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Investigation of The Effect of Thermomechanical Processing on The Mechanical Properties of Recycled Aluminum Alloys

Ergashev Jaxongir Oblakulovich
Trainee Lecturer, Yangiyer Branch of Tashkent Institute of Chemical Technology, Uzbekistan

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Abstract: Recycled aluminum alloys offer large energy savings, yet accumulated impurities, particularly iron, often reduce strength and ductility. This article examines how thermomechanical processing influences the mechanical properties of a recycled Al–Mg–Si alloy. A processing matrix combining three hot-deformation temperatures (400, 450 and 500 °C) and two thickness reductions (30% and 60%), followed by solution treatment and artificial aging, is evaluated through tensile testing, Vickers hardness, electron backscatter diffraction and two-way analysis of variance. Because no verified laboratory dataset is available, the quantitative results are explicitly hypothetical scenario values, not measurements. They illustrate how lower deformation temperature and larger reduction refine grains and raise strength, whereas higher temperature favors ductility through fragmentation of iron-rich particles. The framework supports reproducible experimental validation and informs industrial processing of recycled wrought aluminum.

Keywords: Recycled aluminum alloys; thermomechanical processing; mechanical properties; microstructural evolution; heat treatment; hardness; tensile strength; material recycling.

Introduction: Aluminum alloys are widely used in transport, construction and packaging because of their low density, corrosion resistance and formability, but primary production from ore is very energy-intensive [1, 2]. Melting scrap needs only about 5% of the energy of ore reduction [1], and about 15 MJ/kg against 180 MJ/kg has been quoted for secondary and primary production [2]; scrap preparation and melting largely determine the quality of the recycled metal [3]. The difficulty is that contamination raises iron, copper and manganese levels. Iron forms brittle, needle-like intermetallics that lower ductility, and repeated remelting coarsens the microstructure [2]; impurities also alter precipitation and the response to processing [1].

Thermomechanical processing combines deformation and heat treatment. In general metallurgical terms, hot deformation introduces substructure, drives recovery or recrystallization and fragments coarse particles, while solution treatment and aging set grain size and precipitation; strength rises with grain refinement, whereas high temperatures favor softening. Published work on recycled aluminum is dominated by casting and remelting, and the combined effect of deformation temperature and magnitude on recycled wrought-type alloys has not been mapped systematically (Section 4). The objective of this study is to quantify and explain the effect of thermomechanical processing on the mechanical properties of a recycled Al–Mg–Si alloy. The tasks are to (i) define a processing matrix, (ii) determine strength, elongation and hardness, (iii) characterize grains and Fe-rich particles, and (iv) relate microstructure to properties and to the literature.

LITERATURE REVIEW

Reviews agree that scrap quality limits performance: impurity effects on precipitation and processing [1], Fe-rich phases as the main cause of downcycling [2] and the importance of scrap preparation and melting [3]. Notably, the survey in [2] excluded non-casting routes such as extrusion and called for solid mechanical

characterization, so processing after melting is under-examined. Studies involving deformation show that recycled metal can reach standard properties. Extruded and T6- or T73-treated recycled 7075 exceeded ASTM B209-14 and B221M-13 requirements [4]; 6181 sheet with high scrap content behaved like primary material, but with lower biaxial formability [5]; and solid-state recycled EN AW 6082 chips (hot extrusion, ECAP and heat treatment) matched commercial T6 properties, with a lower extrusion ratio acceptable when ECAP and heat treatment followed [6]. Each of these tests one fixed route, however, and none varies deformation temperature and magnitude.

Casting studies show how phase control governs ductility. A Mn content of 0.40–0.60 wt.% (Mn/Fe ≈ 1) and high cooling rates give fine α-Al15(Fe,Mn)3Si2 and shift crack initiation to eutectic silicon [7], and sludge-particle nucleation depends on the Fe, Mn and Cr levels and on cooling rate [8]. Repeated remelting of AlSi9Cu3 lowered strength and elongation by the fourth cycle [9], although aging restored properties in multiply remelted alloy (as summarized in [2]), and alloys with 0.9 and 4.2 wt.% Fe differed in Fe-phase morphology and porosity [10] (as described in [2]). These works control intermetallics through composition and cooling, not deformation. The gap is therefore a factorial study of deformation temperature and magnitude in a recycled wrought-type alloy linked quantitatively to grain and particle state, which this study addresses.

MATERIALS AND METHODOLOGY

Materials

The alloy is a recycled 6xxx Al–Mg–Si alloy from sorted extrusion scrap, argon-degassed, grain-refined and direct-chill cast, then homogenized (540 °C, 6 h) to an equiaxed grain structure with coarse Fe-rich particles. Its nominal composition (hypothetical) is given in Table 1 with AA6061 limits.

Table 1. Chemical composition (wt.%; hypothetical) and AA6061 limits.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.72	0.38	0.21	0.09	0.85	0.06	0.12	0.03	Bal.
0.40–0.80	≤ 0.70	0.15–0.40	≤ 0.15	0.80–1.20	0.04–0.35	≤ 0.25	≤ 0.15	Bal.

Row 1: recycled alloy (hypothetical); row 2: AA6061 limits.

Thermomechanical Processing

Slabs (40 × 80 × 150 mm) are heated at 10 °C/min to 400, 450 or 500 °C and soaked for 30 min, then hot rolled in multiple passes (reheating 5 min between passes) at a mean strain rate of about 1–3 s^{-1} and air cooled. Strips are solution treated (530 °C, 1 h), water quenched (delay < 10 s), naturally aged for 24 h and artificially aged (175 °C, 8 h).

Experimental Design

A full factorial design of three temperatures and two reductions plus a reference without hot rolling gives seven conditions (Table 2).

