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TAILORED THICKNESS HOT STAMPING OF HIGH STRENGTH ALUMINUM SHEET

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ABSTRACT

The adoption of tailored-rolled or tailor-welded blanks (i.e. TRB/TWB) in the automotive industry has been known to offer great potential for the optimization of weight, function, cost and complexity. Vehicle light weighting can further be achieved by using high strength aluminum alloys like the 7xxx-series. 7xxx-series alloys are capable of delivering specific strengths equal to or greater than high strength steels. However, room temperature formability of this aluminum class is limited, so one approach to forming 7xxx-series alloys is by hot stamping. Hot stamping utilizes an elevated temperature blank and the high pressure stamping contact of the forming die to simultaneously quench and form the sheet. This paper explores the initial feasibility of tailored thickness material for body-in-white applications when processed under hot stamping conditions.

KEYWORDS

Aluminum, Friction stir welded, Hot stamping, Tailor-rolled, Tailor-welded, 7xxx-series

INTRODUCTION

Steel tailor-rolled blanks (TRB) or tailor-welded blanks (TWB) have been used within the automotive industry as a method of reducing weight, expanding material utilization, and decreasing overall part/assembly cost (Ganeasan et al., 2015; Merklein et al., 2014; Hirt et al., 2005; Kridli et al., 2000). The production of such tailored thickness materials has resulted in over $2.5 billion (2016) in combined industry sales (Mubea, 2018). As automakers begin to adopt the manufacturing practices traditionally reserved for steel such as tailor rolling/welding with greater enthusiasm for vehicle light weighting, there exist an opportunity to expand the material database to extend beyond the traditional aluminum alloys found in current production.

High strength aluminum alloys, i.e. 7xxx-series, are ideal for structural automotive applications due to their high specific strength; however, they have limited room temperature formability. Hot stamping, another manufacturing practice used by the steel industry, can be used to form these high strength materials. The combination of tailoring the thickness of a sheet material and hot stamping provides an opportunity for significant weight saving within an existing manufacturing footprint. This paper explores the potential and challenges of this approach when applied to structural body-in-white components. The methods for tailor rolling, tailor welding and hot stamping are described and applied to the production of a 7075 aluminum alloy B-pillar. The results are discussed in terms of feasibility and weight savings.

TAILOR-ROLLED BLANKS

Background

Flexible rolling of steel represents a well-accepted technology to exploit lightweight potential within the stamped parts. During the past decade, the company Muhr and Bender KG (Mubea, Germany) has developed this technology together with the Aachen University (Germany). The flexible rolling process allows for continuous thickness variation within a cold rolled material. Hence, load adapted thickness material runs are possible which lead to semi-finished products (tailor rolled blanks) and parts (stamped parts and tubes made from tailor rolled blanks). As a result of the flexible rolling process, the number of thickness changes within one part does not affect part costs. A complex sheet thickness design can thus lead to a more economical part by optimizing the raw material usage, both for steel and for aluminum TRBs. An estimated weight reduction of 15% to 25% by the TRB technology is induced by load adapted thickness runs as well as part consolidation.

In the past, high volume car lines, did not allow for effective serial production of aluminum tailor rolled blanks (Al-TRB) due to the small usage of rolled aluminum components. Conversely, the niche markets presented by high-end cars and sports cars did not offer sufficient market volume. Today, however, the trend of aluminum-intensive material and mix material vehicle applications have encouraged the development of effective process chains for flexibly rolled aluminum blanks. Particularly in combination with the hot forming process of aluminum, the flexible rolling can be very effective by simplifying the annealing process in comparison to cold rolling of aluminum; for example 6000 series alloys. The principle of flexible rolling is based on a standard continuous cold rolling process, whereas the rolls are hydraulically shifted according to the defined thickness runs (Figure 1). The high thickness accuracy of +/-50µm at each point of the blank is generated by an adaptive adjustment control system.

