Forming of an axially tailored automotive channel section through hot stamping of tailor-welded blanks

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Abstract. In this work, top-hat cross-section axial crush rail specimens with tailored properties along their length were investigated. These top-hat channels were hot stamped in a fully cooled die set from tailor-welded blanks (TWBs). The blanks were laser-welded and comprised Usibor® 1500-AS joined to Ductibor® 500-AS in 1.2 mm and 1.6 mm thicknesses. Micro-hardness measurements were taken along the length of the formed specimens to map the hardness profile along their length. The effect of gauge thickness on hardness was evaluated. The hardness profile of these TWB parts was compared to that of parts formed using tailored in-die heating (IDH).

1. Introduction

Increasing standards for fuel efficiency and passenger safety have put significant pressure on the automotive industry. Advanced high strength, lightweight materials such as ultra high strength steel (UHSS) present the opportunity for weight savings through thickness reduction, while improving crash performance and occupant safety. In the hot stamping process, boron steel blanks are austenitized in a furnace for several minutes before being rapidly formed and quenched between cooled dies, transforming the austenite into 100% martensite [1]. These fully martensitic parts are very hard and have limited ductility, which has hindered their application in energy absorbing crush structures for which there is significant potential for improved vehicle safety and weight reduction.

The ductility of these hot stamped parts can be improved by using tailoring methods. Tailor-welded blanks (TWBs) are composed of multiple sheets of metal with differing thicknesses and/or strengths [2] that are laser welded together along their edges. When these TWBs are formed in a stamping operation, the resulting part will have areas of differing strength and ductility [1]. Choi et al. [3] studied the effect of different forming parameters on the mechanical properties of hot stamped TWBs composed of HSLA 340Y steel and a boron added steel. Múnera et al. (2006) [4] numerically compared monolithic front rails to those formed from high and very high strength steel TWBs and predicted a reduction in passenger...
compartment intrusion distance when using TWBs. Múnera et al. (2008) [5] performed a numerical study on hot stamped tailor-welded blanks for front and rear rails, and found significant potential for weight reduction and improved crash performance. Kang et al. [6] found that in the laser welds in Usibor® - Ductibor® TWBs, the hardness of the fusion zone was higher than that of the Ductibor® base metal, and fracture occurred in the Ductibor® base metal in a tensile test.

In this work, TWBs were hot stamped to form top-hat channels with axial tailoring along their length. The hardness at different positions on the channels was measured and the results from different thicknesses are compared. The hardness distributions of the TWB parts are compared to those developed through tailored in-die heating (IDH). The goal of this work is to compare the hardness of parts formed with the TWB tailoring method to IDH parts that were formed on the same die set but with differing thermal conditions. This will show whether an adequate quench rate is being achieved in the die to give the desired material properties. These top-hat channels will be assembled into axial crush rails and dynamically tested in future work.

2. Material
The tailor-welded blanks that were studied in this work were composed of two materials. Usibor® 1500-AS is a hot stamping steel that hardens during quenching and can reach ultra high strengths of 1500 MPa, while Ductibor® 500-AS is a more ductile hot stamping steel with an ultimate strength of about 600 MPa [5]. These two materials are joined by a laser weld along their abutting edges to form the welded blank. The weld line is slightly offset from the center of the blank to allow tooling clearance in multi-gauge sheets, as shown in Figure 1.

![Figure 1: Laser-welded blank for forming top-hat channels.](image-url)

3. Experimental Setup
A hydraulic press manufactured by Macrodyne Technologies Inc. was used in this work. The actuator has a capacity of 120 tons, and is controlled using a 100 GPM servo valve to achieve a displacement speed of approximately 10 in/s. The tooling was designed for forming of top-hat channels with in-die heating in work by Omer et al. [7]. The fully quenched configuration that was used to form these TWB top-hat channels consisted of a fixed water cooled punch, a room temperature binder mounted on nitrogen cylinders, and a water cooled die cavity. The binder exerted a force of 23 kN when fully displaced. Chilled water was pumped through channels in the cooled tools to remove the heat from quenching. The tool was installed in the press such that the punch was fixed and the die was displaced downward by the press.
Figure 2: Cross-sectional view of tooling used to form the quenched top-hat channels.

