Effect of Warm Forming on Formability and Springback of Aluminum Alloy Brazing Sheet

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Abstract. This paper investigates the effect of warm forming (up to 350°C) on the formability and springback behavior of AA3003/AA4045 brazing sheet (0.2 mm gauge) for two temper conditions: O- and H24-temper. The key objective is to utilize warm forming to form aggressive geometries and control the springback to improve the part flatness which enables the use of harder temper material with improved strength. Simulations and experiments are performed considering heated dies at several different temperatures up to 350 °C and the blanks are pre-heated in the dies. The geometry under study is referred as a surrogate heat-exchanger component (SHC) and contains complex features found on commercial automotive thermal management systems. An in-depth springback characterization was completed for a wide range of forming process parameters such as: temperature, punch load, sheet direction, and holding time. Numerical simulations were also performed to predict the springback behavior and were compared to the experiments. There were no clear results showing improvement in formability using the warm forming process. However, increased temperatures (above 250 °C) offered significant improvement in springback for the harder H24 material temper.

1. Introduction

With more strict regulations on fuel economy and emissions, the automotive industry is being pushed towards electric and hybrid electric vehicles (EVs and HEVs) that require effective thermal management systems. Currently, battery cooling plates are manufactured using aluminum alloy brazing sheet in the O-temper condition to enable higher formability and reduce springback. Harder sheet tempers, such as H24 for example, are desirable due to greater ease of handling and strength; however, these harder tempers often have lower formability and higher springback.

One approach to improving formability of aluminum alloy sheet is through use of warm forming techniques. Numerous studies have reported increased formability for 5000-series alloys due to the reduced stresses and increased strain rate sensitivity operating at temperatures in the 200-300 °C range [1-3]. Studies of warm forming of 3000-series aluminum are more limited, notable exceptions being Abedrabbo et al. [4] who demonstrated increased formability at elevated temperatures for AA3003 sheet and more recent studies by Bagheriasl et al. [5,6] who characterized the increase in forming limit of 0.5 mm brazing sheet used in automotive heat exchangers (radiators).

Warm forming has also been shown to reduce springback in aluminum alloys [7-9], largely through a reduction in operative stresses during forming. Verma et al. [10] studied the effect of temperature and temper condition on springback in u-channels fabricated from 0.2 mm brazing sheet, the focus of the
current paper. They found that springback increased dramatically with increased temper (hardness), but reduced to nearly zero at temperatures of 250 °C or higher.

The current paper presents numerical predictions of formability and springback in warm formed heat exchanger components fabricated using 0.2 mm brazing sheet in various as-received tempers. The effect of forming temperature on predicted formability and springback is presented, along with comparison with measured data.

2. Experiments

2.1. Material Characterization
The brazing sheet considered in the current research is a multi-layer aluminum composite structure that consists of an AA3003 core and a thin AA4045 clad on one side. The total sheet thickness is only 0.2 mm and was received in the O- and H24-tempers. Both conditions exhibit significant thermal softening and increased rate sensitivity at elevated temperature (Figure 1). The effect of initial temper is evident in the higher initial strength of the H24 condition which results in lower work hardening and even strain softening at elevated temperature (Figure 1(b)) [11]. This lower work hardening is manifest as a lower formability for the H24 condition (Figure 2), although increased temperature does increase formability, as reported by Jain [12]. Further material data is provided by Han [13].

![Figure 1. Effect of temperature and strain rate on constitutive response [11]](image1)

![Figure 2. Effect of temperature on measured formability [12].](image2)
2.2. Forming Experiments

Figure 3 shows the component studied which is referred to as a surrogate heat-exchanger component (SHC) and is a small-sized version of the battery cooling plates normally inserted between battery cells in electric vehicles, for example. Two plates are formed and then brazed together to form serpentine cooling channels with inlet/outlet ports as shown in the figure.

![Figure 3](image-url)  
**Figure 3.** (a) SHC and (b) close-up of inlet/outlet port.

The SHC is formed using a pair of heated dies without a binder. Considerable effort was expended to develop a viable forming process which resulted in the tooling and developed blank shown in Figure 4. Details regarding the process and process development are provided by Verma [14]. The forming process comprises insertion of the blank between the pre-heated dies which then are just brought into contact with the blank which is then allowed to heat to the forming temperature (40 seconds). Once the blank reaches the target temperature the dies are closed and held for two seconds after which the part is removed. Note that several lubricants were considered, including Teflon spray and the Fuchs 278 Hydrodraw solid film lubricant, as well as a dry condition.

![Figure 4](image-url)  
**Figure 4.** (a) CAD of tooling surfaces and developed blank and (b) formed part.

After forming, the part was placed in a custom fixture which clamps one side of the part. The fixture and part are then placed on a flatbed scanner which then acquires the profile of the edge opposite the I/O ports, as shown in Figure 5. The acquired pixel data (after scaling) was used to extract the part curvature and displacement relative to the fixture associated with springback after forming.

![Figure 5](image-url)  
**Figure 5.** Scanned edge of H24 part formed at 250 °C (Teflon lubricant).
3. Model
The forming operation was simulated using the explicit dynamic solver within LS-DYNA, while springback was predicted using the implicit solver. The material properties described in Section 2.1 and further detailed by Han [13] were used to implement a temperature- and strain rate-dependent constitutive model using an extension of the Nadai model proposed by van den Boogaard [14]. Details of the constitutive model implementation and adopted material parameters are provided by Han [13]. A simple von Mises yield approximation was adopted, although it is recognized that aluminum alloys possess a relatively low r-value. Non-quadratic, anisotropic yield criteria will be investigated in future work. Note that Young’s modulus was taken as temperature sensitive [13].