Table 2. Experimental design (all conditions receive the same solution and aging treatment).

Code	Temperature (°C)	Reduction (%)	True strain (–)
AR-T6	none	0	0
TMP-1	400	30	0.36
TMP-2	400	60	0.92
TMP-3	450	30	0.36
TMP-4	450	60	0.92
TMP-5	500	30	0.36
TMP-6	500	60	0.92

Mechanical Testing

Yield strength (0.2% offset), tensile strength and elongation are measured on sub-size flat specimens (25 mm gauge, rolling direction; n = 5) per ASTM E8/E8M at 10^{-3} s^{-1} with an extensometer. The strain-hardening exponent follows from a Hollomon fit. Vickers hardness (HV5, ASTM E92) uses ten indents, and fracture surfaces are examined by SEM.

Microstructural Analysis

Sections are prepared per ASTM E3. Grain size (mean equivalent diameter, 15° threshold) and low-angle boundary fraction are obtained by EBSD (1 µm step, ≥ 500 grains); Fe-rich particles are measured by SEM-BSE image analysis. Microstructural parameters are plotted against properties.

Data Analysis

Results are mean ± SD. After Shapiro–Wilk and Levene checks, two-way ANOVA (α = 0.05) with Tukey's test assesses temperature, reduction and interaction; each condition is compared with the reference by Welch's t-test with Bonferroni correction. Yield strength is regressed on grain size$^{-½}$. No p-values are given for the hypothetical data.

RESULTS AND DISCUSSION

All values below are hypothetical scenario values built to follow trends in [4, 6, 7]; they are not findings.

Mechanical response

In the illustrative scenario every processed condition exceeds the reference in strength, elongation and hardness (Table 3). Strength falls with temperature: at 60% reduction yield strength drops from 281 to 270 and 258 MPa between 400 and 500 °C, while elongation rises from 12.4% to 13.4%, consistent with faster recovery and more complete particle fragmentation at higher temperature. Larger reduction raises strength at every temperature, most strongly at 400 °C (262 to 281 MPa), where recovery is slowest. Simultaneous gains in strength and ductility, unlike pure work hardening, would indicate that particle refinement offsets strain hardening; real data must confirm this.

Table 3. Mechanical properties after processing (mean ± SD, n = 5; hypothetical).

Condition	T (°C)	Reduction (%)	YS (MPa)	UTS (MPa)	Elongation (%)	Hardness (HV5)
AR-T6	–	0	246 ± 5	292 ± 5	10.8 ± 0.6	96 ± 2
TMP-1	400	30	262 ± 4	306 ± 4	11.5 ± 0.5	101 ± 2
TMP-2	400	60	281 ± 4	322 ± 5	12.4 ± 0.5	108 ± 2
TMP-3	450	30	255 ± 5	299 ± 4	11.9 ± 0.6	99 ± 2
TMP-4	450	60	270 ± 4	313 ± 4	13.0 ± 0.5	104 ± 2
TMP-5	500	30	249 ± 5	293 ± 5	12.1 ± 0.6	97 ± 2
TMP-6	500	60	258 ± 5	301 ± 4	13.4 ± 0.6	100 ± 2

YS: yield strength; UTS: ultimate tensile strength.

Microstructure and structure–property relationships

The scenario grain size falls from 82 µm to 24 µm (400 °C, 60%) and only 66 µm (500 °C, 30%), with low-angle boundaries (retained substructure) and Fe-rich particle size following the same ordering (Table 4). A fit of yield strength against grain size$^{-½}$ gives an apparent slope of about 376 MPa·µm½, intercept 203 MPa and $R^2 = 0.989$ (hypothetical); the slope exceeds usual Hall–Petch constants because substructure and particle fragmentation vary together with grain size, so it is not a pure grain-boundary term. Table 5 contrasts the strongest (TMP-2) and most ductile (TMP-6) conditions with the reference.

Table 4. Grain-structure parameters (hypothetical).

Condition	Grain size (µm)	Low-angle boundaries (%)	Fe-rich particle size (µm)
AR-T6	82	12	6.8
TMP-1	41	46	5.1
TMP-2	24	58	4.0
TMP-3	52	38	5.4
TMP-4	31	47	4.3
TMP-5	66	29	5.7
TMP-6	43	36	4.6

Table 5. Change relative to the reference condition (hypothetical).

Property	AR-T6	TMP-2	Change (%)	TMP-6	Change (%)
YS (MPa)	246	281	+14.2	258	+4.9
UTS (MPa)	292	322	+10.3	301	+3.1
Elongation (%)	10.8	12.4	+14.8	13.4	+24.1
Hardness (HV5)	96	108	+12.5	100	+4.2

Comparison with previous studies

The trends agree qualitatively with the literature: deformation plus T6-type treatment brought recycled material to commercial levels [4, 6]; Fe-phase morphology controls ductility [7, 8]; and heat treatment helps degraded recycled alloy [2, 9]. The reduced formability at high scrap content [5] warns that tensile gains do not guarantee forming performance. Suggested figures for real data are stress–strain curves, EBSD maps of AR-T6, TMP-2 and TMP-6, and SEM-BSE images of Fe-rich particles.

CONCLUSION

The literature shows that iron-rich phases limit recycled aluminum, and that deformation with T6-type heat treatment can restore commercial property levels [4, 6]. In the illustrative scenario, low deformation temperature and large reduction refine grains and raise strength and hardness (yield strength up to +14.2%), whereas high temperature maximizes elongation (up to +24.1%) through particle fragmentation. These are scenario outcomes, not measured findings. Recycled extrusions and rolled products could use the processing window chosen for strength or formability. The protocol must now be executed with real data.

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