INLINE MEASUREMENTS OF TEXTURE AND RECRYSTALLIZATION ON ALUMINUM ALLOYS

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Abstract: The recrystallization of hot-rolled aluminum strips was monitored inline after inline annealing at Commonwealth Aluminum Corporation (CAC) using laser-ultrasonics. The non-contact measurement is based on sensing the ratio of the compressional to the shear sound velocity in the strip thickness direction. This ratio is insensitive to strip thickness variations and varies with crystallographic texture and temperature. Therefore, recrystallization is sensed as a change of texture, from a rolling to an annealing texture. A pyrometer is used to decouple temperature and texture effects on the velocity ratio. The measurements were made on two alloys: AA5754 and AA5052. The capabilities and limitations of the sensor are discussed.

Introduction: Aluminum sheets are often made by melting scrap aluminum, adjusting the chemistry, casting using a twin belt caster, hot rolling, cooling, batch annealing, and cold rolling. Clearly, letting the hot-rolled coil cool to subsequently anneal in a batch anneal furnace is less energy efficient than would be a new process involving hot rolling followed immediately by inline annealing. Moreover, energy savings and sheet quality would be optimal if the degree of recrystallization, a critical parameter in determining formability, could be sensed inline, following inline annealing. The inline annealing process (see Fig. 1) was demonstrated at the Commonwealth Aluminum Corporation (CAC) in Carson, California, together with a novel laser-ultrasonic sensor to monitor recrystallization. This paper reports on the ability of the laser-ultrasonic sensor to monitor recrystallization inline.

Recrystallization measurement using laser-ultrasonic resonance spectroscopy: Previous work[1-3] has shown that during recrystallization, the ultrasound velocity (longitudinal and transverse) varies monotonically from some initial, hot- or cold-rolled value, to a final, annealed value. These velocity variations are essentially caused by changes in the crystallographic orientation distribution (also called texture) that occur during recrystallization. Generally, these initial and final velocities depend on temperature, alloy grade, and processing. However for a given industrial production line and alloy, a calibration can be obtained as a function of recrystallization state and temperature.

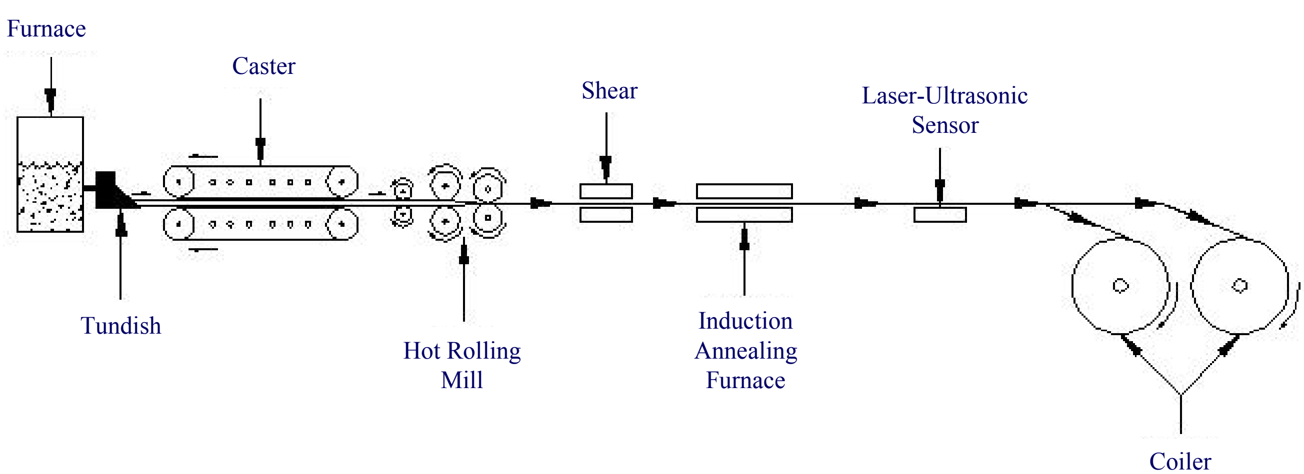
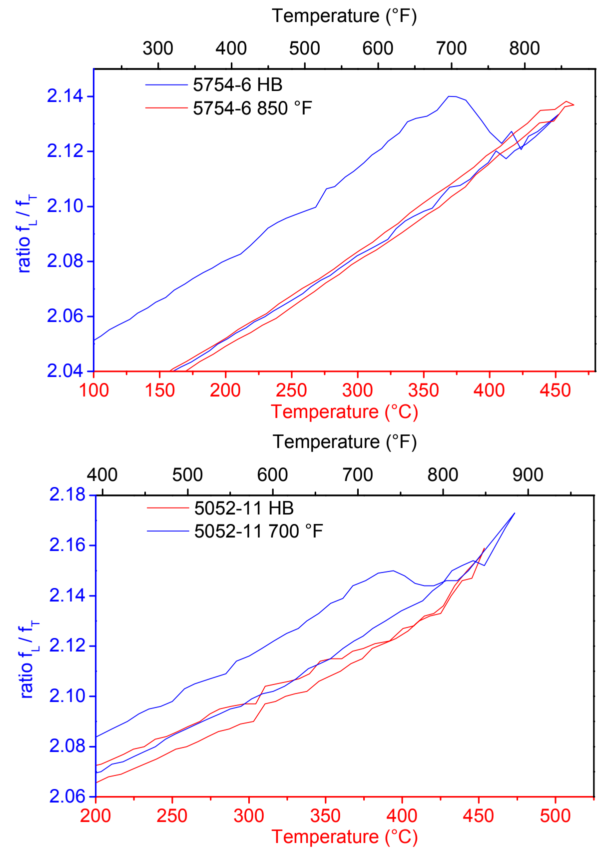


