

Residual Stress Analysis of Punched Holes in 6013 Aluminum Alloy Commercial Vehicle Side Rails

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Tory Smith and Jeremy Rickli
Virginia Polytechnic Inst & State Univ

Sean Fleming
Metalsa

Jaime Andres Camelio
Virginia Polytechnic Inst & State Univ

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ABSTRACT

Compliance with tighter emission regulations has increased the proportion of parasitic weight in commercial vehicles. In turn, the amount of payload must be reduced to comply with transportation weight requirements. A re-design of commercial vehicle components is necessary to decrease the vehicle weight and improve payload capacity. Side rails have traditionally been manufactured from high strength steels, but significant weight reductions can be achieved by substituting steel side rails with 6013 high strength aluminum alloy side rails. Material and stress analyses are presented in this paper in order to understand the effect of manufacturing process on the material's mechanical behavior. Metallographic and tensile test experiments for the 6013-T4 alloy were performed in preparation for residual stress measurements of a punching operation. Punched holes are critical to the function of the side rail and can lead to high stress levels and cracking. Residual stresses were measured for holes positioned in the web center and near the forming edge of the side rail using x-ray diffraction methods. Comparisons are made between 6013-T4 and 6013-T6 as well as roll-formed and nonroll-formed specimens. The results have been used to identify critical areas that may be susceptible to cracking and failure.

INTRODUCTION

In an ongoing effort to mitigate harmful emissions generated from commercial vehicles, the United States government has mandated significant reductions in engine emissions, namely US07 and US10. These regulations have reduced commercial

vehicle maximum payload by at least 1200 lbs. The bulk hauling sector of commercial vehicles is constrained by weight rather than volume, and must comply by sacrificing valuable payload. Tradeoffs between payload and low emission systems have motivated commercial vehicle manufacturers and suppliers to investigate methods of reducing vehicle weight by 15% - 25%. Metalsa Roanoke, Inc. is a producer of commercial vehicle heat-treated and high strength, low alloy steel side rails, and is investigating the use of 6013-T6 aluminum side rails as a weight conscious alternative. As much as a 410 lb weight reduction per frame rail set, nearly half of the current side rail weight, would be accomplished by transferring from steel to aluminum.

The 6013 aluminum alloy, developed by ALCOA in the early 1980s, is a medium strength, heat treatable alloy that is currently used in many automotive and aerospace applications [2]. The primary alloy elements are magnesium, silicon, and copper. 6013 aluminum is an attractive material as it can be processed to obtain properties superior to other alloys in the 6xxx series. In its T4 state, 6013 aluminum has excellent stretch-forming characteristics. The potential of 6013 aluminum for use in commercial vehicle side rails comes from its strength characteristics that are similar to some high strength steels but it weighs up to 60% less [3].

The tradeoff of aluminum alloy side rail weight reductions is a material behavior that contrasts with traditional steel side rails, both in manufacturing and use phases. Particularly, residual stresses induced in aluminum alloys by rolling and punching processes cannot be assumed analogous to those in

steel. Therefore, analyzing residual stress impacts is critical to the manufacturability, reliability, and performance of aluminum alloy side rails. This paper focuses on the alloy's manufacturability by characterizing the residual stress behavior of 6013-T4 aluminum in punching operations. Specimens were measured using x-ray diffraction. Two different hole locations were analyzed: the web center and near the flange (Fig. 1). Measurements were obtained before and after roll-forming performed at Metalsa Roanoke Inc., and compared with a 6013-T6 aluminum side rail.

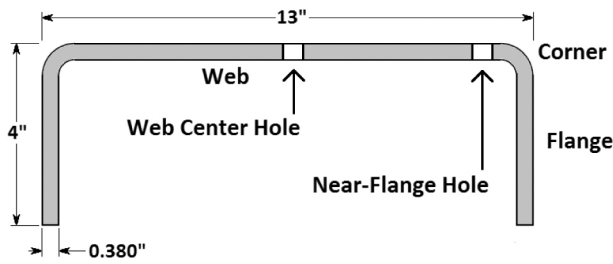


Figure 1. Cross sectional profile of a 6013-T4 aluminum alloy side rail post roll-forming showing the two locations considered for residual stress measurements

