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SPRAY ROLLING ALUMINUM STRIP FOR TRANSPORTATION APPLICATIONS

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Abstract

Spray rolling is a novel strip casting technology in which molten aluminum alloy is atomized and deposited into the roll gap of mill rolls to produce aluminum strip. A combined experimental/modeling approach has been followed in developing this technology with active participation from industry. The feasibility of this technology has been demonstrated at the laboratory scale and it is currently being scaled-up. This paper provides an overview of the process and compares the microstructure and properties of spray-rolled 2124 aluminum alloy with commercial ingot-processed material.

Introduction

Wrought aluminum flat products for transportation applications are manufactured primarily by conventional ingot processing. Ingots are direct-chill (DC) cast to about 0.6 m thick, scalped, homogenized, hot rolled to about 5-mm-thick re-roll stock, trimmed, and coiled. Following this, the coils are further processed (e.g. heat treated, cold rolled to final gauge, etc.) according to alloy composition and desired properties. Some transportation alloys can be processed into strip by continuous casting approaches such as twin-roll casting. In twin-roll casting, molten aluminum is fed into the gap between large water-cooled rolls where it solidifies to form strip up to about 6 mm thick. Coils of re-roll stock are annealed and cold rolled to final gauge. Commercial twin-roll casting is limited to alloys with a suitably narrow freezing range [1-6].

This paper describes a new strip/sheet casting process termed “spray rolling” that is currently under development at the Idaho National Engineering and Environmental Laboratory (INEEL), University of California-Davis and Colorado School of Mines, in a collaborative program with Alcoa, Pechiney Rolled Products, Inductotherm Corp., and Metals Technology, Inc. In general terms, spray rolling combines features of twin-roll casting and conventional spray forming. A schematic of the approach is shown in Figure 1. Molten aluminum is atomized into small droplets with the aid of a high velocity nitrogen flow and deposited onto mill rolls for consolidation. Much of metal’s latent heat is extracted by convection cooling as the droplets travel from the atomizer toward the rolls, resulting in about 70% solid fraction in the deposited material. The metal is consolidated into strip/sheet while still in a semi-solid and highly formable condition. As with twin-roll casting, it is believed that approximately 15% solid state compaction (hot rolling) occurs as the strip advances through the roll nip.

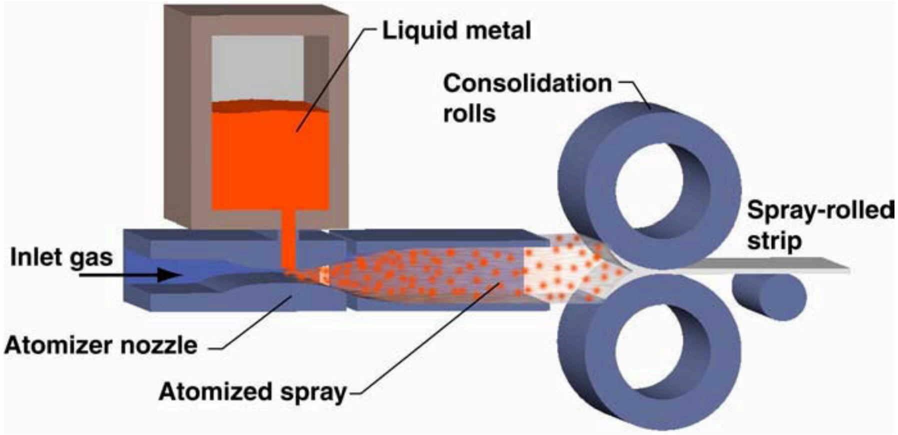

Figure 1. Schematic of spray rolling approach.

While spray rolling shares many similarities with twin-roll strip casting, there are important differences:

1. In twin-roll casting, the metal's latent heat is dissipated almost exclusively by conduction heat transfer to water-cooled rolls. In spray rolling, convection heat transfer from small atomized droplets teams with conduction transfer at the rolls to increase the production rate and limit segregation.
2. The metal introduced to the rolls in twin-roll casting is molten, while in spray rolling, it has a semi-solid "slushy" character. Solid particles in the slush act as nucleation sites, producing a near-equiaxed grain structure with very limited segregation. Aluminum alloys with high alloy content and a broad freezing range have been successfully spray rolled at comparatively high production rates.

