Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 744-751
doi:10.4028/p-fpbrul

Submitted: 2021-12-07
Revised: 2022-02-01
Accepted: 2022-02-17
Online: 2022-07-22

A Materials Science-Based Approach to Finite Element Simulation of Warm-Forming of Al-Mg-Zn Alloys

Florian GRABNER[1,a] and Johannes Albert ÖSTERREICHER[1,b*]

[1]LKR Light Metals Technologies, Austrian Institute of Technology, Lamprechtshausener Str. 61, 5282 Ranshofen, Austria

[a]florian.grabner@ait.ac.at, [b]johannes.oesterreicher@ait.ac.at

Keywords: Finite elements, deep-drawing, warm-forming, LS-DYNA, failure, precipitation hardening

Abstract. Warm deep-drawing of pre-aged (under-aged) blanks of 7xxx series aluminum alloys (Al-Zn-Mg) at moderate temperatures of roughly 120–230°C is a promising route for producing parts with considerable geometrical complexity, good paint bake hardening response, and, thus, excellent final mechanical properties. Furthermore, oil-based lubricants can be used, eliminating the need for elaborate cleaning routines. However, finite element (FE) simulation of the process is challenging: time-temperature regimes during coupon testing for material cards should closely follow the real conditions in the press because the material undergoes significant changes at warm-forming temperatures, such as recovery and precipitation/coarsening/reversion of hardening phases. When convective heating is used for Nakajima or tensile testing, heating rates are usually too low to adequately represent real process conditions (where inductive or contact heating may be used). Here we present a method for establishing FE material cards and calibrating the GISSMO damage model using miniaturized tensile specimens for a dilatometer with inductive heating. The simulations are compared with warm deep-drawing experiments of pre-aged 7xxx and good agreement of minimum draw temperature for two alloys is achieved. The findings are discussed with regards to transmission electron microscopy investigations and final mechanical properties published earlier. It was found that warm-forming is suitable to produce complex 7xxx parts with high final strength. Conditions in the press can be represented by using miniaturized tensile specimens and inductive heating for calibration of material cards/damage models.

Introduction

Automakers aiming to reduce vehicle weight and aircraft industry striving to cut production costs in the wake of the Covid-19 crisis require economical sheet metal forming processes for Al-Zn-Mg(-Cu) alloys (7xxx series). We have shown recently [1,2] that warm-forming of under-aged (pre-aged) blanks is a process with distinct advantages over other approaches, including:

- Good paint-bake response: material achieves roughly 95% of T6 yield strength
- Alternatively: Possibility to use a shortened T6 treatment, achieving 98–99% of reference T6 yield strength
- Oil-based lubricants can be used instead of special high-temperature lubricants, resulting in reduced cleaning operations
- Low investment costs (no solution annealing necessary at the stamping plant)

The process consists of solution heat treatment (SHT) and quenching to dissolve all hardening precipitates and obtain a super-saturated solid solution. Subsequently, the blanks are stored for 24 h and pre-aged (stabilized) for a duration that is only a fraction of the time needed for peak-ageing (T6), e.g., 110 °C for 1–2 h [3]. These under-aged blanks are then deep-drawn at elevated temperature (120–230 °C) and undergo a final artificial ageing treatment, which may consist of a paint bake hardening treatment or a shortened T6 treatment [4]. A time-temperature schema is given in Figure 1.

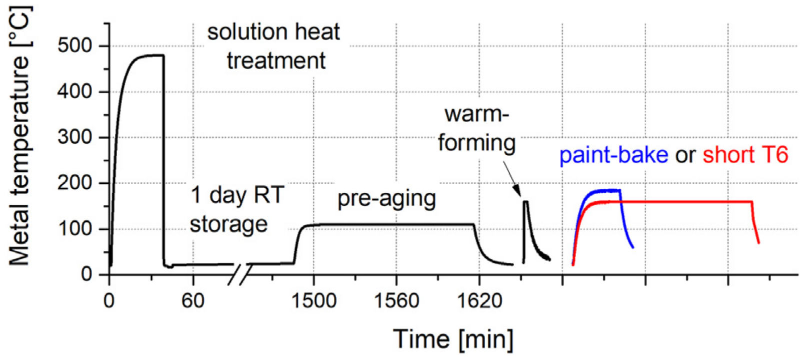

Figure 1: Diagram of the warm-forming process using under-aged blanks [1].