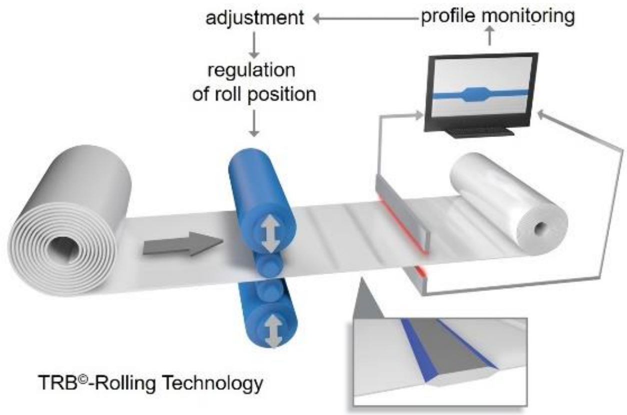

Figure 1. Principle of the flexible rolling process

Experimental Set-up

The AA7075 raw material supplied for this work was rolled by Mubea and received in an O-temper (soft annealed) with an initial thickness of 3 mm. As the thickness run of the tailor-rolled blanks varies between 1.6 mm and 2.0 mm, the achieved reduction during the flexible rolling process was between 33% and 47% of the thickness. Additionally, AA7075 test material was rolled with a maximum reduction in thickness of 70%. Even at this degree of deformation, rolled sheets without any edge cracks were obtained. Edge cracking is a significant concern when it comes to rolled sheet products. Large edge cracks can transverse the width of the coil which would result in scrapped metal or deem the coil unusable because coil production specifications are not meet due to trimming of the cracked edges.

The velocity for all rolling operations was fixed to a value of 20 m/min. The lubricant used during the aluminum rolling process consisted of an oil-water emulsion similar to that applied for the flexible rolling of steel. As the main function of the emulsion is the cooling of the coil material, only a limited amount of lubricant was necessary for the aluminum rolling process. In contrast to steel, the rolling forces of aluminum are significantly lower resulting in less deformation heat. Age-hardenable 7xxx series alloys typically require an annealing process prior to the forming due to the work hardening induced into the material by the flexible rolling. The AA7075 material used for hot stamping, however, will be heat treated as part of the forming process thus reducing the process chain of the flexible rolling (Figure 2).

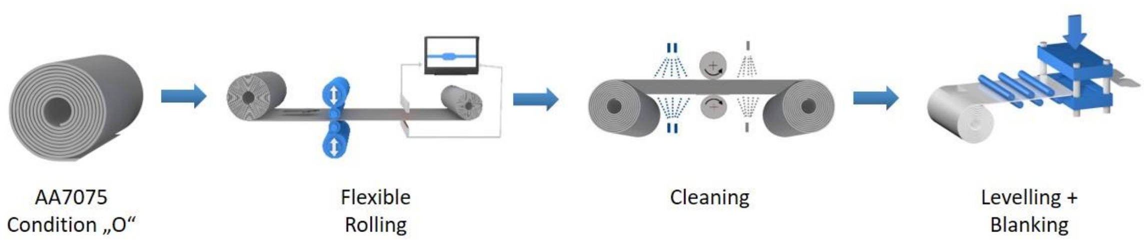

Figure 2. Process chain of flexible rolling

The AA7075 material was rolled on a production flex-rolling mill, which is optimized for steel grades. Therefore, a subsequent cleaning process of the aluminum coil was mandatory to avoid steel flakes on the aluminum sheet surface. Such flakes would cause corrosion particularly in combination with residual emulsion. The cleaning process itself was subdivided into chemical cleaning, brushing, washing with water and drying. During the rolling and blanking processes the thickness run is measured by a laser system at several points along the entire width of the sheet. The laser measurement system, which has been optimized for steel, must be adapted because aluminum surfaces typically have higher reflectivity. Upon identifying the ideal process parameters for generating the desired TRB 1500 mm × 500 mm blanks were produced. The blanks were then laser trimmed to a trapezoid geometry. Further discussion of blank geometry is given in the hot stamping section.

