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OPTIMIZING THE COMPRESSION STRESS RELIEF PROCESS FOR 7050AL FORGINGS

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ABSTRACT

Structural components machined from aluminum forgings can exhibit distortion and poor dimensional quality due to residual stresses formed primarily during heat treatment. To alleviate these problems, mechanically stress-relieved tempers are used in which a small amount of plastic strain is introduced after solution heat treatment and prior to aging. For hand-forged billets and die forgings, this strain is introduced by compression. Process specifications for compression stress relief typically allow a range of strains, and this process variability can in turn lead to inconsistent forging performance in machining. In addition, since cold work is known to accelerate the aging response and decrease the peak strength in alloys such as 7050Al, it is important to control the compression stress relief process to achieve the stress relief while maintaining acceptable mechanical properties. The purpose of this investigation was to experimentally characterize the influence of compressive strain on the mechanical properties achieved after subsequent aging treatment in aluminum alloy 7050. We have also used finite element modeling of the residual stress state in a typical forging to predict optimum compression parameters for stress relief.

INTRODUCTION

Residual stresses are generated in aluminum mill products during quenching after solution heat treatment. These quench stresses can result in distortion and poor dimensional quality of parts machined from that mill stock [1,2,3]. Additional problems may be encountered due to improper fit of parts on assembly. An example of distortion during machining of an airframe component due to these residual stresses is shown in Figure 1. To alleviate quench stresses in forged products, a mechanical stress relief is performed after solution treatment and prior to aging in which a small amount of plastic strain is introduced by compression [4-6]. Process specifications for compression stress relief (CSR) typically allow from 1 to 5% compressive strain, and in practice there is wide variability in the CSR process. For die forgings having variable section thickness within the forging, a CSR process that introduces a constant compression level can yield a forging with characteristics that vary within the forging envelope.

The effects of compressive strain on material characteristics have been analyzed, including hardness and tensile strength, developed upon aging after CSR in aluminum alloy 7050Al. A two-dimensional finite element model of a typical forged billet was also constructed, and the influence of CSR process variables on the resulting residual stress state was examined. Results indicate that there is an optimum CSR process that will yield both effective stress relief and acceptable mechanical properties in the final forged product. Experimental procedures are presented in the following section.

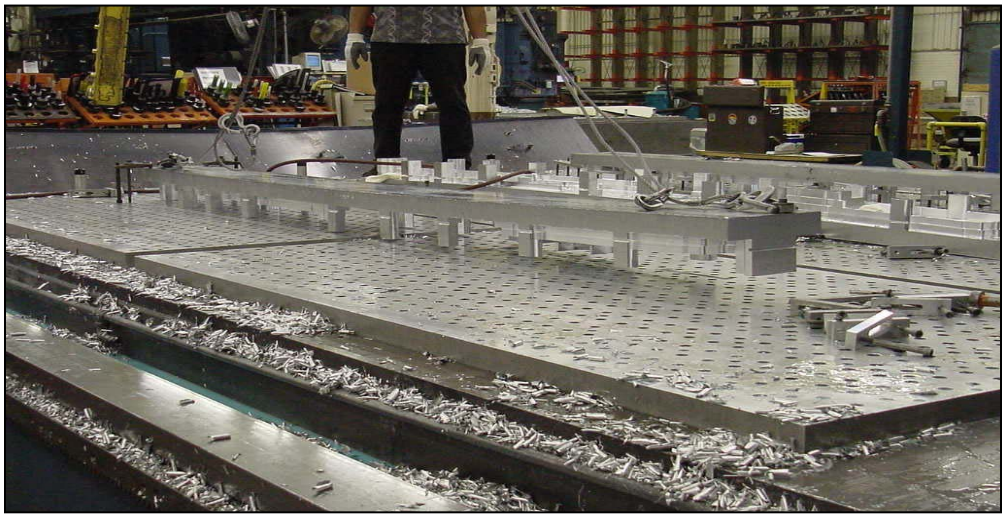

Figure 1. Distortion During Machining Due to Residual Stresses

EXPERIMENTAL PROCEDURES

To examine the influence of compressive strain on aging response in an affordable manner, 7050-T7451 aluminum plate stock was used to simulate hand forged billet material. Sample blocks cut from plate stock of varying thickness were re-solution heat-treated to erase the previous processing, and water quenched to reintroduce quench stresses. While there may be microstructural differences between the plate used in this study and an actual forging, the resulting sample block approximates the condition of a forged billet in terms of the residual stress profile existing after solution treatment as well as the strain profile induced by compression. The specimens thus provide a starting point to examine the relative influence of compression stress relief process parameters and section thickness on subsequent aging response and resulting properties.