The laboratory-scale strip caster at INEEL has, to date, produced strips up to 200 mm wide and 1.6–6.4 mm thick over a production rate range of 1800-4500 kg/h-m. Aluminum transportation alloys processed and analyzed thus far are 2124, 3003, 5083, 6111 and 7050. Plans to upgrade the INEEL caster, scale the process to 500 mm (20") wide sheet, and demonstrate steady-state operation are underway. This paper examines the influence droplet cooling rate has on the microstructure and tensile properties of spray-rolled 2124, and compares these properties with those of ingot-processed material. Further details of spray-rolled 2124 have been published previously [7].

Experimental

2124 alloy was induction heated under a nitrogen atmosphere, superheated about 100°C above the liquidus temperature, and pressure-fed into an atomizer designed and constructed in-house. Atomized droplets were deposited into the roll gap of a 0.2 m x 0.3 m 2-HI Fenn rolling mill (Model 4-081) to produce strips measuring about 200 mm wide by 4.3 mm thick. The mill had standard tool-steel mill rolls that were not water-cooled. A nitrogen atmosphere within the spray apparatus minimized in-flight oxidation of the atomized droplets. Strips were produced at gas-to-metal mass flow ratios (G/M) of 0.15 and 0.3 while maintaining other processing conditions constant. The production rate was 4100 kg/h-m.

The microstructure was evaluated using an Olympus Model PME-3 metallograph. X-ray diffraction was performed using Cu ($K\alpha1 + K\alpha2$) radiation on a Bruker Model D-8 Advance system operating at a sampling rate 0.6° (2 theta) per minute. Resulting patterns were analyzed with EVA software.

Tensile testing was performed with an Instron 4505 screw-driven test machine following the ASTM E-8 procedure. Spray-rolled 2124 strips were heat treated to the T851 temper, with cold rolling substituted for the normal commercial practice of stretching. Samples were solution treated at 493°C for 1 hr, water quenched, cold rolled 3%, and aged at 190°C for 12 hrs. Annealing was performed by heating strip to 413°C, soaking for 5 min to 24h, cooling at 25 °C/h to 232°C, holding at temperature for 4h, followed by slow cooling in the furnace.

Results and Discussion

The nominal composition and melting range of 2124 are summarized in Table I. The broad freezing range makes this alloy difficult to process by twin-roll casting. When processed by spray rolling, the properties of 2124 alloy were found to be sensitive to the solid fraction of the spray when it impacts the rolls. Solid fraction can be controlled by adjusting G/M which influences average droplet size in the spray, and consequently, droplet cooling rate. Strip samples produced at G/M values of 0.15 and 0.30 showed marked differences in constituent particle size and distribution and resultant tensile properties in both the as-spray-rolled and T851 temper states.

Figure 2 compares the microstructure of cast 2124 with as-spray-rolled strips produced at two G/M values. The cast material is characterized by a coarse dendritic structure and extensive interdendritic segregation of the solute-rich phases. In contrast, strip-cast material exhibited a fine-grain size (about 15 μm), nearly equiaxed structure with relatively small Al_2CuMg and Al_2Cu constituents. The material produced at G/M = 0.15 had a somewhat larger average grain size, with larger and more numerous constituent particles, particularly near the surface of the strip. This was due to the solute-rich phase being squeezed to the surface during compaction in the roll gap.