TAILOR-WELDED BLANKS

Background

A tailor-welded blank (TWB) is a good option for weight savings as it joins two or more sheets of similar or dissimilar gauge and or material grades. TWBs allow for a decrease in sheet thickness at determined sections which can lead to weight reduction between 10-12% in aluminum structural parts. Although productivity is improved by using laser welding, weld defects, such as weld concavity, remain a constant challenge on aluminum tailor welded blanks (Hovanski, 2014). In addition, AA7075 is susceptible to hot cracking for fusion welding processes and widely considered non-weldable. Friction stir welding, as a solid-state welding process, has been proven suitable for AA7075 (Tavares, 2011; Khaled, 2005). This welding process, applied to tailor welded blanks, is slower than laser welding but shows relatively high cadency (≥3m/min) in thin sheets (≤2.0mm) and a good surface appearance (Nadeau, 2015). One concern of friction stir welds subjected to elevated temperature upon a specific time and temperature is abnormal grain growth (AGG). Many authors reported this behavior after a complete post-weld heat treatment or superplastic forming applications (Nadeau et al., 2013; Aydin et al., 2010; Sun & Apelian, 2001).

Experimental Set-up

Tailor-welded blank coupons were produced by joining 1.6 mm to 2.0 mm AA7075-T6 of 100 mm wide by 300 mm long for qualification purpose. The coupons were used to determine the process window as well as post-weld mechanical properties, using MTS I-Stir PDS gantry type equipment as shown in Figure 3. Two (2) FSW tool designs were evaluated using an 8.5 mm diameter shoulder, respectively cup and scroll-convex features, before manufacturing of the larger final tailor-welded blank for part production. The process windows were quite similar but the cup shoulder design gave slightly higher process flexibility at high travel speeds (Figure 4). This preferred tool design was then used for subsequent steps but caution was required with respect to using high rotational speeds (≥1500RPM); hot welds can result which in turn can induce surface galling defects or internal insipient melting. These defects are detrimental and unacceptable prior to hot stamping. The various process parameters studied passed the AWS D17.3 standard for post-weld mechanical properties with joint efficiencies over the ultimate tensile strength between 77% and 87% of the as received material strength.

Figure 3. FSW tailor welded coupons development.

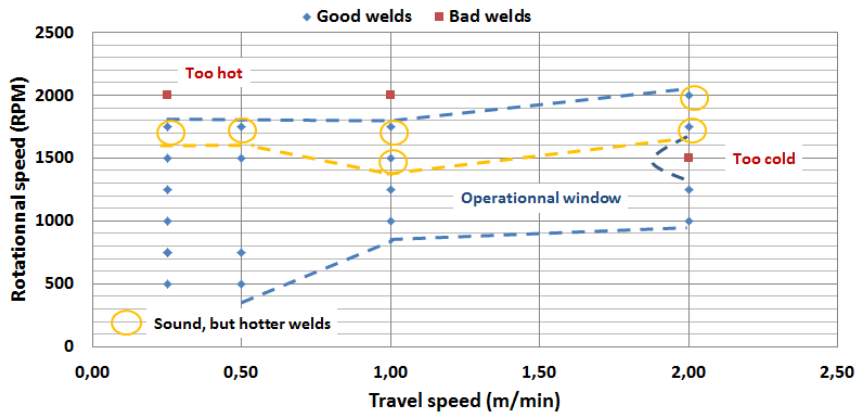

Figure 4. Process window determination for cup shoulder design FSW tool.

In order to evaluate the hot stamping microstructural behavior of various friction stir welding conditions, the heat cycle (480°C ±10°C for 12 minutes, water-quenched, and artificially aged 125°C for 24 hours) was simulated and analyzed through optical microscopy (Figure 5). As observed in Figure 5, no process conditions completely suppressed the AGG phenomena. However, a few conditions operating under a low rotational speed, thus a lower heat input, gave rise to homogenous smaller grain sizes which were recognized as a competitive grain growth behavior (Figure 6).