Figure 1. Schematics of the inline annealing process, including inline laser-ultrasonic monitoring of recrystallization.

In practice, we do not measure ultrasound velocity, but the resonance frequency of an acoustic mode in the thickness of the strip because measuring such resonance frequencies allows unambiguous measurements of shear waves (precise velocity measurements of shear waves are difficult in the time domain). To relate a resonance frequency to velocity, one could measure thickness, but introducing a sufficiently accurate (of order 0.1%) thickness gauge in the process would add cost. Thickness can also be measured ultrasonically, independently of texture, using laser-ultrasound resonance spectroscopy.[4] Still, a simpler approach can be used. The ratio of two sound velocities (or the ratio of two resonance frequencies) is independent of thickness and also varies with temperature and texture variations during recrystallization. Therefore, the ratio of the longitudinal to transverse resonance frequencies can be used to monitor the recrystallization state. Although such measurements were made using EMATs at selected temperatures for a few samples,[1] we have re-made such measurements using laser-ultrasonic resonance spectroscopy and a Gleeble thermomechanical simulator on samples from CAC's production line. Two samples were selected from each of two grades: a hot band sample (ID 5754-6 HB and ID 5052-11 HB) and an inline annealed sample (ID 5754-6, 850 °F and ID 5052-11, 700 °F). Here, 5754 and 5052 in the sample ID relates to the alloy grades which are AA5754 and AA5052, respectively. Also, the 850 °F and 700 °F designation refer to an approximate inline annealing temperature. The samples were heated to 500 °C (932 °F) and cooled back to room temperatures. The heating and cooling rates were 1 °C/s. Figures 2a and 2b show the ratio of the longitudinal to transverse resonance frequency, f_L/f_T, measured *in-situ* during thermal processing.

Metallographic and texture measurements of the inline annealed samples show that these samples were fully recrystallized before they were heat treated in the Gleeble. In agreement with this, the two annealed samples displayed a completely reversible behavior of f_L/f_T vs. temperature. On the other hand, the hot bands samples should not be fully recrystallized and recrystallization should occur during thermal treatment in the Gleeble. Correspondingly, the ratio f_L/f_T is initially higher than for the annealed samples and suddenly drops above a certain temperature to rejoin the behavior of the annealed samples (see Fig. 2). Once fully recrystallized, as the temperature is raised to a maximum value and subsequently lowered back to room temperature, the dependence of f_L/f_T on temperature for the hot band samples is identical to that of the inline annealed samples. Note that the temperature at which recrystallization begins is approximately 370 °C for the alloy 5754, and approximately 390 °C for the alloy 5052.



a) b)

Figure 2. Temperature dependence of the ratio of the longitudinal to transverse sound velocity during heating and cooling at a rate of 1 ºC/s for, a) two samples of AA5754 and, b) two samples of AA5052. The designation HB (blue line) refers to hot band samples that are not fully annealed, while the temperature designation (850 ºF or 700 ºF, red line) refers to the approximate maximum temperature the inline annealed samples reached during inline annealing.