The primary concern with the switch to 6013-T4 aluminum is its undocumented residual stress behavior when subjected to punching and roll-forming operations. Residual stresses, those which remain within a component when external forces are no longer present, are generally smaller in magnitude and more difficult to measure than primary stresses, largely because such measurements typically require complex methods. In this study, the x-ray diffraction technique is used to characterize residual stresses in 6013 aluminum. Residual stresses often arise from machining operations associated with component manufacturing [4]. Prior research has revealed that areas in close proximity to cutting operations, in addition to experiencing significant residual stresses, also experience much higher strain rates [5]. Higher rates of deformation generally correlate to greater residual stress intensity, as the most deformed material in the vicinity of the cutting tool is also deformed at the greatest rate. This is of special concern because punching is a high-speed process. Characterizing these stresses is critical because they can cause warping or distortion and significantly accelerate material fatigue [6]. A thorough investigation of residual stresses provides a more complete understanding of the manufacturing of 6013 aluminum side rails at the T4 state, and eventually the T6 use phase.

SIDE RAIL RESIDUAL STRESS ORIGINS

ROLL-FORMING

Critical residual stresses in side rails occur as a result of two manufacturing processes: roll-forming and punching. At

Metalsa Roanoke, Inc., aluminum side rails are roll-formed at a 6013-T4 state to form flanges lengthwise on either edge, Fig. 1. Raw, flat material is passed through a series of rollers that are set to specific side rail dimensions to gradually form ninety degree flanges. The material thickness is not significantly affected like in traditional rolling processes, but can still initiate surface level residual stresses. Residual stresses can be significant at the flange radius and can couple with punching residual stresses to make holes located near flanges more susceptible to cracking.

PUNCHING OPERATION

Punching is an essential process for commercial vehicle side rails because the holes allow for the fastening of cross-members and other supporting equipment. Side rail performance is directly related to punching operations, among others, because poor punching can lead to cracking at hole edges resulting in the side rail failure. The punching process consists of forcing a punch through the aluminum alloy, piercing a hole. A die on the opposite face of the side rail supports the hole edge during the process to minimize deformation in the surrounding material [6]. Studies performed on 6061-T6 aluminum alloy regarding fatigue life have revealed that among laser cutting, plasma cutting, and standard punching, the standard punching process yields the best performance [7]. Additionally, prior residual stress measurements in steel side rails have supported using a punching operation due to lower tensile residual stresses, although higher compressive normal residual stresses were observed [8].

MATERIALS LEVEL TESTING

Materials level testing was performed in order to fully understand the behavior and anisotropy of the 6013-T4 aluminum side rails. Yield strength, ultimate tensile strength, elastic modulus, and any potential anisotropy were determined through tensile testing. Metallography results were used to verify that the material's grain structure was appropriate for x-ray diffraction measurements.

TENSILE TESTING

Nine flat tensile specimens were extracted from rolled plates of 6013-T4 aluminum with nominal thicknesses of 0.380 inches. The specimens were prepared in three batches of three: three side rail web roll-formed with a longitudinally oriented gage section (L1, L2, L3), three "bare" specimens which had only received rolling from the original manufacturer (B1, B2, B3), and three side rail web roll-formed specimens with a transversely oriented gage section (T1, T2, T3). The specimens were machined in accordance with the ASTM E8-09 standard [9] with overall dimensions $8.50 \times 2.00 \times 0.38$ inches and a 2-inch gage section, Fig. 2. The objectives of the tensile testing were threefold: to verify the manufacturer's listed material properties of the 6013-T4