In order for such a process to be adopted by industry, OEMs, aircraft manufacturers, and their suppliers need to be able to perform reliable finite element (FE) simulations of deep-drawing including failure. For this purpose, GISSMO (= General Incremental Stress State dependent damage MOdel) is widely used when simulating with LS-Dyna [5]. GISSMO is a failure and damage model which takes different stress states into consideration. To identify the actual load case, triaxiality η is used. The most important part of the model is the failure curve, which is failure strain over triaxiality. For the calibration of this curve, tensile specimens with different geometries (smooth, notched, shear, …) must be tested at the relevant temperatures. For this purpose, a tensile testing machine equipped with a temperature chamber could be employed. However, heating by convection requires the specimens to be soaked for a few minutes at least to achieve uniform temperature. In contrast, blank heating in the warm-forming process is achieved by contact heating and takes only a few seconds (heating rate ~20 K/s) [2]. Therefore, when convective heating is used, the conditions in the press cannot be adequately mimicked. Furthermore, the temperatures achievable in temperature chambers for tensile testing machines are usually limited (e.g., max. 250 or 360 °C [6]). Similar limitations usually apply to Nakajima tests, used for creating forming limit diagrams (FLD).

Age-hardenable aluminum alloys undergo microstructural changes when held at warm-forming temperatures (ranging roughly from 120–230 °C) [7]. Depending on the temperature and the starting temper, the following processes may occur:

- Nucleation and growth of precipitates
- Dissolution of precipitates
- Recovery (annihilation of dislocations by increased mobility of dislocations)

Dissolution of small particles and growth of larger hardening precipitates may occur simultaneously, leading to an overall coarsening of the precipitate structure; this is desired in retrogression and re-ageing (RRA) processes to improve stress-corrosion cracking resistance of 7xxx series alloys [8].

Long et al. [9] showed that the ultimate tensile strength of warm-formed 7xxx parts after paint bake is reduced as a function of warm-forming temperature and time. Österreicher et al. [2] found differences in the differential scanning calorimetry dissolution peak temperatures of hardening precipitates in AA7075 warm-formed at different temperatures; these results indicate different grades of coarsening of the hardening precipitates as a function of warm-forming temperature. Rader et al. [10] reported extensive warm tensile test data for AA7075 at various warm-forming temperatures, strain rates, and holding times.

The microstructural changes at warm-forming temperatures are time-dependent and influence not only the final product properties, but also mechanical properties and failure behavior during warm-forming. Therefore, it is desirable to achieve the same heating rates and holding times as in the press when testing coupons for FE calibration.

Here we test miniaturized smooth, notched, and shear tensile specimens from pre-aged sheets of two 7xxx series alloys in a quenching and deformation dilatometer, capable of rapid inductive heating up to 1,500 °C. The results are used to calibrate the GISSMO model and perform FE simulation of the warm-forming process at various temperatures. Good agreement with deep-drawing experiments is achieved.

Materials and Methods

Materials. We used rolled sheet of Alclad 7075 (O temper, 1.4 mm) and 7021+ (F temper, 1.5 mm), both obtained from AMAG rolling GmbH. 7021+ is a non-standard alloy based on AA7021 with increased Mg and Zn levels. The chemical compositions are reported in [1].

Deep-drawing and heat treatment. Long octagonal blanks (dimensions given in [1]) were cut. Solution heat treatment (SHT) was performed by placing the blanks in a pre-heated oven (AA7075: 480 °C, 25 min; AA7021+: 515 °C, 15 min) followed by quenching in water. After one day (24 h) of natural ageing, the blanks were placed in an oven preheated to 110 °C for 2 h [4] and subsequently allowed to cool to room temperature (RT) at ambient air. The blanks were lubricated with Zeller + Gmelin Multidraw Drylube E1 and placed in a preheated blank holder (RT, 120, or 160 °C). Punch and die were also pre-heated to the desired temperature. A drawing of the long cup tool and additional information are given in [1]. The blank holder was closed with 50 kN (~25 bar) and after 30 s, deep-drawing was started (20 mm/s) to a draw depth of ~50 mm. A 160 t single-acting hydraulic press was used. Final heat treatment of the parts was performed using either a simulated paint-bake treatment at 185 °C for 34 min or a “short-T6” treatment at 165 °C for 130 min (furnace time) [4].