For the forming model, the tooling surfaces were discretized using rigid quadrilateral elements. The tooling element sizes were adjusted so as to ensure at least 6 elements would transfer major tooling features (radii). So-called fully integrated Type 16 elements were used for the blank, with seven through-thickness integration points. The blank element size was 0.15 mm.

A penalty function-based contact algorithm was adopted with a friction coefficient scaled as a function of temperature 0.15-0.37 (Teflon) or 0.87-1.5 (dry). A half-symmetry assumption was adopted to reduce computational time. Mass scaling was employed with a factor of 10^7. Care was taken to monitor (limit) inertial energy and simulations were also run using a mass scaling factor of 10^8 with and no significant differences in predictions [13].

The springback simulations approximated the clamping fixture used in the measurements as illustrated in Figure 6. The y-displacement contours shown correspond to the displacement measurement illustrated in Figure 5. The curvature was extracted along the edge in a similar manner to that used for the measured curvature. The deformed profile indicates that the formed parts are relatively stiff along the length of the cooling channels, but bending stresses in the channel sidewalls likely account for most the observed springback distortion.

![Figure 6. Boundary conditions and predicted shape from springback analysis (case shown is H24, 250 °C forming temperature, Teflon lubricant.](image)

4. Results and Discussion
Figure 7 serves to illustrate the as-warm formed condition of the SHC component with Teflon lubricant. Thinning is observed to be limited to 11.5% in the sharp corner radii of the I/O ports. In addition, the predicted strains all lie below the warm forming limit curve for this temperature, suggesting a viable forming process. This outcome was confirmed experimentally, as seen in Figure 8 which compares H24 parts formed at 250 °C, with and without lubricant. The lubricated parts are intact whereas the un lubricated components exhibited necking at the I/O port radius. Note that O-temper components were able to be formed without necking for all conditions considered (including room temperature).
Figure 7. Contours of percent thickness reduction for (H24-temper, 250°C, Teflon) and corresponding forming limit plot. Forming limit curve (red) due to Jain [12].

Figure 8. H24 component formed at 250 °C, (a) dry and (b) with Teflon lubrication.

The effect of material temper and forming temperature can be seen in Figure 9. In general, the H24 sheet has higher springback as expected (note differences in scale between plots). The H24 sheet also exhibited a monotonic decrease in springback with temperature. Interestingly, the O-temper sheet actually exhibits an increase in springback with forming temperature. This result was surprising, but was observed in both the measured and predicted data and could be due to the fact that the ratio of yield-strength-to-elastic-modulus actually increases with temperature for the O temper sheet, whereas the H24 sheet exhibits a decrease with temperature [13]. The correlation between predicted and measured springback is qualitative at best. The model is able to capture the trends in springback variation with forming temperature and sheet temper; however, additional work is required to achieve stronger quantitative agreement.
Figure 9. Predicted springback displacement and part curvature after forming of O- and H24-temper blanks at the temperatures shown (dry condition).

5. Conclusions
A viable warm forming process has been developed that enables reduction of springback for harder material tempers. The agreement between predicted and measured springback was judged to be qualitative in that the measured trends were captured by the model with some differences in magnitude.

References
[1] Li D and Ghosh AK 2004 J. Mater. Process. Technol. 3 281
[2] Naka T and Yoshida F 1999 J. Mater. Process. Technol. 89–90 19
[3] van den Boogaard AH and Huétink J 2006 Comput. Methods Appl. Mech. Eng. 195 (48-49) 6691
[4] Abedrabbo N, Pourboghrat F and Carsley J 2006 Int. J. Plast. 22, 342
[5] Bagheriasl R and Worswick MJ 2015 Int. J. Mater. Form., vol. 8 (2) 229
[6] Bagheriasl R, Ghavam K and Worswick MJ 2014 Int. J. Mater. Form. 7 (2) 139
[7] Moon YH, Kang SS, Cho JR, and Kim TG 2003 132 365
[8] Kim H and Koc M 2008 J. Mater. Process. Tech., 204 370
[9] Greze R, Manach PY, Laurent H, Thuillier A and Menezes LF 2010 Int. J. Mech. Sci. 52 1094
[10] Verma R, George R, Kurukuri D, Worswick MJ and Winkler S 2015 Proc. IDDRG 2015, (Shanghai)
[11] Verma R 2016 Effect of Elevated Temperature on Mechanical Behaviour and Springback of Aluminum Alloy Brazing Sheets MASc Thesis University of Waterloo http://hdl.handle.net/10012/10421
[12] Jain E 2016 Investigation of effect of temperature and forming speed on the formability of AA3003 Brazing Sheets MASc Thesis University of Waterloo http://hdl.handle.net/10012/10578
[13] Han KB 2018 A Component-Level Study on the Effect of Warm Forming on Formability and Springback of Aluminum Alloy Brazing Sheet MASc Thesis University of Waterloo http://hdl.handle.net/10012/12937
[14] van den Boogaard AH 2004 AIP Conference Proceedings 712