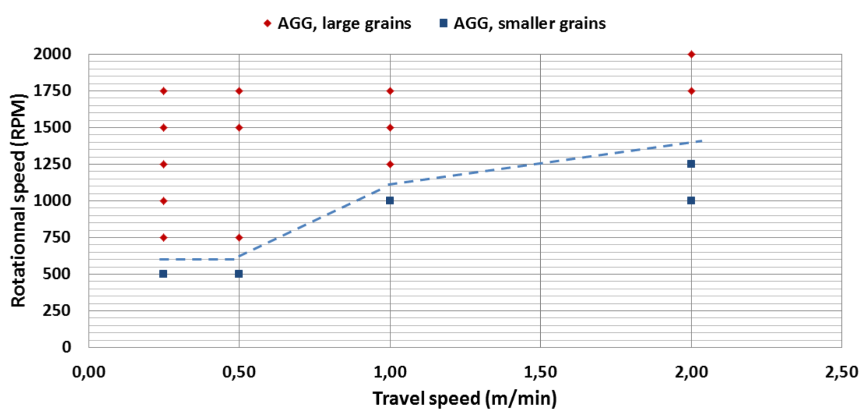

Figure 5. Abnormal grain growth behavior upon various FSW process conditions.

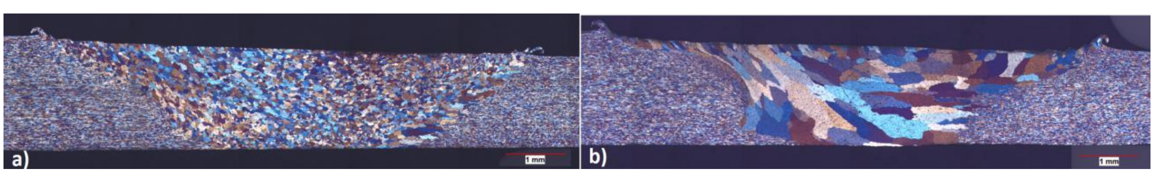

Figure 6. Microstructural analysis after high temperature heat cycle; a) competitive grain growth; b) abnormal grain growth.

In order to validate the hot stamping mechanical behavior, high temperature tensile tests were conducted as they are a suitable indicator of the complex forming behavior. The target temperature was set at 440°C ±2°C at a strain rate of $1.0s^{-1}$. As expected, large grains have a detrimental effect on forming operations and premature failure was observed at the weld nugget, whereas small homogenous grains showed base metal failure which indicated preferable formability (Figure 7). For these conditions, a mean grain size threshold had been assessed prior to hot stamping which is between 97.1 µm and 149 µm to prevent any premature weld nugget failure. Despite the successful concept demonstration of FSW for hot stamping applications, there is still room for optimization of the travel speed before a potential production implementation.

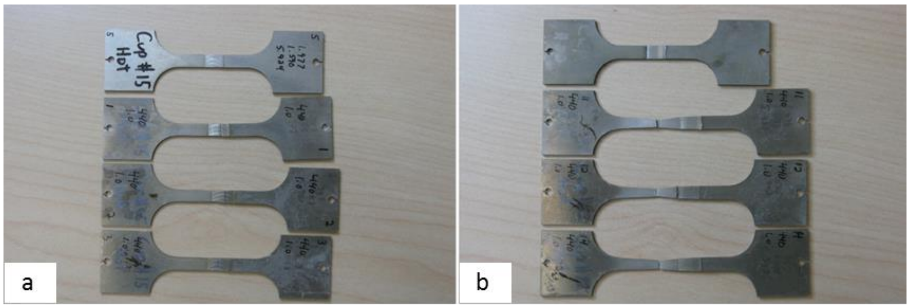

Figure 7. Hot tensile testing behavior; a) abnormal grain growth; b) competitive grain growth.