Tensile testing. Miniaturized tensile tests (smooth, notched, and smiley shear – see Figure 3) at various strain rates and temperatures were conducted in triplicate using a Bähr DIL 805 A/D deformation dilatometer (see Figure 4 and [2]). The smiley shear specimen was adapted from Gorji et al. [11]. Specimens were cut in rolling direction from pre-aged sheet (heat treatment as described above). For the warm tensile tests, the specimens were heated at a rate of 20 K/s to 120 or 160 °C and held at this temperature until 30 s after the beginning of heating; then, deformation was started at a strain rate of 0.0067 s^{-1}. The heating and soaking regime was chosen to simulate contact heating of the blanks in the blank holder before deep-drawing [2]. Strain measurement was accomplished using quartz push rods hooked to the shoulders of the tensile specimens and connected to a linear variable differential transformer (LVDT).

FE simulations. The FE Solver LS-Dyna R11 double precision was used. First, the flow curves were extrapolated from experimental data using a Hocket-Sherby formulation to numerically match the uniaxial smooth tensile test results. Since no anisotropic behavior in the experiments was investigated, a von Mises plasticity model (*MAT_024) was used. Then, to define the failure curve for GISSMO, miniature notched and shear tensile tests were simulated. Considering the specimens’ geometries (Figure 3), modelling with shell elements is not expedient due to a significant width to thickness ratio in the deformation zone. Therefore, linear 8-noded hexahedron (solid) elements with an edge length of 0.1 mm and 14 elements in the thickness direction where used, see Figure 2 (left). To apply the calibrated model to other mesh sizes, a regularization procedure must be conducted for different element sizes, which scales the failure curve accordingly.

For deep-drawing simulations, tool parts (namely die, punch, blank holder) were modeled using rigid shell elements; for the blank, fully integrated shell elements with an edge length of 1 and 2 mm were used, see Figure 2 (right). All numerical simulations were carried out isothermal.

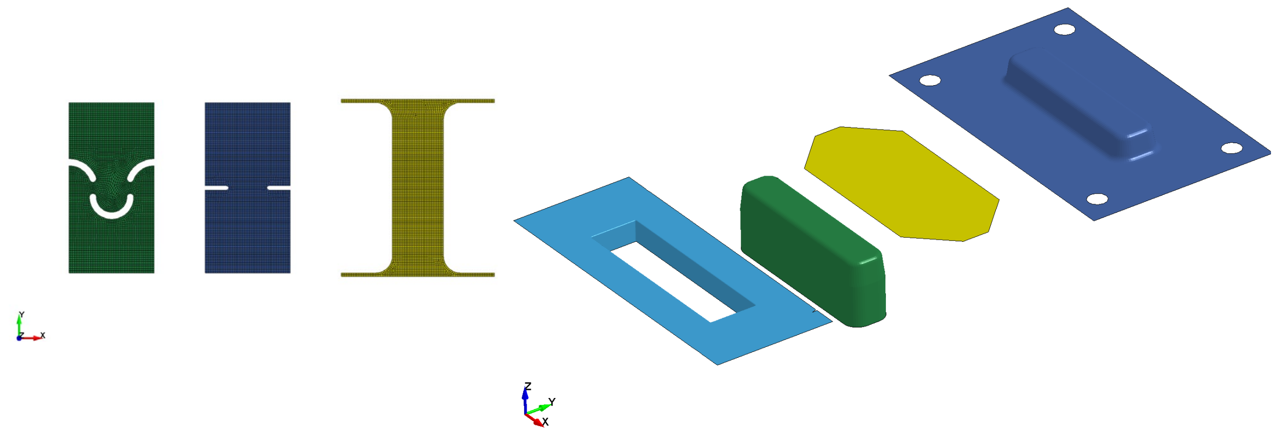

Figure 2: FE-model of tensile specimens (left) and model of deep-drawing trials (right).