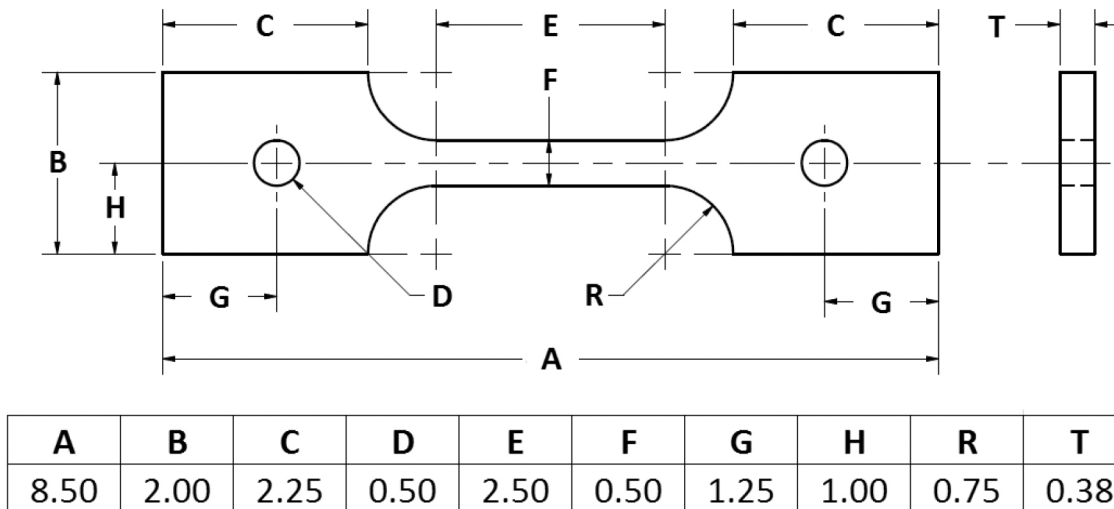


Figure 2. Tensile test specimen (all dimensions are in inches)

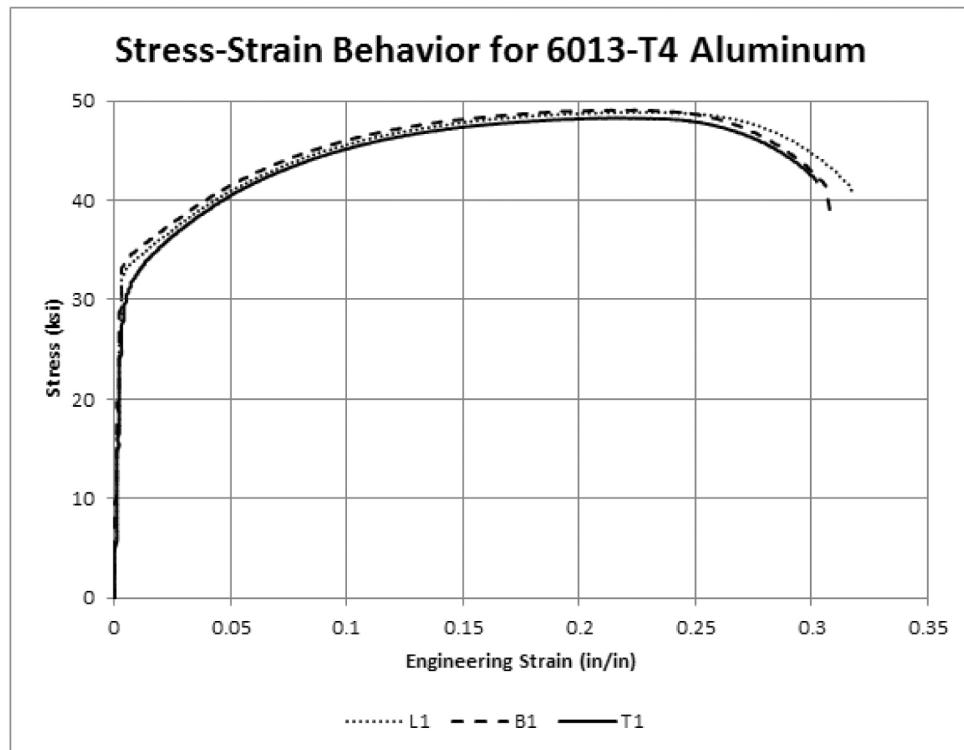


Figure 3. Stress-strain curves for samples “L1,” “B1,” and “T1.” Fracture occurs at approximately 32% elongation.

aluminum, to determine the effects, if any, of Metals's roll-forming process on the material properties, and to identify the extent of any anisotropy resulting from the rolling process.

Tensile tests were performed using a 30-kip axial loading apparatus. In each test, the tensile specimen was locked into place using clamps and affixed with a 50% maximum-elongation extensometer. A strain-rate of 0.0787 inches (2.00 mm) per minute was used to elongate each specimen to the

point of fracture. Stress/strain data was collected at a sampling rate of 1.25 Hz. Each test spanned approximately ten minutes from the first application of load to specimen failure. Representative stress-strain behavior is illustrated in [Fig. 3](#).