Details of the friction stir welding process development of AA7075 for hot stamping applications are further discussed by Nadeau and Harrison (2017). Upon identifying the ideal process parameters for generating a friction stir weld that would result in a competitive grain structure, 1500 mm x 500 mm blanks were produced. The blanks were then laser trimmed in a trapezoid geometry. Further discussion of blank geometry is given in the following section.

ALUMINUM HOT STAMPING

Background

Hot stamping refers to a metal forming process in which an elevated temperature blank is simultaneously formed and quenched by a water-cooled die. The hot stamping process takes advantage of the low flow stresses and high ductility of a heated blank. The rapid transfer of heat from the blank to the die allows for alloying elements to be locked in a supersaturated solution state (SSSS). Post formed artificial aging allows for the part to then achieve peak strength. This process has been carried out in practice by Harrison and Luckey (2014) to produce a B-pillar from AA7075 heat treated to a T6 temper for a monolithic blank design.

While hot stamping has been demonstrated with respect to formability, there still remain challenges with respect to lubrication and furnace/oven technology. Lubrication is necessary to minimize die galling and to support material flow into the die cavities. While the die itself can be lubed using sprayers, this approach is wet and lube particles can clog the spray nozzle causing dry zones on the die surface. A more preferred approach is for a lubricant that will survive the 480°C solution heat treatment temperature so that it may be applied to the blank by the sheet manufacturer prior to hot stamping. In addition to lubrication challenges, most ovens currently used for sheet heating for hot stamping are radiative stacked ovens. Aluminum placed in a radiative oven heats up slower than steel due to its higher specific heat capacity. By adding convection heating (i.e. air circulation) to the oven design, the time required to heat the blank can be reduced by a half in addition to supporting temperature uniformity. Hearth ovens can also be used as a method of decreasing cycle time, but require substantial floor space (i.e. 30 to 40 meters).

Experimental Set-up

The demonstration part originated from a 3.0 mm 6xxx-series B-pillar from the MY2015 F150. The original CAD part geometry was modified for a 2.0 mm hot stamped part; the increased strength of 7xxx versus 6xxx allows for the material thickness reduction. The original production part was formed via a 3-piece draw die whereas the hot stamped part was formed via a 2-piece crash die. Additional features had to be added to the die surface such as steps, which act similarly to die beads, to support formability. Fingers were added to the die to elevate the blank above the die surface so as to minimize blank cooling. Finite element simulation was used to target shape and blank geometry for optimal formability. The profile of the die face was similar to the TRB profile. This approach was necessary to ensure sufficient contact between the die and the blank during the quench and forming of the part as well as to minimize material lock up so as to support material flow. Due to cost limitations the die was not recut to specifically accommodate the weld lines of the TWB material and the TWB material was formed in the same tool. The lower cavity of the tailored thickness tool is shown in Figure 8.

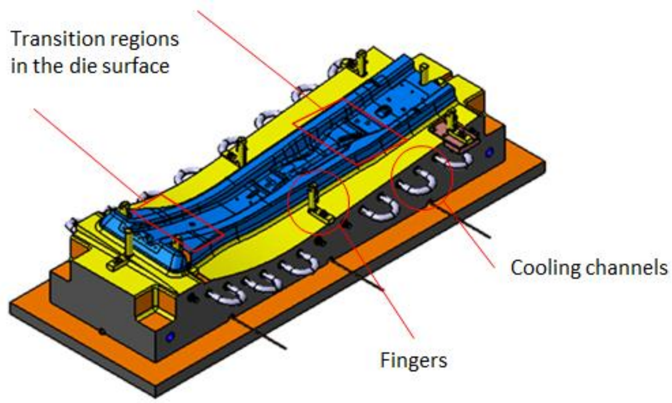

Figure 8. Tool CAD of tailored thickness die.

