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ADVANCED TECHNOLOGY FOR
LARGE
STRUCTURAL SYSTEMS

Lehigh University

A STUDY OF ALUMINUM-LITHIUM SOLIDIFICATION USING ACOUSTIC EMISSION TECHNOLOGIES

by

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INTRODUCTION

Material scientists are as interested in developing new methods of evaluating material properties as they are in developing new materials. One relatively new method of non-destructive evaluation (NDE) which has been receiving much attention, is acoustic emission (AE). The present study examined the solidification of an AA2090 aluminum-lithium alloy using acoustic emission technology with an emphasis on characterizing defects as they develop in the material. The acoustic emission techniques that were developed, when combined with thermal and metallographic techniques, provided a successful method of real-time defect detection in small-scale castings.

Acoustic emission is the term applied to both a physical phenomenon and the NDE technique used to detect it. As a physical phenomenon, AE is a transient elastic wave or set of waves generated by a rapid release of strain energy from localized sources within a material. As a passive NDE technique, AE measures strain energy released during events such as dislocation motion, diffusionless phase transformations and micro-cracking. The level of energy associated with these events is very low, being at least an order of magnitude lower than that produced by stroking the material with the end of a frayed cotton thread [1]. For reliable data acquisition during solidification, it was necessary to amplify the detected AE signals by 90 dB (100,000x) which required special consideration of noise imposed by the environment and the experimental system.

Any material under stress and containing internal defects has stored elastic strain energy. While most of this energy is released in the form of heat or surface area changes, a small percent (approximately 1%) is released as acoustic stress waves, with some residual stored elastic energy [2]. As the waves propagate to free surfaces of the material (Figure 1), small vibrations are generated. A piezoelectric transducer coupled to the surface converts the displacement of these vibrations to proportional voltages. The voltage signals may then be amplified, filtered, and digitally processed to analyze trends in waveform characteristics that could be associated with the development of internal material defects.

Acoustic emission sources have been proposed by others in solidification studies of aluminum alloys. Feurer and Wunderlin [3] demonstrated that, as the fraction of porosity increases in a solidifying Al-4.5wt%Cu-0.2wt%Ti alloy, the acoustic emission activity increases proportionally. They observed a period at the beginning of solidification, attributed to the formation of small pores between dendrite arms, and a period at the end, attributed to the formation of larger pores between adjacent dendrites.

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Kumar and Prabhakar [4] studied acoustic emission during the solidification of Al-11.6wt%Si and Al-4.0wt%Cu alloys. They concluded from plots of cumulative AE events versus signal amplitude that the AE energy in the Al-Cu alloy, which contained hot tears, was higher than that of the Al-Si alloy which had no hot tearing. Sharma, et al. [5], from experiments with restrained specimens, also concluded that hot tearing in Al-Cu alloys generated acoustic emission. They suggested that the mechanism was dendrite tip fracture, induced by the restraint, but conceded that a certain level of AE activity was also present in unrestrained specimens. Their explanation was that it was probably due to the formation of pores as proposed by Feurer and Wunderlin.