Experimental setup, measurements, and data analysis: The laser-ultrasound measurement system was installed to monitor the strip approximately 5 meters after the induction annealing furnace and before the coilers (Fig. 1). The ultrasound was generated by a KrF excimer laser providing 15 ns, 600 mJ pulses of ultraviolet light at 248 nm. The detection laser interferometer consisted of an infrared long-pulse laser of 200 µs duration, 1064 nm wavelength, and 200 mJ/pulse, and a 50 cm confocal Fabry-Perot interferometer. The system was assembled from laboratory components mounted in a rugged protective enclosure. The generation laser was located under a roller table used to guide the strip from the annealing furnace to the coilers. This is shown in Fig. 3, where the generation laser is contained within the large blue box. The laser light was fully contained within the laser enclosure until it passed through a hole made in the roller table, to impinge on the bottom side of the aluminum strip (there is no aluminum strip in Fig. 3). The detection laser interferometer was located remotely in a simple cabin and the light traveled from the laser to the enclosure under the line within an optical fiber. The reflected laser light was collected through the same hole and sent to the interferometer using another optical fiber. Some of the light reflected from the aluminum strip was diffusely scattered and could escape the small gap between the strip and the roller table. A vertical shield at the edge of the roller table and a safety perimeter provided the necessary laser light protection. A one-sided pinch roll (shown in retracted upward position in Fig. 3) was also used to maintain the strip height no higher than about 10 cm above the roller table. In addition, other safety measures insured that the lasers could not be fired when no aluminum strip was present.

As indicated in Fig. 2, it is necessary to know the strip temperature to monitor the recrystallization state by measuring the ratio f_L/f_T. To this end, a Williamson multi-wavelength pyrometer was installed above the strip, at the exit of the annealing furnace, as shown in Fig. 3. Also, a broadband infrared (8-12 μm wavelength) camera was installed at the same location as the camera that took the picture of Fig. 3. This camera measured the temperature drop from the furnace exit to the laser-ultrasonic measurement point. Finally, contact measurements were also made sporadically using a thermocouple mounted on wheels. Unfortunately, an incident damaged the pyrometer's wiring during the inline measurements and the pyrometer data could not be used for the analysis presented in this paper. However, the pyrometer data was sufficient to provide a calibration of the infrared camera for the AA5754 alloy. Consequently, the camera and this calibration had to serve as the primary temperature sensor. The calibration of the infrared camera was done for the location under the pyrometer and we defined the temperature at that point as the temperature at the exit of the furnace, or "Furnace temperature" in Figs. 6. The temperature at the laser-ultrasonic measurement point was approximately 15 to 30 ºC cooler, depending on strip thickness and line speed, due to the time delay (approximately 4 s) and air-cooling between the two locations.