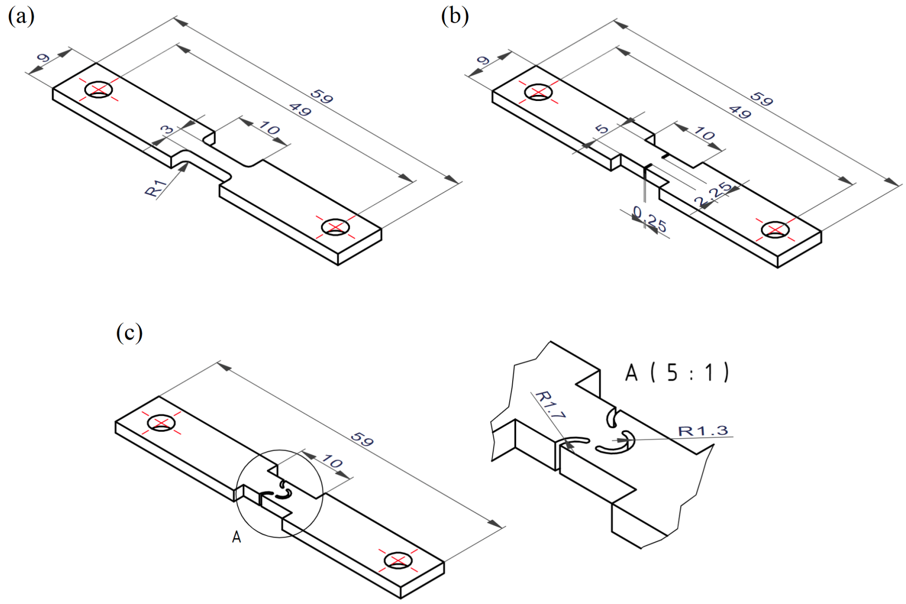

Figure 3: Miniaturized tensile specimens for use in the deformation dilatometer: (a) smooth, (b) notched, (c) smiley shear.

Figure 4: Quenching and deformation dilatometer Bähr DIL 805 A/D at LKR.

Results and Discussion

Examples of experimental warm tensile test results and their FE simulations for Alclad 7075 are given in Figure 5. Overall, good agreement was achieved. Sometimes, one of the ligaments of the smiley shear specimen cracks first. In other cases, both ligaments fail virtually simultaneously. Interestingly, this two-stage cracking behavior was also observed in FE simulation. While non-simultaneous cracking is not desired, the smiley shear specimen geometry has the advantage of higher resilience against handling prior to testing. We also experimented with “classical” single-ligament shear specimens but those tend to be damaged during handling due to their instability and fail very early during testing. For the calibration of GISSMO, the failure of the first ligament was taken as failure criterion. In the simulation of the notched tensile specimen, progressive failure of elements can be observed.