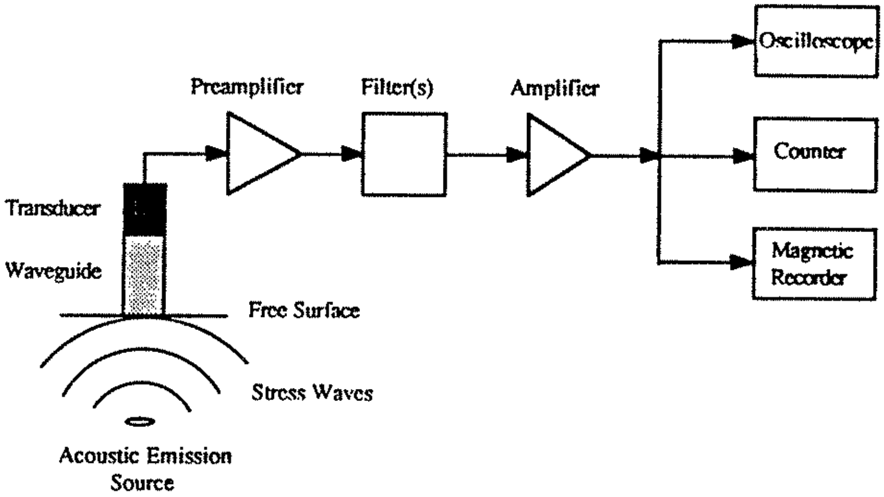

Figure 1: Generation and detection of acoustic emission signals.

A much different model by Xiufang, et al. [6] proposed grain formation as an acoustic emission source during solidification. They stated that, in a non-porous Al-Si alloy without hot tears, the number of grains is directly proportional to the number of AE signals per unit time, the AE count rate. They concluded that nucleation and growth of solid particles, as they form grains, is a process of energy liberation which results in the generation of stress waves, i.e., acoustic emission. The present study considered each of these explanations and developed a new model based on comparative experiments with an ultra-pure aluminum, an Al-4.7wt%Cu binary alloy and a commercial AA2090 Al-Li alloy.

EXPERIMENTAL PROCEDURES

The three materials, described above, were each cast by placing a machined and polished pellet, approximately 2.7 g, into an integral crucible and waveguide fabricated from amorphous boron nitride (BN). The atmosphere surrounding the specimen was controlled by placing the crucible/waveguide inside a fused quartz tube which was sealed at the top and the bottom. Inlet and outlet vents were provided to allow low pressure ultra-high purity (UHP) argon to flow through the tube and blanket the specimen with an inert atmosphere. A type-J thermocouple was inserted through the top seal and into the crucible to monitor the temperature of the melt.

The resistance furnace temperature was increased above the liquidus of the specimen and held to ensure a uniform liquid state before being allowed to cool. Cooling rate was controlled by a regulated flow of compressed air at the base of the waveguide which extended outside the furnace. In a second series of experiments, the UHP argon was replaced by a mixture of argon and 4.1% H_2. The intent was to permit additional hydrogen to diffuse into the melt and produce castings with increased porosity. The final series of experiments involved larger specimens with masses above 10g. Acoustic emission could, therefore, be considered as a function of the number of grains or the volume. It is important to add that, in the larger volume tests, the BN crucible was replaced by an alumina crucible.

Conventional AE analysis is the term applied to the method of digitally recording seven parameters from each amplified AE signal. These include, among others, the peak amplitude, event number and duration of the signal above a preset threshold. In general, these were plotted versus time and correlated to temperature using the cooling curve data. In addition to conventional AE analysis, waveform analysis in the time and frequency domains was performed on selected AE signals during solidification. Optical metallography was used to examine the microstructures of the specimens for defects that could be considered as sources of AE activity.

RESULTS AND CONCLUSIONS

Experiments were first completed on ultra-high purity aluminum specimens. A common pattern of acoustic emission was seen each time: a single period of AE as the last ten percent of the material solidified (Figure 2). The system was quiet throughout the nucleation and most of the grain growth regime. Metallographic analysis revealed equiaxed grains with evidence of dendritic growth but no porosity or micro-cracking. The cumulative number of hits varied from 200 to over 1,000 for specimens of similar volume and grain size. Changing the furnace atmosphere from UHP argon to the Ar-H_2 mixture had no prominent effect on either the microstructure or the acoustic emission. By doubling the volume of the specimen, the cumulative number of AE hits increased to a range of 1,000-1,600 hits by the end of solidification. There was an additional period of high AE activity several minutes after solidification was complete, caused by specimen restraint induced by adhesion to the alumina crucible.