Sample blocks were cut from plate having a thickness of 50.8, 76.2, and 101.6 mm (2.0, 3.0, and 4.0 in.). The sample cross sectional area was held constant at 38 mm by 38 mm (1.5 inches by 1.5 in.) for each thickness in order to establish a constant cooling rate, as defined by the diameter of the largest sphere that can be contained within the material envelope, for all sample blocks. Sample blocks were solution heat treated at 471°C (880ºF) for 2.5 hours and water quenched to the AQ condition. Blocks were then subjected to compression while in the AQ condition to introduce a permanent plastic compressive strain of 1, 2, 3, 4, or 5%. The surface area of the sample blocks allowed full contact of the top and bottom surfaces with the loading rams. Because the AQ condition is retained at room temperature for a maximum of one hour, sample blocks were immediately placed in a freezer to maintain this condition for up to 12 additional hours. Following compression, blocks were then aged to the T7452 temper in a two-stage thermal treatment of 121°C (250ºF) for 6 hours followed by 176°C (350ºF) for 8 hours. Aging was performed in a single furnace cycle using a controller to ramp from stage 1 to stage 2 temperatures at a rate of 7°C (44°F) per minute. Sample blocks were sectioned as illustrated in Figure 2, and hardness profiles were taken through the thickness by measuring hardness at

3.175 mm (0.125 in.) intervals. Profiles were taken at three different vertical positions, and the three readings obtained at each measuring depth were then averaged to represent the hardness at that depth. Triplicate sample blocks were processed for each combination of sample block thickness and percent compression. For the 3 thickness and 5 compression levels used in the study, a total of 45 sample blocks were processed.