Table I. Nominal composition and melting range of 2124 aluminum alloy

Alloy	Composition	Melting Range
2124	Al-4.4 Cu-1.5 Mg-0.6 Mn	502 – 638°C

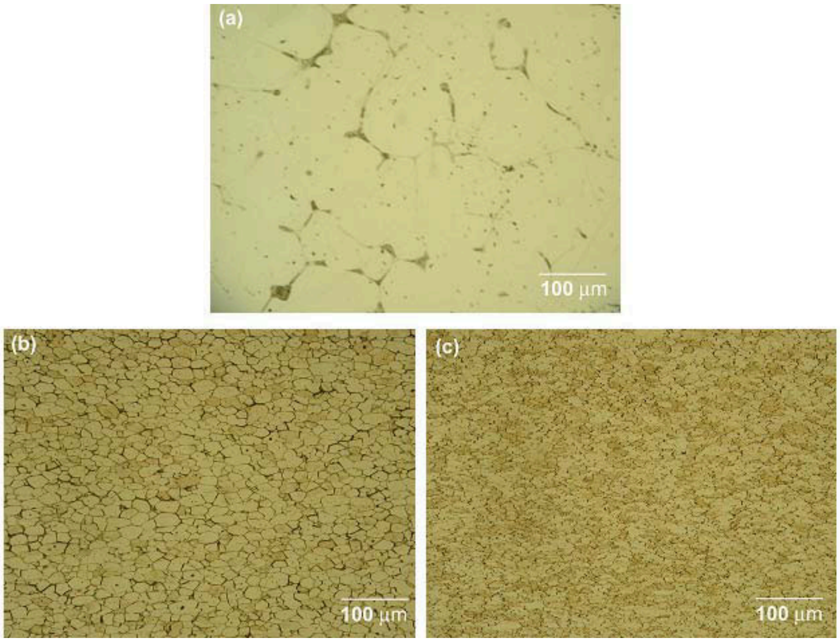

Figure 2. Photomicrographs of 2124 aluminum. (a) Cast. (b) As-spray-rolled using G/M = 0.15. (c) As-spray-rolled using G/M = 0.30.

Tempering spray-rolled 2124 to the T851 condition resulted in a recrystallized grain structure with some spheroidization of constituents. The microstructure of longitudinal sections of strip samples produced at G/M = 0.15 and 0.30 was similar in terms of grain size and morphology (Figure 3a and 3b), with little grain elongation compared to commercial 2124 (Figure 3c) due to the relatively modest amount of rolling during processing. Moreover, tensile properties of transverse and longitudinal sections cut from spray-rolled strip are very nearly identical, in contrast to commercial material. A 1 hour solution heat treatment at 493°C did not effectively redistribute the solute-rich phases. This was best accomplished during processing by controlling droplet cooling rate and solid fraction of the "slush" introduced to the roll gap.

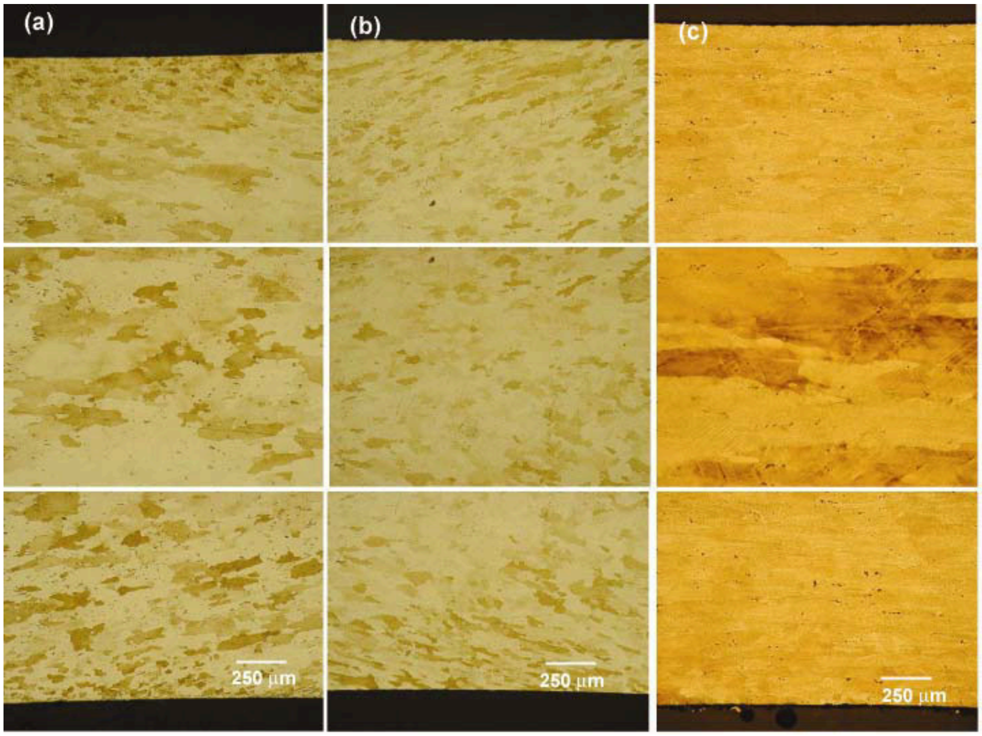

Figure 3. Longitudinal photomicrographs of 2124-T851 aluminum. (a) Spray rolled at G/M = 0.15 near each rolling surface (top, bottom) and near the center of a 4.3 mm thick strip. (b) Same as (a) but spray rolled at G/M = 0.3. (c) Commercial plate near each rolling surface (top, bottom) and near the center.

X-ray diffraction analysis of as-spray-rolled 2124, spray-rolled 2124-T851 and commercial 2124-T851 are summarized in Figure 4. Scan profiles of both 2124-T851 strips were similar. Primary Al peaks in the as-spray-rolled 2124 scan were shifted somewhat due to lattice strain, and show more clearly resolved peaks corresponding to Al_2CuMg and Al_2Cu constituent phases.