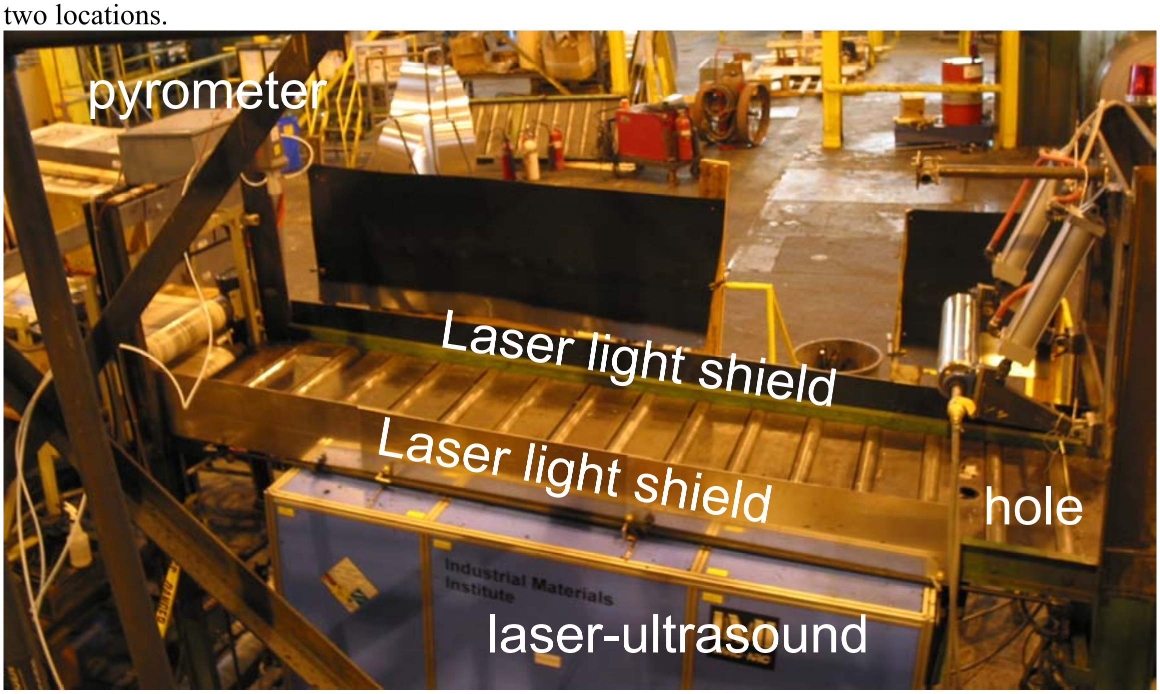


Figure 3. Roller table guiding the strip from the inline annealing furnace (outside the left side of the picture) to the coilers (outside the right side of the picture). Identified on the picture are the enclosure containing the generation laser, the hole allowing the laser light to reach the strip, the pyrometer, and laser light shields. One can also see a pinch roll to the right.

The repetition rate of the lasers was 40 Hz and limited by the power supplies of the detection laser. However, it the repetition rate could be increased up to 400 Hz using other commercially available components. The signal was averaged 20 to 100 times to improve signal to noise ratio. Therefore, the measurement rate was of order one per second. The surface displacement was recorded as a function of time using a 1 GSample/s, 8-bit digitizer. One such time signal measured at approximately 300 ºC for a 2.7 mm thick strip is shown in Fig. 4. The signal was Fourier transformed and an average of 100 Fourier transforms is shown in Fig. 5. The sixth harmonic shear resonance and the fifth harmonic longitudinal resonance locations are located within the blue and red lines, respectively. The center frequency of all harmonics with sufficiently high signal to noise ratio were measured and divided by the order of the harmonics to provide multiple measurements of the fundamental resonance frequency. These measurements were averaged together and the ratio f_L/f_T was computed.

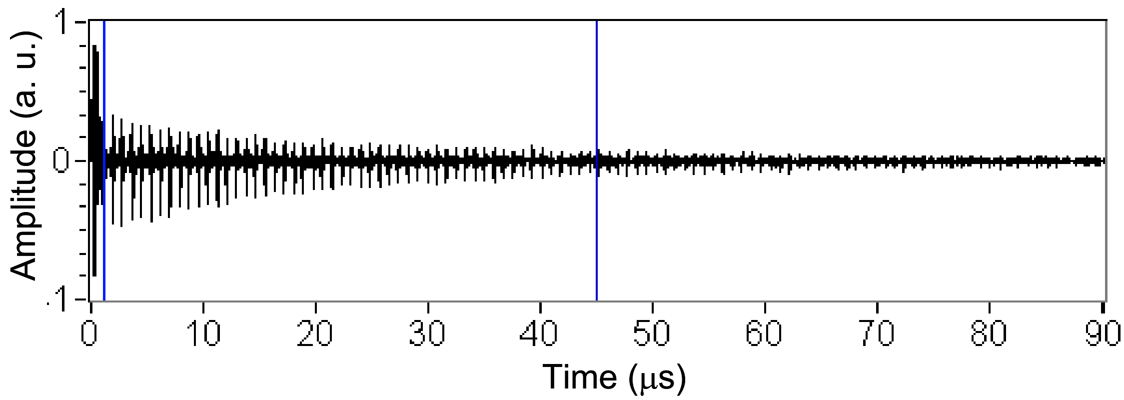


Figure 4. Single-shot measurement of surface displacement as a function of time as measured inline at a temperature of approximately 300 ºC.