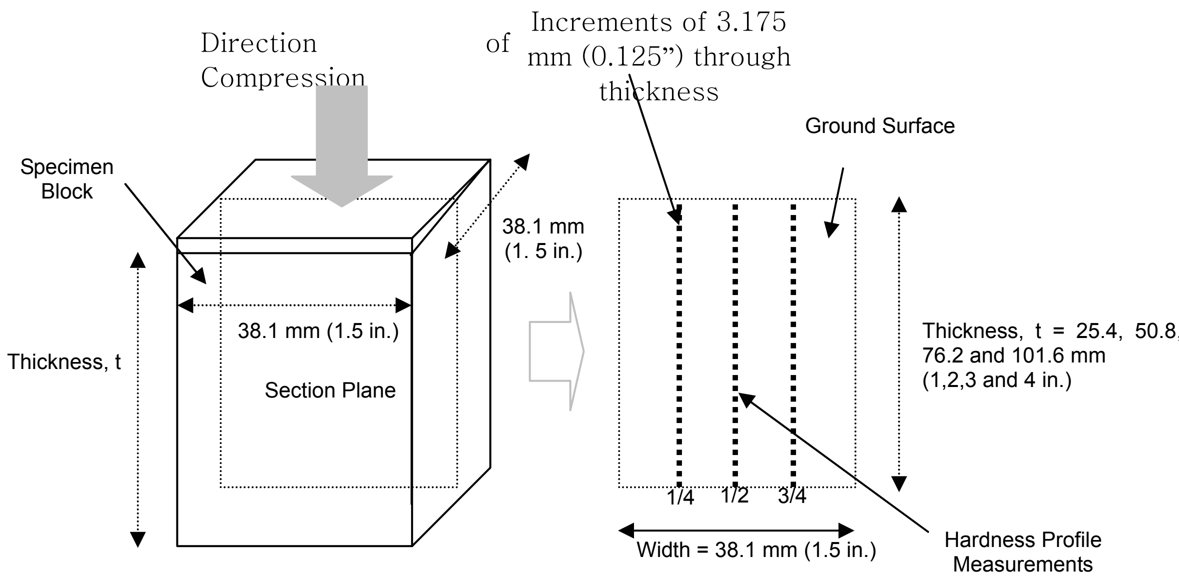

Figure 2. Specimen Configuration for Hardness Profiling

For tensile testing, a larger sample block was used. After solution treatment, compression blocks were used to apply the compression load to the middle section of the sample block as illustrated in Figure 3. After processing to the final T7452 temper, flat tensile specimens were machined from the sample blocks with the gage section centered in the compressed region. Specimens were taken from within the sample block at depth intervals according to the schematic shown in Figure 3, with the axis of the test specimen parallel to the long (152 mm) dimension of the sample block. All tests for a given depth were performed in triplicate to demonstrate reproducibility of results, and the average strength for each condition (a specific combination of sample block thickness, percent compression, and sample depth) was determined. For this part of the study, a total of 3 sample blocks were processed.

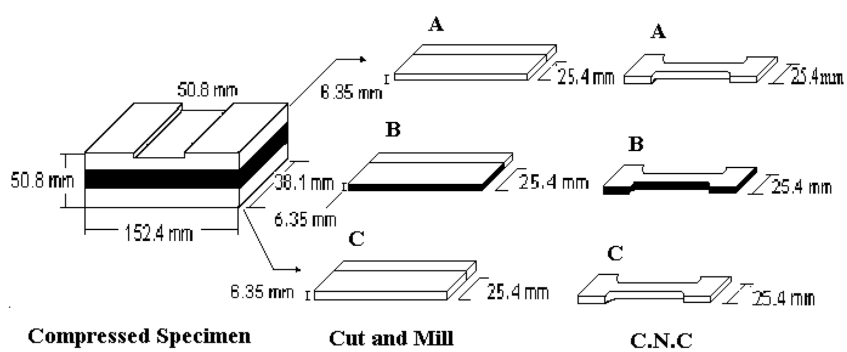

Figure 3. Specimen Configuration for Tensile Testing

RESULTS AND DISCUSSION

Hardness profiles for sample blocks of each section thickness are presented in Figures 4-6. The acceptable hardness range for alloy 7050-T7452 is from 80-88 on the Rockwell B scale. For a given sample block, the hardness profile does not vary significantly across the sample width at a given measuring depth, but does show a distinct pattern as a function of sample depth. For each thickness, the hardness decreases in the center of the sample block, and the amount of decrease tends to increase with increasing amount of compression. This decreasing hardness obtained upon aging after compression is due to the detrimental effect of cold work on aging response in 7050Al. Cold work accelerates aging kinetics, with the dislocation network providing additional sites for precipitation. And, it is known to decrease the maximum hardness obtainable upon aging. Because the compression blocks exhibit a slight barreling effect, the lateral strain in the center of the sample block is higher than in either the top or bottom regions. Because of this increased strain, the effect of cold work on aging is more pronounced in the center of the block. Thus, the minimum hardness in the center region tends to decrease with increasing amount of compression.