The parts formed in this die were channels 590 mm in length, with a top-hat cross-section of about 50 mm high by 65 mm wide, and flanges of about 125 mm wide (Figure 3). They were hot stamped in this chilled tool from the TWBs described previously. The blank was heated in a furnace to 930°C for seven minutes to austenize it, after which it was transferred to the press using an automated material transfer system. The die was displaced downward by the press to form the part, and maintained a force of 588 kN for a period of 10 seconds to quench the part. The formed channel was removed from the tool and air cooled to room temperature. This hot stamping process caused the Usibor\textsuperscript{®} section of the part to form a hard, fully martensitic material, while the Ductibor\textsuperscript{®} formed less martensite and remained softer, creating a rail with axial tailoring.

Figure 3: Dimensions of formed top-hat channels.

3.1. Measuring Vickers Hardness
From the 1.2 mm thick formed top-hat channels, strip specimens were water jet cut from the top, sidewall, and flange in a 200 mm long section centered on the weld joint. These strips were cut into pieces 20 mm long and mounted in resin pucks. All 10 pieces of a 200 mm strip were mounted in a single puck. The pucks were polished using silicon carbide grit paper in the order: 240, 500, 800, 1200,
2400 using an automated polishing apparatus for about 4 minutes per grit, to obtain a mirror finish. Vickers hardness measurements using a micro-hardness tester with 500 gf indentation force, 10 second dwell time, and a pyramidal diamond indenter were then taken at 20 mm intervals, with five much smaller 0.5 mm intervals measured across the weld line. Three through thickness hardness measurements were taken at each point, and specimens from three parts were measured. In the 1.6 mm gauge thickness, strips from the top section only were prepared and measured in the same way to compare their behaviour.

![Figure 4](image)

**Figure 4**: (a) Locations where specimens were cut from formed channels, (b) 200 mm long strip sectioned and mounted in a resin puck.

4. **Hardness Measurement Results**

4.1. **Measured Hardness Distribution in 1.2 mm Parts**

In Figure 5, below, the measured hardnesses of the 1.2 mm thick tailor-welded parts in the three measurement locations are compared. The solid line shows the average of the three through thickness measurements in each section, while the error bars show the standard deviation in the three measurements at each point.

![Figure 5](image)

**Figure 5**: Measured hardness distributions in the top, sidewall, and flange regions of the 1.2 mm channels.
The measured hardnesses show that the part clearly had tailored properties along its length resulting from the TWB. The Ductibor® section had an average measured hardness of 235 HV in the top section, 205 HV in the sidewall, and 185 HV in the flange. The Usibor® section measured 500 HV at the top, 495 HV in the sidewall, and 480 HV in the flange. The reduced hardness in the sidewall and flange were likely the result of decreased contact force, which slows down heat transfer and reduces the cooling rate. In the sidewall, the orientation and relief angle made it difficult to exert a great deal of force. In the flange, the contact force was reduced as the binder force was an order of magnitude lower than the press force acting on the top of the die.

The standard deviations in the measured hardness data were expressed as a percentage of the average hardness at each measurement point, and then averaged over the length of the rail. Table 1 shows that the measurement scatter was 3 to 4 percent in the top, sidewall, and flange of the 1.2 mm parts, indicating that the repeatability of the forming and measurement processes is good. The largest through-thickness changes in hardness were observed when traversing the weld line.

**Table 1:** Percentage scatter in hardness measurements.

|            | Top (%) | Sidewall (%) | Flange (%) |
|------------|---------|--------------|------------|
|            | 4.1     | 3.7          | 4.2        |

4.2. Effect of Sheet Thickness

The average hardness values in the 1.2 mm and 1.6 mm thick channels are compared in Figure 6. The hardness in the 1.2 mm and 1.6 mm channels is very similar in both the Ductibor® and Usibor® materials, and across the weld line transition. In the top section, the hardness is slightly lower in the 1.6 mm channels by about 6 HV in each material. In the sidewall, the Ductibor® is 10 HV harder in the 1.6 mm channels, while the 1.6 mm Usibor® is 10-40 HV softer. In the flanges, the hardness is nearly identical between the two thicknesses. In all of the sections, the differences in hardness between the two material thicknesses is within the standard deviation of the measured data.