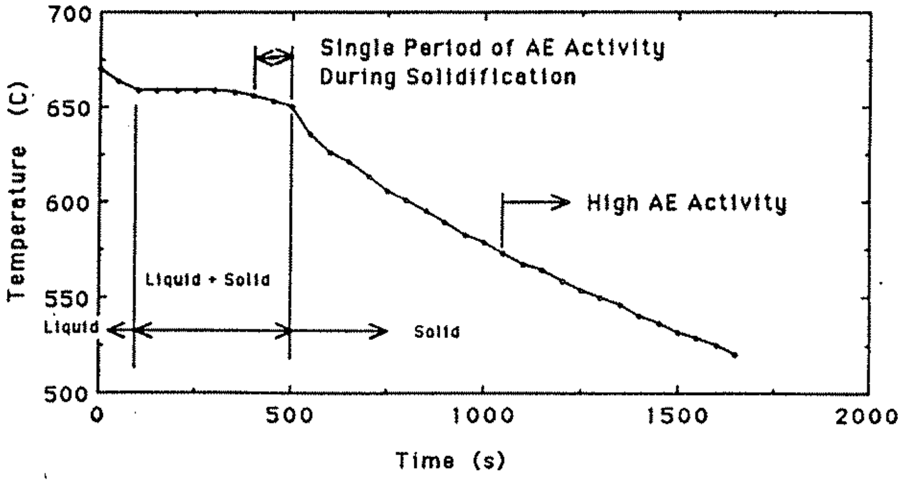

Figure 2: Typical cooling curve of UHP aluminum indicating range corresponding to single period of high acoustic emission activity.

The results of these experiments lead to several conclusions. Nucleation and porosity are not sources of AE in solidifying ultra-pure aluminum. Dendritic impact was discounted since the growth rates were determined to be too slow to generate stress waves with detectable amplitudes. Mold friction, oxide cracking, and volumetric shrinkage are not reasonable sources because the AE activity occurred in a discrete time period, the end of solidification. The model that is proposed is grain boundary formation as adjacent equiaxed dendrites meet in opposing growth directions while surrounded by the remaining liquid. The internal stresses that develop at high temperature provide a driving force for diffusion-controlled dislocation creep. This, combined with grain boundary sliding, is the strain energy release mechanism proposed as the source of acoustic emission in solidifying ultra-pure aluminum.

In contrast with UHP aluminum, Al-Li alloys generated two discrete periods of acoustic emission during solidification (Figure 3). A period of high activity coincided with the beginning of solidification (prior to a 0.2 fraction of solid); the system was then quiet until a second period of activity occurred near the end (above 0.9 fraction of solid). The only AE source mechanism present at the beginning of the Al-Li alloy solidification that was not present in the UHP aluminum is the formation of interdendritic porosity. Increasing the volume of the Al-Li alloy had the effect of increasing the cumulative number of AE events in the first period. It was also observed, by comparing the AE data with the microstructures, that as the type of grain structure changed from equiaxed to columnar, the number of AE hits in the second period decreased. A mixture of low and high intensity signals occurred during each period but neither conventional AE nor waveform analysis were able to identify specific trends in waveform characteristics. The waveform is typically dominated by resonant effects from the waveguide or, if high frequency filtering is used, the transfer function of the transducer controls the waveshape.