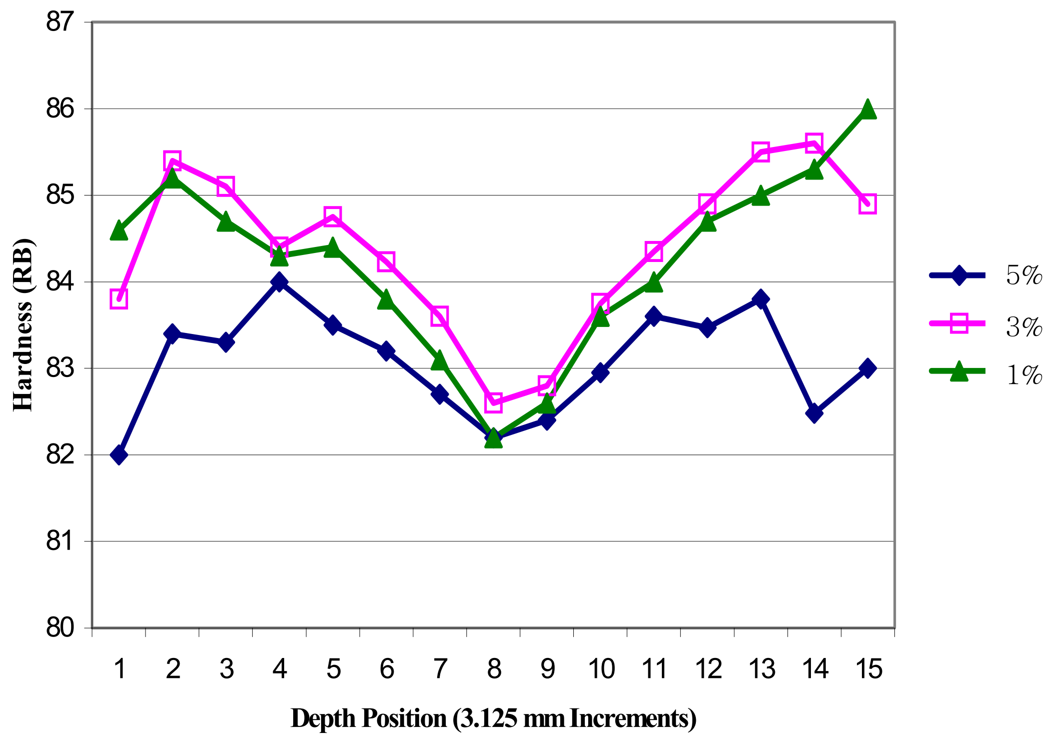

Figure 4. Hardness Profiles of 50.8 mm (2.0 in.) Sample Blocks as a Function of Compression

As the sample block thickness increases, the minimum hardness obtained in the center region begins to increase, even though the same general hardness profile is observed. While the range of hardness values obtained in the 2.0 in sample block is 82–86 R_B, it is 84-89 R_B in the thickest sample block. The reduced effect of compression in the thicker sections may be due to a more uniform strain distribution, and we are currently performing more detailed analysis to better define the strain distribution obtained. A second observation in the profiles is an apparent hardness peak at approximately one-quarter thickness from the top and bottom of the sample block. This peak may be due to frictional effects during compression at the top and bottom of the sample block, which somehow limit the strain introduced into these regions. A more detailed analysis of strain distributions is necessary to further elucidate a rationale for these apparent peaks.