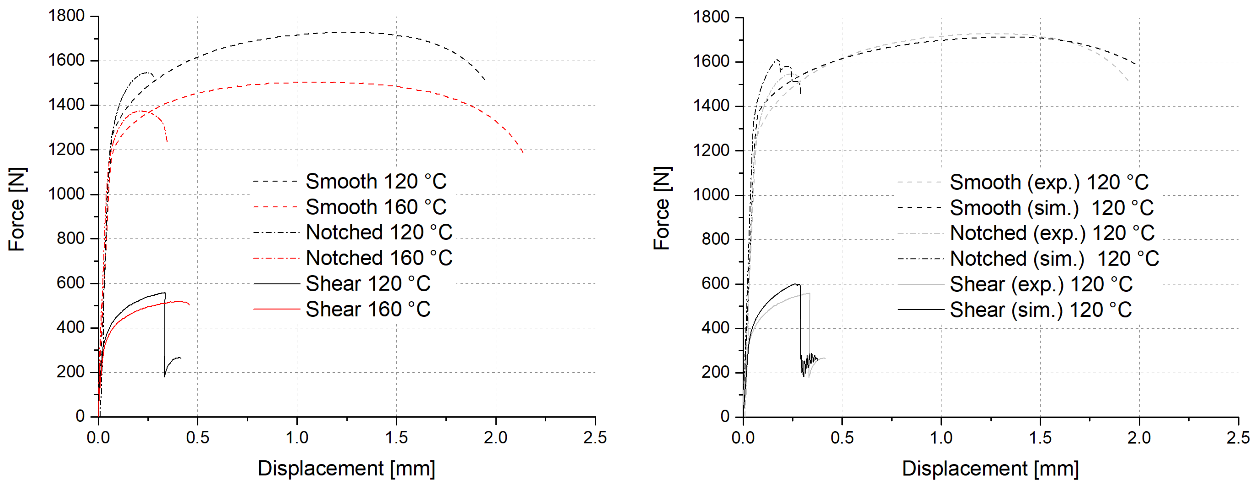

Figure 5: Experimental tensile test results for Alclad 7075 (left) and simulated results for 120 °C (right – experimental results given again for comparison, gray lines).

In Figure 6, the FE results for Alclad 7075 and 7021+ are given. As observed also in experiments, cracking occurs on the radii of the short side for certain deep-drawing temperatures. A summary of experimental and simulation results is given in Table 1. Deep-drawing at RT was not possible for either of the alloys and deep-drawing at 120 °C without cracking was only feasible for 7021+. Both alloys could be deep-drawn at 160 °C. The agreement between experiments and simulation was very good for the conditions studied, although the numerical results only show minimal cracks for 7021+ at RT.