**Figure 6:** Comparison of hardnesses in 1.2 mm and 1.6 mm rails.

4.3. Comparison with In-Die Heating Results

In Figure 7, the average micro-hardnesses in the top and sidewall sections of these tailor-welded parts were compared to those of in-die heated parts that were measured by Omer [7]. These IDH parts were
composed of Usibor® 1500-AS that was formed in a tailor-heated configuration of the same tooling that was used for this TWB work. In the IDH configuration, half of the tool was fully cooled and the other half was heated to 700°C. This elevated die temperature decreased the cooling rate, resulting in a soft zone.

The hardnesses of the fully cooled Usibor® sections are similar, although the TWB had less variation in hardness along its length. In the soft section, the IDH Usibor® has a slightly lower hardness than the Ductibor® at the top of the rail, and the hardnesses are similar in the sidewall. The hardness of the flanges was not compared, because the flanges in the in-die heated tool were heated along their entire length, softening the flanges along the full length of the part. Overall, the two different tailoring strategies achieve similar hardneses in both the top and sidewall sections of the top-hat channel away from the transition zone.

The size of the transition zone between the different hardness zones is much larger in the IDH heated parts than in the tailor-welded parts. This is the result of thermal gradients in the IDH part, where the heat from the 700°C die conducts along the length of the part, softening the material beyond the heated zone.

The transition zone in the tailor-welded parts is very small, spanning just 2 mm between the soft Ductibor® and the hard quenched Usibor®, as shown in Figure 8 below. Additionally, there was a smooth transition between the two materials, without a weakened heat affected zone, which is consistent with the literature [5, 6]. This smooth transition is the result of carbon dilution in the molten zone between the low-carbon Ductibor® and higher-carbon Usibor® [5].

**Figure 7:** Comparison of hardneses in top and sidewall sections of 1.2 mm tailor-welded and 700°C in-die heated tailored channels.

**Figure 8:** Detailed hardness traverse across laser weld in each measurement section of the 1.2 mm tailored channel.
5. Discussion and Conclusions

The hardness measurements that were taken from the formed 1.2 mm top-hat channel parts showed that the use of laser welded blanks comprised of Usibor® 1500-AS and Ductibor® 500-AS will produce a part with tailored properties along its length when it is formed in a fully cooled die. The Ductibor® section of the blank achieved hardnesses that were similar to the hardness measurements in the literature [5, 6]. The Usibor® section of the blank achieved hardnesses in the top and flange that aligned with Omer’s results [7]. The flange hardness of 480 HV was significantly higher than the 250 HV reported in the literature.

The hardnesses along the top, side, and flange surfaces of 1.2 and 1.6 mm parts were very similar and within measurement scatter. With a larger difference in sheet thickness, differences in cooling rate and thus hardness would be expected.

The hardnesses on the top and sidewall surfaces of the Ductibor® section were similar to those in the 700ºC heated die soft zone in Omer’s work [7], and the quenched Usibor® sections were also similar. This showed that parts with similar hardness profiles can be generated using the tailored hot stamping methods of IDH and TWB when using the appropriate die temperatures and materials. Tailored in-die heated parts have a much larger transition zone between the desired strengths due to thermal conduction within the part. A weakened heat affected zone was not observed on either side adjacent to the weld in the TWB parts.

6. Future Work

The ability to combine sheets of different gauge thicknesses in a single blank is a key advantage of the TWB process. In addition to the single-gauge channels used in this work, multi-gauge channels composed of 1.2 mm Ductibor® welded to 1.6 mm Usibor® will be formed. This will give a larger difference in stiffness between the soft and hard zones. Forming of these channels requires modification of the tooling to allow for the use of different binder heights in each half of the die.

These tailored channels are intended for use in energy absorbing crush structures, such as front axial crush rails. The soft Ductibor® region is expected to absorb crash energy as it collapses, then the hard Usibor® will resist intrusion into the passenger compartment. The next step in this work is to characterize the axial crush behaviour of crush rails made from these channels. Crush rails will be assembled by spotwelding together the flanges of two of these top-hat channels, and tested dynamically and quasi-statically to assess the forces and energy absorption during deformation with different gauge thicknesses. These results will be compared to those of IDH as well as non-tailored rails.

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