TRB transitions were determined via finite element analysis (FEA) and crash simulation. It was found the upper B-pillar transition from 2.0 mm to 1.6 mm (left to right) could be narrow because formability was of the transition zone was fairly simple; see Figure 9. However, the formability FEA of the lower region of the B-pillar, where the door striker is typically located, showed the material would buckle or fold over itself during the forming operation. For this reason, a wider transition zone was used to increase from 1.6 mm to 2.0 mm (left to right). The increase in transition helped to reduce the folding/wrinkling of the material but did not completely eliminate the issue. The influence of the transition zones on the final part performance had been verified using vehicle level safety CAE models for side intrusion and roof strength. Due to a formability concern of material folding/wrinkling in the transition from 1.6 to 2.0 mm, two versions were TWB created. One in which the weld line avoids the formability issue by moving the transition line higher (TWB-1) and the second in which the weld line is positioned for optimal material efficiency (TWB-2). The transition from 2.0 to 1.6 mm (left to right) is the same for TWB-1 and TWB-2.

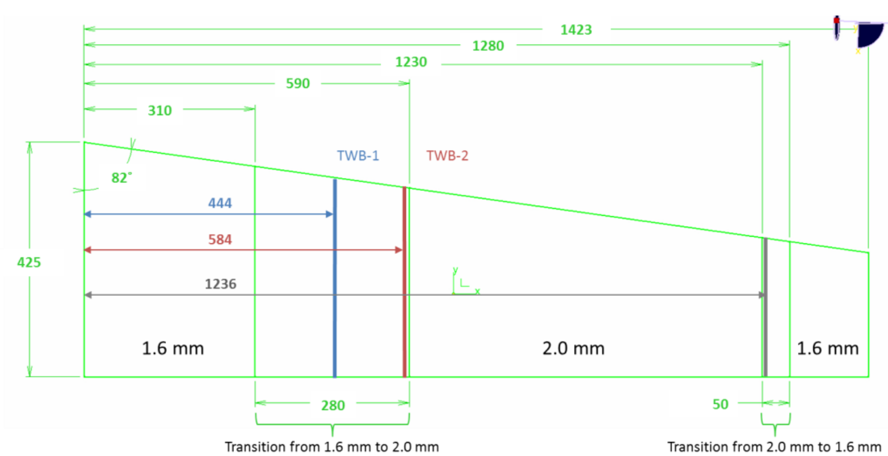

Figure 9. Blank dimensions for tailor rolled/welded blanks.

The tailor rolled/welded blanks for this work were prepared by Mubea/NRC respectively per the previously discussed methods. The tailor rolled/welded blanks of AA7075 were solution heat treated between 480–500°C for 10 minutes. The blanks were removed from the furnace and transferred to the die using automation; the approximate temperature of the blank prior to complete die close was 460°C. In this application, the die was lubricated with Fuchs Forge Ease, a water-based lubricant, which had been diluted with isopropyl alcohol by a 1:4 ratio. Once positioned on the die, the ram of the press travelled at an estimated speed of 200–250 mm/s with an applied tonnage of 500. Simultaneous blank forming and quenching occurred upon closing of the die. The die was allowed to dwell in the closed position for 15 seconds before releasing the stamped part; the part temperature was between 30-40°C. Parts were then artificially aged at 125°C for 24 hours; it should be noted that significant reductions to artificial aging time may be achieved by implementing a 2-step artificial aging practice (Harrison & Luckey, 2015). The sequencing of process steps is shown in Figure 10.