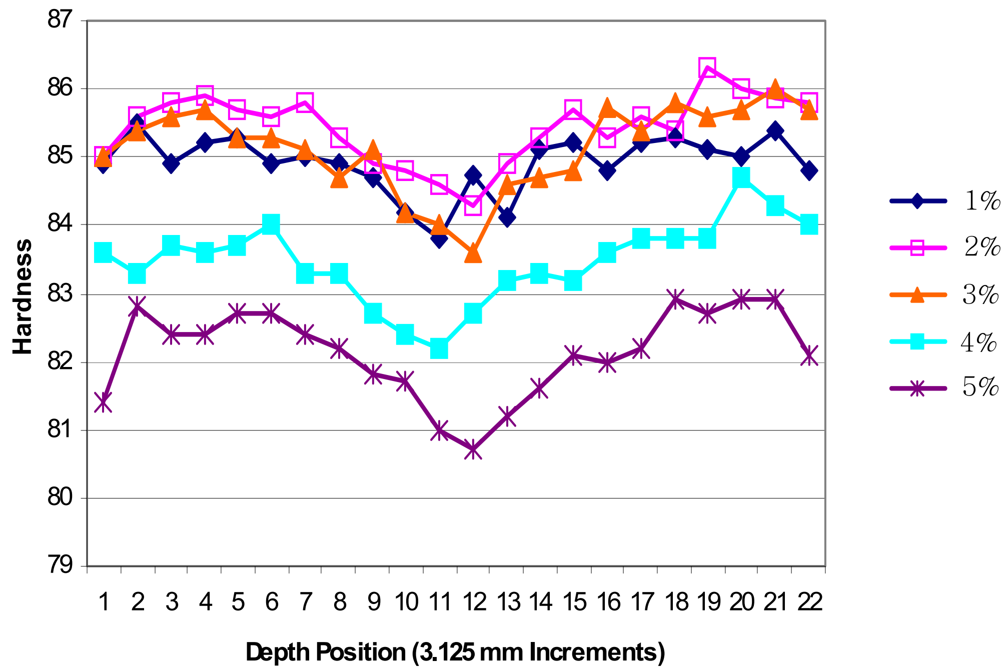

Figure 5. Hardness Profiles of 76.2 mm (3.0 in.) Sample Blocks as a Function of Compression

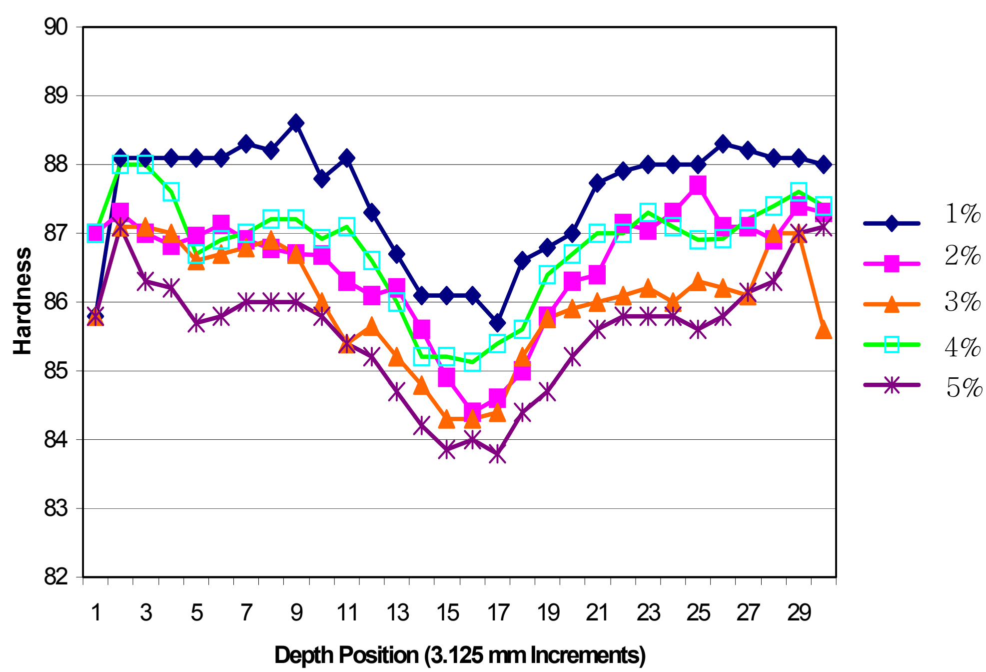

Figure 6. Hardness Profiles of 101.6 mm (4.0 in.) Sample Blocks as a Function of Compression

While hardness measurements are often used to study aging kinetics, tensile strength achieved upon aging is the most important property for design. The results of tensile testing of specimens taken from three depths in a 50.8 mm sample block subjected to various levels of compression are presented in Figure 7. There is a clear trend to reduced yield strength with increasing compression level at all depth levels within the sample block. The design minimum yield strength for a 7050-T7452 forging having a section thickness of 50.8 mm is on the order of 434 MPa (62 ksi). It is evident that the yield strength achievable upon aging after compression stress relief may not meet this requirement if the strain introduced in the CSR process is too high. There is an apparent limit of approximately 3% compression, at this section thickness, beyond which the yield strength achieved upon subsequent aging falls below the minimum design allowable.