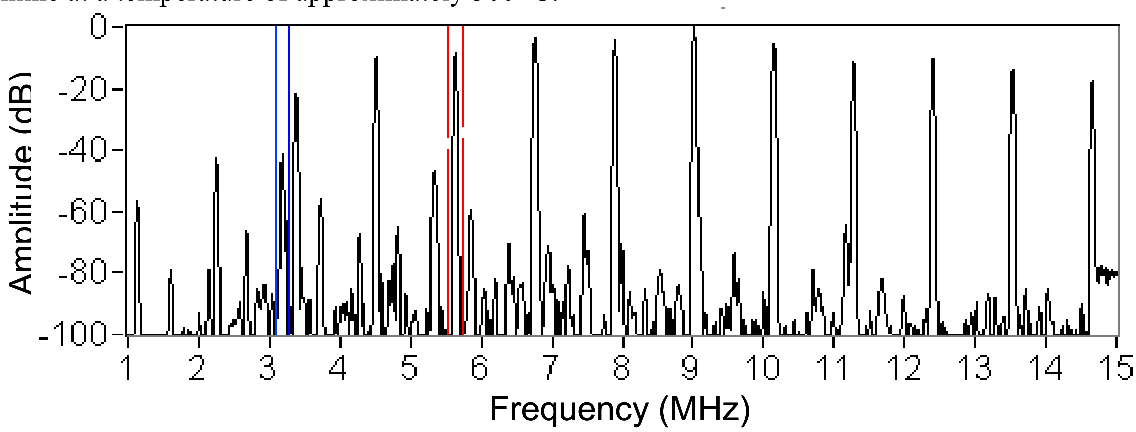
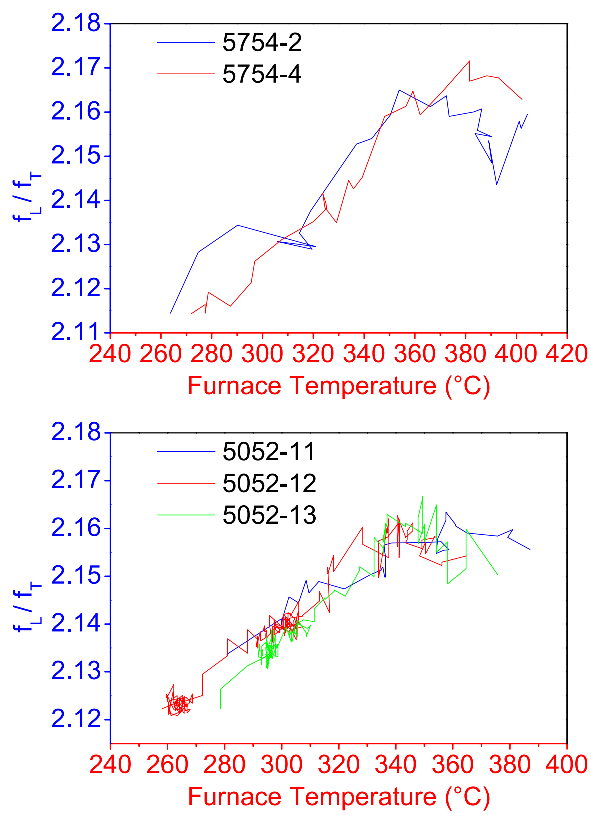


Figure 5. Average of 100 Fourier transforms of signals similar to Figure 4. The sixth harmonic shear resonance and the fifth harmonic longitudinal resonance are located within the blue and red lines, respectively.

Results: The line was started and the strip was guided through the inline annealing furnace, onto the roller table, and to the coiler. After a moment, power was increased in steps at the annealing furnace until the strip reached some maximum temperature that was hopefully above the necessary temperature for inline annealing. Then the line was stopped. Therefore, the laser-ultrasonic measurements were made at temperatures ranging from that of the hot strip before annealing (when there was no power applied to the annealing furnace), to some maximum temperature after annealing. As temperature increased, the signal to noise ratio of the measurement decreased due to an increase in ultrasonic absorption with increasing temperature. This absorption phenomenon affects primarily the shear waves, is intrinsic to the alloys considered, and it is not a consequence of the inline measurement setup. We plan to report on this in a future paper.

