (**b**)

Fig. 15 Microstructure of homogenized (**a**) 6061-H and (**b**) 6069-H before rolling

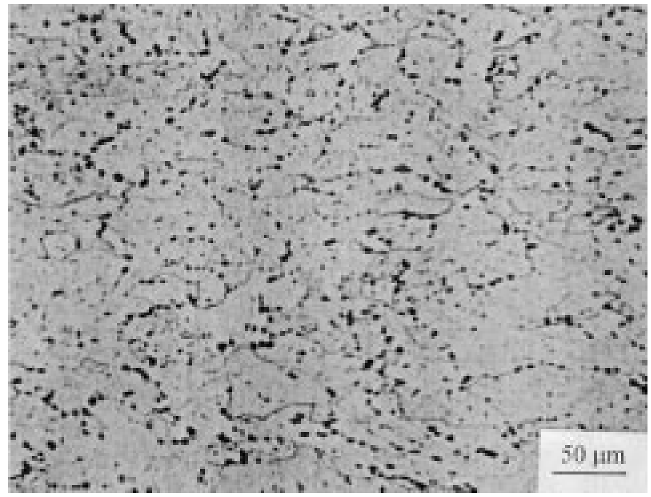


(**a**)

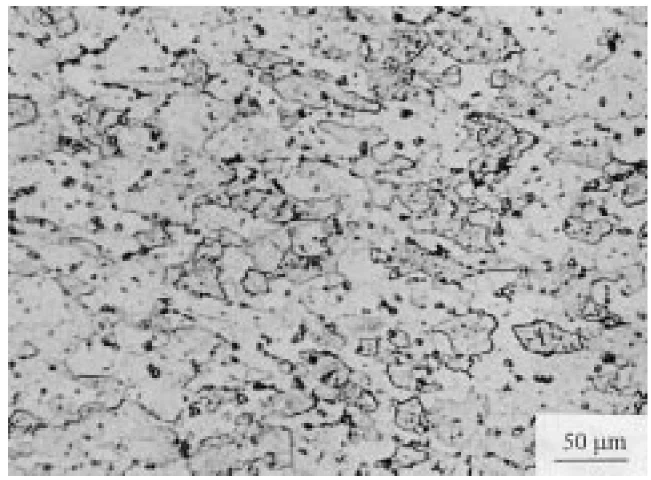


(**b**)

Fig. 16 Microstructure of rolled (**a**) 6061-H (1.5% R_x) and (**b**) 6069-H (3% R_x) with a 40% thickness reduction following heat treatment at 316 °C for 1 h



(**a**)



(b)

Fig. 17 Microstructure of rolled (**a**) 6061-H (74.2% R_x) and (**b**) 6069-H (88% R_x) with a 40% thickness reduction following heat treatment at 482 °C for 1 h

6069 recrystallization trends. Figure 15 shows the microstructure of the homogenized ASDC 6061 and 6069 ingots prior to rolling. The differences in etching are believed to be at least substantially structurally and compositionally based. Figure 15 also shows the differences in particle concentrations, with homogenized 6069 clearly having a higher concentration of larger (and smaller[1]) particles. Figure 16 shows only a small amount of recrystallization (1 to 3%) after 1 h at 316 °C for 40% CW. Figure 17 shows recrystallization in homogenized 6061 and 6069, 40% CW (as in Fig. 16), with 88% recrystallization for 6069, and only 74% in 6061 for heat treatment at 482 °C for 1 h. The difference in the recrystallization behavior may be related to the increased alloy additions, in excess of the solubility, leading to relatively large second-phase particles, particularly $MgSi_2$. This can lead to particle stimulated recrystallization.[3]

4. Conclusions

- The rolling characteristics (% reduction before cracking) of 6069 ASDC ingots are similar to those of 6061 ingots. Annealed and homogenized 6061 and 6069 ingots have better rolling characteristics than as-cast 6061 and 6069 ingots.
- As expected, the results of microstructural observation and image analysis indicate that the % R_x at a given heat-treatment temperature increases as the fraction reduction in thickness (% CW) increases for all rolled ingots of 6061 and 6069. The % R_x increases as the heat-treatment temperature increases for all rolled ingots of 6061 and 6069 alloys, as expected.

- The % R_x for annealed and homogenized 6061 and 6069 ingots is higher than that of as-cast 6061 and 6069 ingots at a given % CW and heat-treatment temperature. There is no significant difference in % R_x between annealed ingots and homogenized ingots at a given % CW composition and heat-treatment temperature.
- The % R_x for 6069-AC ingot is higher than that of 6061-AC ingot at a given % CW and heat-treatment temperature, especially at low heat-treatment temperatures. The % R_x of annealed 6069 ingot (6069-A) and homogenized 6069 ingot (6069-H) is also higher than that of corresponding 6061 ingots at a given % CW and heat-treatment temperature, although the differences are not as substantial as for as-cast alloys. The difference in the recrystallization behavior may be related to the increased 6069 alloy additions, in excess of the solubility, leading to relatively large second-phase particles, particularly $MgSi_2$. This can lead to particle-stimulated recrystallization.

Acknowledgments

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