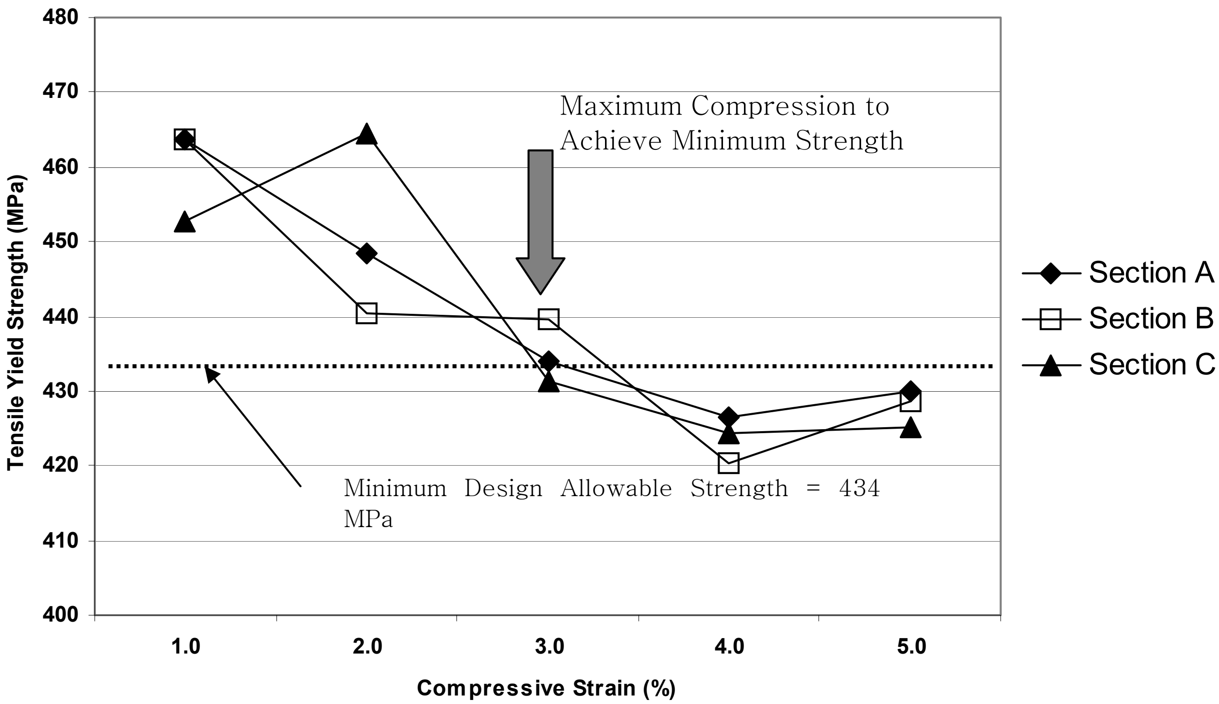

Figure 7. Effect of Compression on Tensile Strength After Aging

The influence of cold work on aging response in aluminum alloys can be quite complex [7]. It is known that cold work prior to aging both accelerates the aging response and reduces the peak strength obtainable in alloy 7050Al. The tensile data obtained illustrates this effect, and must be taken into account in optimizing the CSR process as well as the aging treatment following CSR.

To support the development of an optimum CSR process, we have performed a preliminary finite element analysis of the residual stress state in a hand-forged billet [8]. The two-dimensional finite element model was developed using ABAQUS. In the analysis, thermal profiles during quenching are determined. Then, these thermal profiles are converted to thermally-induced stress profiles to establish the initial residual stress state. Finally, a given amount of compression is introduced, and the final stress distribution calculated. A friction coefficient of 0.25 is assumed for interaction between the compression ram and forging. Results of this analysis are presented in Figure 8 for a representative hand-forged billet having a section thickness of 14.0 cm. The ideal CSR will yield a uniform material, with low magnitudes of tensile and compressive stress. After quenching, at 0% compression, high compressive stresses are formed in the surface regions, which experience the fastest cooling, which are balanced by high tensile stresses in the center of the billet, where cooling is slowest. Forging quality and the ability to produce a distortion-free component by machining may be predicted by the magnitude of the difference between the highest tensile and compressive stresses. The larger this difference, the more likely distortion will occur in machining a component from that forging. In the stress plots, it appears that a uniform material with low stress magnitude is accomplished at a compression of approximately 3%. Beyond this amount of compression, the stress profile becomes more complex, and stress magnitudes increase. The model indicates that, with increasing compression beyond 3%, high compressive stress regions develop in the top and bottom subsurface regions of the forging. It is possible that frictional effects between the billet and compression rams are responsible for these apparent compression lobes. Further analysis is needed to more fully understand these effects in the CSR process.