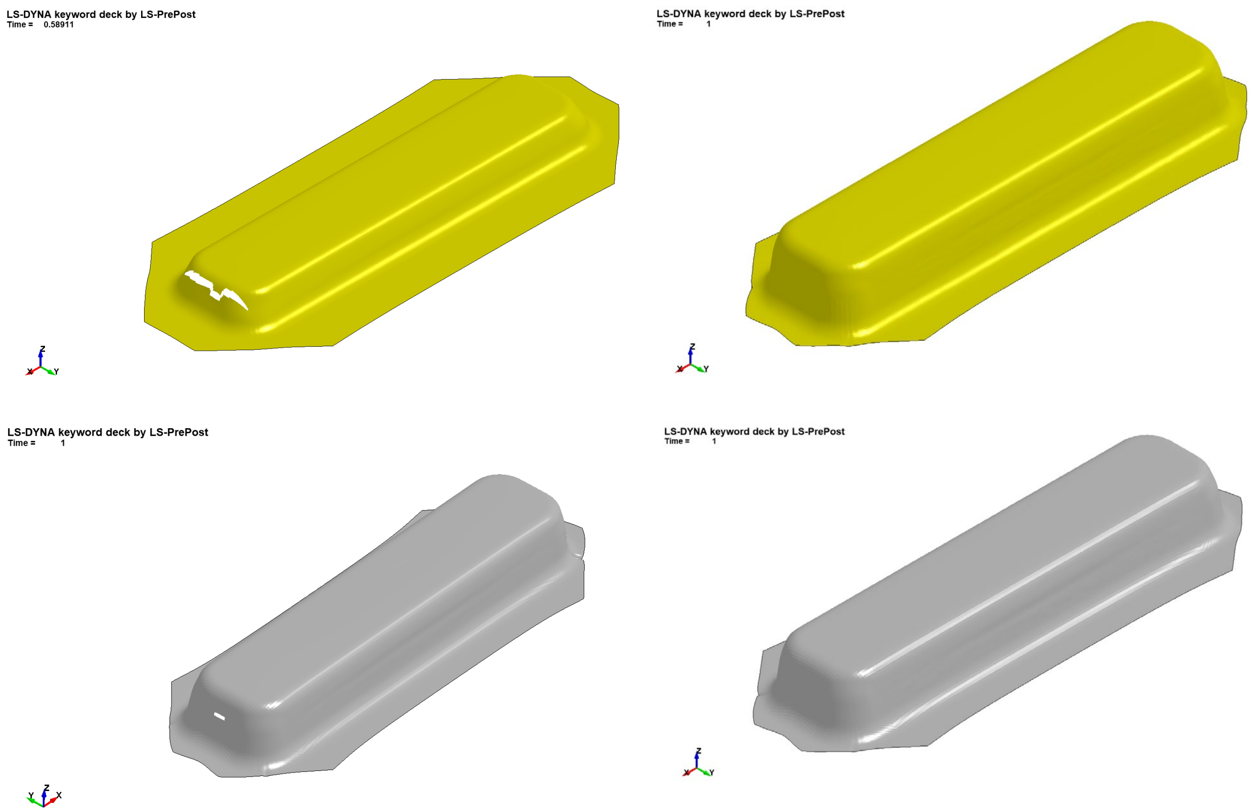

Figure 6: FE results. Top (yellow): Alclad 7075 at 120 °C (left) and at 160 °C (right); bottom (gray): 7021+ at RT (left) and 120 °C (right).

Table 1: Overview of simulated and experimental deep-drawing results. Legend: OK – successful; X – not successful due to cracking; n. t. – not tested.

	7021+		**Alclad 7075**	
	Simulation	Experiment	Simulation	Experiment
RT	X	X	n. t.	X
120 °C	OK	OK	X	X
160 °C	n. t.	OK	OK	OK

As reported in [1], the experimentally produced parts were subjected to a simulated paint-bake heat treatment or the longer “short-T6” treatment and compared to T6. Alclad 7075 achieved 98 and 99 % of T6 yield strength (456 MPa) for paint-bake and the short-T6 treatment, respectively. 7021+ achieved 92 and 95 % of T6 yield strength (442 MPa) for paint-bake and short-T6, respectively. It was found by transmission electron microscopy that paint-bake results in a coarser structure of hardening Mg-Zn-precipitates than the short-T6 regime, which in turn creates coarser precipitates than a standard T6 treatment [1]. Our results indicate that both alloys are well-suited for the warm-forming process combined with the short-T6 treatment, while Alclad 7075 shows better paint-paint response. Further research could focus on optimizing the pre-ageing conditions for 7021+ to achieve better paint-bake response after warm-forming.

A shortcoming of using miniaturized tensile specimens in a deformation dilatometer is that no tests for a biaxial stress state are possible and thus this point in the failure curve must be extrapolated. However, we believe that the procedure presented here is viable because failure in deep-drawing often occurs in the plane strain condition, which is covered by the notched tensile tests. Nevertheless, further research could focus on adding equi-biaxial tensile experiments with inductive heating and digital image correlation (DIC), as demonstrated by Lin et al. [12], for studying the underaged sheet warm-forming process.

Using miniaturized tensile specimens in the dilatometer allows to mimic thermo-mechanical processes in a wide range of heating and cooling rates, and up to 1,500 °C under protective gas atmosphere. The procedure may be useful also for other processes such as hot stamping/die quenching [13] and other material classes than aluminum alloys, for example high-strength steels [14].

Summary

Warm-forming of under-aged blanks is a promising and economical process route for deep-drawing of 7xxx series aluminum parts. Near-T6 final mechanical properties can be achieved after paint-bake or a “shortened T6” treatment.

For the finite element simulation of such thermo-mechanical process routes, mimicking the actual time-temperature curve of the process also in coupon testing is important, since prolonged holding at elevated temperatures leads to microstructural changes in the material, confounding the mechanical properties. To this end, we employed miniaturized smooth, notched, and smiley shear specimens for testing in a quenching and deformation dilatometer capable of inductive heating.

A GISSMO material card was calibrated and used for simulation of a long cup deep-drawing process at three different temperatures for two 7xxx series alloys. Good agreement with deep-drawing experiments was achieved.

Acknowledgments

Funding: This work received financial support by the Austrian Research Promotion Agency (FFG-No. 872641). We thank our colleague Sheikh Enamul Hoque for suggesting using the smiley shear specimen and fruitful discussion. AMAG rolling GmbH is gratefully acknowledged for providing 7021+ free of charge.