Tensile properties of as-spray-rolled 2124 strip and 2124-T851 strip at G/M=0.15 and 0.30 are summarized in Table II. Results indicate that increasing the solid fraction of the "slush" introduced into the roll gap by increasing G/M improves tensile properties. For as-spray-rolled 2124 strip, increasing G/M from 0.15 to 0.30 resulted in an increase in UTS of 39%, an increase in YS of 46% and a doubling of the ductility. This is largely due to a reduction in segregation, particularly at the strip surface, and more uniform distribution of constituent phases at G/M = 0.30. This trend remained following tempering to the T851 condition. Increasing G/M from 0.15 to 0.30 resulted in an increase in UTS, YS and % elongation of 9%, 15%, and 17%, respectively. As shown in Table II, the tensile properties of 2124-T851 produced at G/M = 0.30 compare favorably with those of commercial material.

Table III summarizes tensile properties of spray-rolled and annealed 2124 produced at G/M = 0.15. Annealing was performed by heating strip to 413°C, soaking for 5 min to 24h, cooling at 25°C/h to 232°C, holding at temperature for 4h, followed by slow cooling in the furnace.

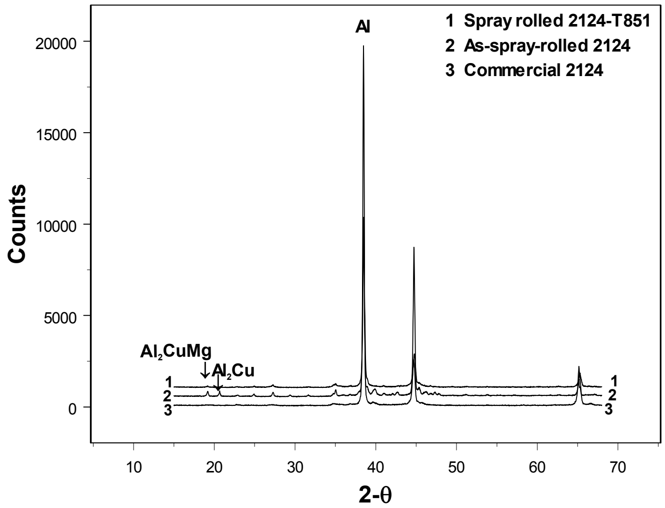

Figure 4. X-ray diffraction scans of as-spray-rolled 2124, spray-rolled 2124-T851 and commercial 2124-T851.

Table II. Tensile properties of as-spray-rolled 2124 and 2124-T851.

Condition	G/M	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Failure (%)
Commercial-T851	-	483	448	6
As spray rolled	0.15	228	179	5
As spray rolled	0.30	317	262	10
Spray rolled –T851	0.15	441	407	6
Spray rolled –T851	0.30	483	469	7

Table III. Tensile properties of annealed 2124. Spray-rolled strip made at G/M = 0.15.

Sample/Soak time at 415°C	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Failure* (%)
Commercial	186	76	20
Spray rolled/ 5 min.	186	90	16
Spray rolled/ 30 min.	200	97	17
Spray rolled/ 1 h.	207	97	18
Spray rolled/ 2 h.	200	97	15
Spray rolled/ 4 h.	200	97	16
Spray rolled/ 8 h.	200	103	15
Spray rolled/ 16 h.	200	97	16
Spray rolled/ 24h.	200	103	18

*The minimum specification for elongation at failure is 12%

Optimal properties were obtained following a soak at 413°C for a period of about 1 h. Compared to commercial 2124, the yield strength of spray-rolled 2124 was higher and the ductility somewhat lower, suggesting the commercial practice for annealing 2124 may not be optimized for spray-rolled 2124.

Conclusions

1. Spray rolling is a new strip/sheet casting technology that shows promise for processing a wide variety of aluminum alloys. By combining convection cooling of atomized droplets with conduction cooling at the rolls, aluminum alloys with wide freezing ranges can be processed at rates that significantly exceed those of today's commercial twin-roll casters.
2. The quality of strip exiting the spray-roll strip caster is sensitive to the solid fraction of the "slush" introduced to the rolls. Low solid fraction can lead to a poor distribution of constituents and surface segregation that decreases tensile properties. With an appropriate solid fraction, strip tensile properties meet or exceed those of strip processed by the conventional ingot practices while eliminating ingot casting, homogenization, and hot rolling unit operations.

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