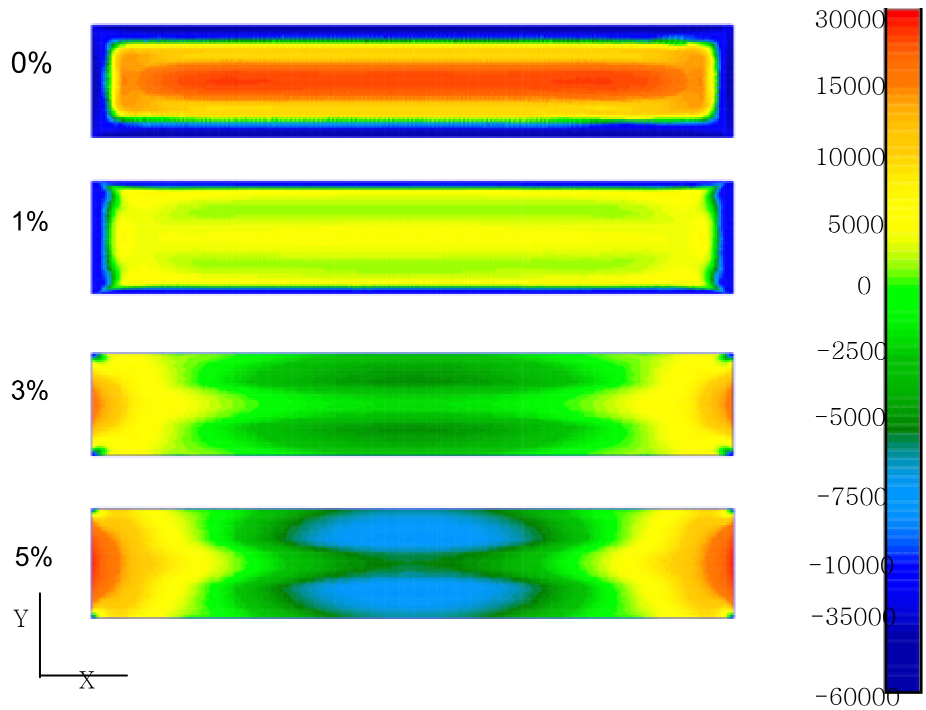

Figure 8. Residual Stress Profiles in Forged Billet as a Function of Compression Level as Predicted by Finite Element Analysis

CONCLUSIONS

Optimization of the CSR process for 7050Al forgings requires both the reduction of residual stresses to provide a uniform product, as well as control of the aging process to develop acceptable mechanical properties. While the results of this study indicate that an optimum CSR process requires at most 3% compressive strain, further work is needed to validate this conclusion. The actual strain profile accomplished in our compression tests need to be determined in order to establish that our experiment accurately simulates the CSR process. And, further tensile testing of specimens taken from thicker sections needs to be performed in order to establish the influence of section thickness on both strain profile and strength obtainable upon aging. At this stage of the investigation, we can conclude that section thickness and compressive strain do influence the hardness and yield strength of 7050-T7452 aluminum alloy. Hardness steadily decreases with thickness position, reaching a minimum at the center of the section. The minimum hardness decreases with decreasing section thickness. For a given section thickness, the minimum hardness decreases with increasing amount of compression. Aging response after compression is strongly influenced by the CSR process. For the 50 mm section thickness, the yield strength obtainable upon aging after cold work decreases steadily with increasing amount of compression. These results indicate that the CSR process must be optimized to obtain both effective residual stress reduction, while at the same time ensuring the ability to achieve the required strength upon subsequent aging.

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