References

[1] J.A. Österreicher, F. Grabner, M.A. Tunes, D.S.R. Coradini, S. Pogatscher, C.M. Schlögl, Two step–ageing of 7xxx series alloys with an intermediate warm-forming step, J. Mater. Res. Technol. 12 (2021) 1508–1515. DOI:10.1016/j.jmrt.2021.03.062

[2] J.A. Österreicher, M.A. Tunes, F. Grabner, A. Arnoldt, T. Kremmer, S. Pogatscher, C.M. Schlögl, Warm-forming of pre-aged Al-Zn-Mg-Cu alloy sheet, Mater. Des. 193 (2020) 108837. DOI:10.1016/j.matdes.2020.108837

[3] J.A. Österreicher, G. Kirov, S.S. Gerstl, E. Mukeli, F. Grabner, M. Kumar, Stabilization of 7xxx aluminium alloys, J. Alloys Compd. 740 (2018) 167–173. DOI:10.1016/j.jallcom.2018.01.003

[4] N.R. Harrison, S.G. Luckey, B. Cappuccilli, G. Kridli, Paint Bake Influence on AA7075 and AA7085, SAE Technical Paper, 2017. DOI:10.4271/2017-01-1265

[5] F. Neukamm, M. Feucht, A. Haufe, K. Roll, On Closing the Constitutive Gap Between Forming and Crash Simulation, in: 10th International LS-DYNA Users Conference, 2008.

[6] Testing under temperature with ZwickRoell's temperature chambers, https://www.zwickroell.com/accessories/temperature-and-climate/temperature-chambers/ (accessed Dec. 07, 2021)

[7] Z. Feng, C. Liu, P. Ma, J. Yang, K. Chen, G. Li, L. Chen, Z. Huang, Initial holding time dependent warm deformation and post-ageing precipitation in an AA7075-T4 aluminum alloy, J. Mater. Proc. Technol. 294 (2021) 117111. DOI:10.1016/j.jmatprotec.2021.117111

[8] C.P. Ferrer, M.G. Koul, B.J. Connolly, A.L. Moran, Improvements in Strength and Stress Corrosion Cracking Properties in Aluminum Alloy 7075 via Low-Temperature Retrogression and Re-Aging Heat Treatments, Corrosion 59 (2003). DOI:10.5006/1.3277583

[9] R. Long, E. Boettcher, D. Crawford, Current and future uses of aluminum in the automotive industry, JOM 69 (2017) 2635–2639. DOI:10.1007/s11837-017-2554-9

[10] K.E. Rader, J.T. Carter, L.G. Hector, E.M. Taleff, Retrogression and Reaging of AA7075 and AA6013 Aluminum Alloys, Metall. Mater. Trans. A 52 (2021) 1006–1018. DOI: 10.1007/s11661-020-06133-0

[11] M.B. Gorji, D. Mohr, Micro-tension and micro-shear experiments to characterize stress-state dependent ductile fracture, Acta Mater. 131 (2017) 65–76. DOI:10.1016/j.actamat.2017.03.034

[12] J. Lin, X. Bao, Y. Hou, J. Min, X. Qu, Z. Tao, J. Chen, Investigation on Yield Behavior of 7075-T6 Aluminum Alloy at Elevated Temperatures, Chin. J. Mech. Eng. 33 (2020) 76. DOI:10.1186/s10033-020-00494-8

[13] N. Wang, A. Ilinich, M. Chen, G. Luckey, G. D'Amours, A comparison study on forming limit prediction methods for hot stamping of 7075 aluminum sheet, Int. J. Mech. Sci. 151 (2019) 444–460. DOI:10.1016/j.ijmecsci.2018.12.002

[14] E. Stockburger, H. Wester, J. Uhe, K. Brunotte, B.-A. Behrens, in: J.P. Wulfsberg, W. Hintze, B.-A. Behrens (Eds.), Production at the Leading Edge of Technology, Springer, Berlin, Heidelberg, 2019, pp. 159–168.