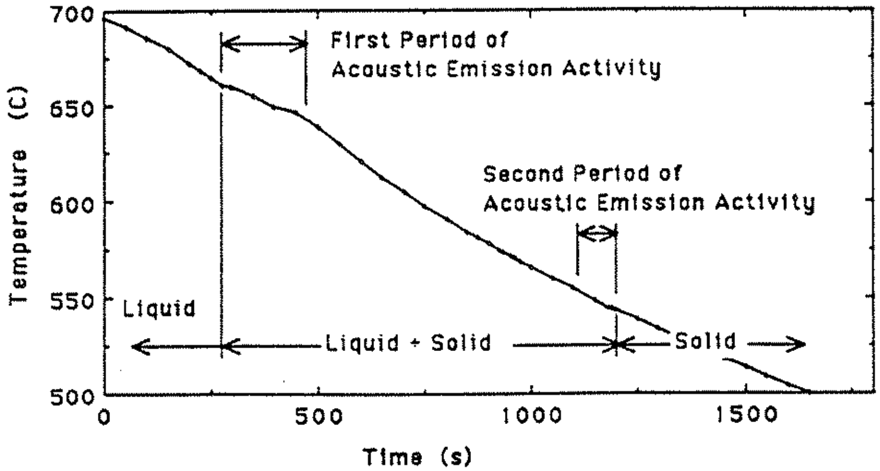

Figure 3: Typical cooling curve of an Al-Li alloy indicating ranges corresponding to two periods of high acoustic emission activity.

The proposed source mechanism responsible for the first period of acoustic emission in the solidifying Al-Li alloy is internal stress produced by the formation of interdendritic porosity. One suggested model involves the expansion of pores which exerts force between dendrite arms, thereby causing movement of dislocations within the growing solid particles suspended in stress-free liquid. Another model describes the release of strain energy resulting from microfracture of dendrite arms induced by hydrostatic pressure from trapped interdendritic hydrogen. The same AE source mechanism attributed to UHP aluminum solidification, grain boundary formation, is also responsible for the second period of activity during Al-Li alloy solidification. Imposed stresses at high temperature cause fracturing of fused dendrite tips and micro-cracking in the presence of interdendritic porosity (Figure 4) as well as diffusion-controlled dislocation creep and grain boundary sliding. A similar two stage AE pattern was seen for the Al-Cu binary alloy although the cumulative hits in both periods was much lower. This was explained by less porosity and micro-cracking than was present in the alloy containing reactive lithium.

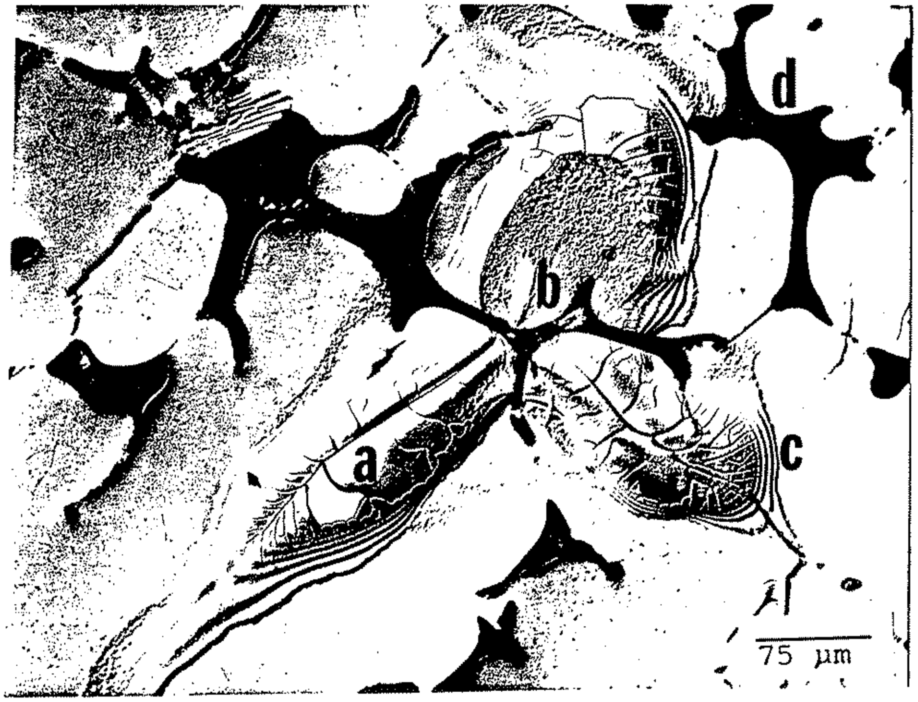

Fig. 4: Micrograph of an as-cast AA2090 Al-Li alloy illustrating the presence of:
(a) solidification cracking, (b) dendrite tip fracture, (c) coring and (d) interdendritic porosity.

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