The ratios f_L/f_T measured inline on two coils of AA5754 alloys and three coils of AA5052 alloys are shown in Fig. 6. In these graphs, the lines link the measurement points in chronological orders. Fluctuations in temperature readings can make the temperature appear to come down at times, but this is not likely to occur often as the furnace power was supposed to be increased monotonically. Just as in Fig. 2, the smooth increase in f_L/f_T with temperature stops at some temperature. We interpret this temperature as the temperature at which annealing begins. This temperature is approximately 380 ºC for the AA5754 alloy, and 350 ºC for the AA5052 alloy. This is in good agreement with what was found in the laboratory for the AA5754 alloy. The agreement is not as good for the AA5052 alloy but this is likely due to a systematic temperature measurement error caused by a difference in emissivity between the two grades. In fact, other considerations based on ultrasonic attenuation suggest that the recrystallization temperature was probably around 400 ºC for the AA5052 alloy. It is also possible that some of the discrepancy between the laboratory and inline measurements could be due to the fact that the two thermal processing routes (inline vs laboratory) were not identical: the heating rates were not the same, the inline measurements were made after a holding time of approximately 4 seconds, and the laboratory measurements were made during continuous ramping of temperature. The holding time is significant because it was found that changing the annealing temperature by 25 ºC changes the time required for recrystallization by a factor of 10.[2] For example, an increase of 25 ºC in annealing temperature can reduce the holding time for recrystallization from 10 to 1 second. Finally, we cannot tell whether the strips were fully recrystallized at the highest temperatures because the temperatures reached were not high enough to let us observe a return to the steady increase in the ratio f_L/f_T with temperature. However, by comparing with the height of the step in Fig. 2, which is of order 0.02, it appears that the end of recrystallization was almost reached.



a) b)

Figure 6. Ratio of the longitudinal to shear resonance frequency as a function of temperature as measured a few seconds after the strips exits the inline annealing furnace for a) alloys AA5754 and b) AA5052.

Measurement accuracy: The measurement accuracy of the ratio f_L/f_T is difficult to assess because f_L/f_T varies with temperature and the temperature data from the IR camera fluctuate. The repeatability of the ratio measurement was estimated by considering a series of measurements where the temperature was relatively constant and where no recrystallization occurred. For the coil 5052-13, there was such a temperature plateau near 300 °C when the induction furnace heating power was constant. During this plateau, the standard deviation of f_L/f_T was ± 0.0008, or less than ± 0.04 % of the mean value. For higher temperatures, when the shear resonance signal-to-noise ratio is lower, the accuracy decreases. However, the strongest fluctuations in f_L/f_T are always less than ± 0.1 %. Therefore, we estimate that measurement precision of f_L/f_T is better than 0.1 % for temperatures of up to about 360 °C (380 °C at the exit of the furnace).

Conclusion: We have demonstrated that laser-ultrasonics can measure the onset of recrystallization inline, after induction annealing at CAC's Carson plant, in two aluminum alloys. The measurement is based on measuring a ratio of two resonance frequencies, f_L/f_T. This ratio is insensitive to strip thickness variations but depends on temperature and texture variations that occur during recrystallization. If temperature is monitored independently, texture variations and recrystallization can be measured. The inline measurement behavior and signal-to-noise ratio of our prototype system were as good as obtained in laboratory simulations with a Gleeble thermomechanical simulator and *in-situ* laser-ultrasonic measurements. This was accomplished by repackaging laboratory equipment in sturdy enclosures and designing a system that was easy to transport and easy to install. Installation took one week, from the moment the truck delivered the system to the moment the system was fully operational and tested on strip samples.

To go further in pursuing the technological application of this technology, two tasks remain. The second one is to design a commercial prototype, capable of unattended operation for extended periods of time. We believe that this would require essentially development time and resources. The first and main task, however, is to prove the economic viability of this application. There are several potential economic gains to realize with a recrystallization sensor. 1) Energy savings resulting from lowering the annealing temperature: Having a recrystallization sensor would allow to avoid over-annealing, something often done to insure a safety margin against fluctuating process parameters. 2) Improved strip uniformity and quality: Insuring that the strip is fully annealed would allow to do further cold rolling or other forming operation with the maximum formability allowed by the fully recrystallized alloy. 3) Reduced setup time when switching the production from one alloy to another: The required annealing temperature and inline annealing furnace power could be rapidly determined by ramping up the furnace temperature as we did in this paper. 4) Reduced scrap and return shipments: Improving strip uniformity (point 2 above) and reducing setup time (point 3 above) would provide additional savings in reducing production scrap and expensive return shipments caused by out-of-specification products.

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