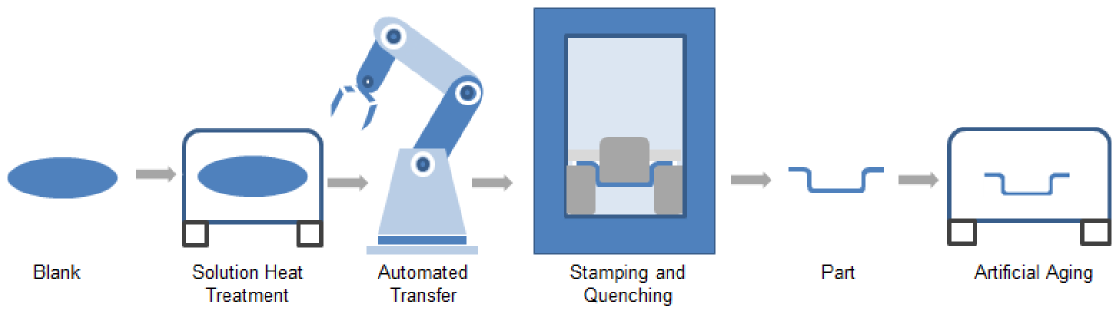

Figure 10. Schematic of the hot stamping process.

RESULTS

A 2 mm B-pillar outer was hot stamped from tailored thickness aluminum alloys, heat treated and trimmed; the final product is shown in Figure 11. Both the tailor-rolled and tailor-welded blanks (i.e. TWB-1 and TWB-2) formed successfully using the hot stamping process. Material buckling or excessive wrinkling in the transition zone from 1.6 to 2.0 mm was not observed during the hot stamping process as predicted by FEA simulation. This under prediction of the material formability suggests that there may be forming parameters that need to be better defined when modeling high strength aluminum alloys. Experience has shown that FEA simulation of 7xxx-series alloys tends to under predict formability often highlighting material failures that are not incurred during practice. Another notable observation was that there were no material handling issues with the tailored materials, in particular the TWB material. The robot was able to successfully transfer the blank with no observed sag of the blank or degradation of the weld line. Formability of the weld line was also possible with no observed stretch or drawing issues as shown in Figure 11.

The tailor-rolled and tailor-welded parts when compared to the current production 6xxx aluminum alloy part have the potential for a minimum 1.1 kg mass savings; weight savings are shown in Table 1. The use of AA7075 versus a 6xxx-series material allows for a 34% mass savings and 38% to 41% when coupled with a tailored thickness design; which is primarily for a one-for-one substitution. The true advantage of using a tailored thickness material, however, is when part consolidation is incorporated into the design. The current design of the B-pillar cross-section consists of a 3.0 mm outer, 2.8 mm reinforcement bracket and a 2.0 mm inner. By using a tailored thickness design the opportunity exist to consolidate the B-pillar outer and reinforcement. Such consolidations allow for better material utilization in addition to a reduction of the costs associated with producing a stamped part such as dies, fixturing, joining, etc.

Figure 11. 6xxx production B-pillar compared to hot stamped B-pillars from AA7075; a) 6xxx; b) 7xxx c) TRB, d) TWB-1, e) TWB-2.

Table 1. Summary of 7xxx blank weights when compared to 6xxx.

Blank type	Weight (kg)	Weight savings (kg)
6xxx - Uniform (3.0 mm)	2.9	--
7xxx - Uniform (2.0 mm)	1.9	1.0
7xxx Tailor Rolled (TRB)	1.8	1.1
7xxx Tailor Welded (TWB-1)	1.8	1.1
7xxx Tailor Welded (TWB-2)	1.7	1.2

CONCLUSIONS

This work explored the production and hot stamping forming feasibility of tailor-rolled and tailor-welded aluminum alloy 7075 blanks. Determination of the tailored sections studied via FEA and crash CAE simulation were identified for maximized material formability and light weighting. Through the method of tailor rolling, material thickness reductions of 33% and 47% were realized without edge cracking. Through the method of tailor welding, parameters were selected that minimized abnormal grain growth. Both tailor welded and tailor rolled blanks survived blank preheating, robot transfer and hot stamping to produce a B-pillar. While work is still on-going to characterize the microstructure within the tailor-rolled and tailor-welded parts, these results indicate the preliminary concept feasibility of tailored-thickness heat-treatable aluminum sheet body structure parts for vehicle light weighting.

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