IOP Conf. Series: Materials Science and Engineering **426** (2018) 012032 doi:10.1088/1757-899X/426/1/012032

Numerical modelling of hot forming of high strength Al-alloys

Zs Lukács[1] M Tisza[2]

[1] Associate professor, University of Miskolc, Institute of MS&T, Miskolc-Egyetemváros, Hungary
[2] Head of department, professor, University of Miskolc, Institute of MS&T, Miskolc-Egyetemváros, Hungary

E-mail: lzsolt@kugli.met.uni-miskolc.hu

Abstract. In this paper, we present the possibility of numerical modeling of high strength aluminum alloys gaining an increasing application in the vehicle industry. Our investigations are based on a comparison of real industrial part produced by Hot Forming and Quenching process (HFQ ™) and its numerical modeling results obtained by the AutoForm program. We will also show what material parameters are needed to successful forming of high-strength aluminum alloy grade AA2060.

1. Introduction of HFQ™ process

The automotive industry has been facing more and more challenges over the last few decades due to the tightening of environmental and safety standards. Mass reduction of vehicles may be regarded as one of the many potential research areas to meet these challenges.

The basic challenge for this is to guarantee greater security while reducing the mass. Therefore, nowadays an increasing development of high-strength metallic alloys can be observed. Among metallic alloys, high-strength aluminum alloys may be regarded as one of the best alternatives due to their low density compared to steel as one of the most potential alternatives for weight reduction [1]. However, their wider application has a serious limitation due to their lower formability properties.

It is well-known that the formability of metallic materials can be improved by increasing the deformation temperature; therefore, it is a plausible solution to apply hot forming processes for manufacturing high-strength aluminum alloys. A number of research projects have been based on this principle in the recent years [2]. As a result, the Hot Forming and Quenching (HFQ™) developed jointly by the University of Birmingham and Imperial College London (ICL) and patented by Impression Technologies Ltd. (ITL). Its basic principle is illustrated in Figure 1. The precipitates present in the alloy in disperse distribution will be totally solved by a Solution Heat Treatment (SHT) process forming a homogeneous solid solution and possessing good formability properties. Then, the sheet is formed in a cold die directly after this heat treatment process. The disadvantage of this process and at the same time the main reason is that it has not gain yet wider application in the industry that the aluminum alloy loses its high strength due to the solution heat treatment. Therefore, after the forming an artificial ageing has to be applied, to restore the high strength properties to the pre-heat-treatment condition.

The everyday work of design and process engineers working in the automotive industry nowadays cannot be imagined without the application of up-to-date numerical modeling software focusing on this target area. Therefore, one of the focal points of any technology to be introduced that processes can be examined using this software prior to the physical production of tools. Therefore, we have to examine whether the forming process is suitable for numerical modelling with the required technological accuracy. Therefore, in this paper, we are aiming to demonstrate how accurately the HFQ™ process can be modeled with one of the industry-leading numerical applications (AutoForm R7^{plus}).

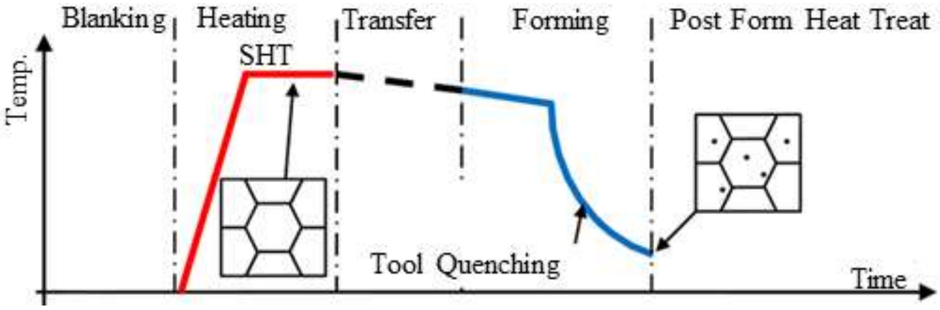

Figure 1. Principal diagram of HFQ™ technology in time vs. temperature coordinates

2. Experimental investigation of an industrial application

For the comparison of experimental investigation and numerical modelling a wing stiffener component will be studied with the geometry shown in Fig. 2 [3]. The raw material of the component is the AA2060 third generation Al-Li alloy not only providing outstanding strength, toughness, rigidity and high temperature performance but also provides superior corrosion resistance and weight saving [4]. The chemical composition of the material is shown in Table 1 [5].

Figure 2. Industrial part: wing stiffener applied for comparison of experimental and numerical modelling results

Table 1. Chemical composition of AA2060 blank

Composition	Li	Mg	Cu	Ag	Mn	Zn	Al
(wt%)	0.6-0.9	0.6-1.1	3.4-3.5	0.05-0.5	0.1-0.5	0.3-05	Bal.

The physical forming process was published in several papers by Gao et al (2015), Mohamed and Szegda (2016), with the exception of the finite element software used for numerical modeling. The basics of these numerical modeling studies, in relation to the material model used, were reported by El Fakir et al (2014) [3], [5], [7].

The numerical modeling of aluminum alloys at high temperatures, which is well-aligned with the experimental results, can be accomplished applying a coupled thermo-mechanical simulation and with a viscoplastic material model [6].

Numerical modeling of the hot forming processes of the 22MnB5 Boron alloyed Manganese steel material (the well-known Press Hardening process) which is widely used in the automotive industry is already available at mass production in industrial circumstances. Therefore, this has provided a good basis for modeling the HFQ™ process that is very similar to the Press Hardening processes, except the technological process parameters. Furthermore, fundamental differences can be observed in the behaviour of the base materials. These differences are strongly connected to the phase transformations in the two types of materials: the phase transformation in the 22MnB5 steel during the forming and quenching cycle provides the high strength properties, while the effects of dissolving dispersed phases

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in the high strength aluminum alloys behaves differently. These different material parameters must be formulated with mathematical relationships in the numerical modelling system.

2.1. Material model for AA2060 in AutoForm
In sheet metal forming, the material models used in finite element software packages should focus on the followings:

- What changes will be caused in the strength properties by the forming?
- What stress state will result in plastic deformation?
- When the limits of the formed material will be reached?

For the first question, the material models should know the strength vs. deformation functions, which are referred to as flow curves. The second question is answered by the yield condition, while the last question is answered by the various forming limit theories.

For high-strength aluminum alloys, the development of material models has been a major field of research for many years besides many other applications in AutoForm. As a result, AutoForm has a material model for hot forming of sheet material AA5457 [8]. Its material parameters can be changed by using the AutoForm Material Generator according to the material properties of the AA2060 considered.

2.1.1. Flow curves
The peculiarity of hot forming processes is that the hardening curve depends on the strain-rate and the forming temperature. In Figure 3.a. the flow curves are shown at T = 350 °C for various strain-rates, while Figure 3.b. shows the flow curves at 1 s^{-1} strain rate for various temperatures. The applied flow curves are based on [3], [5].

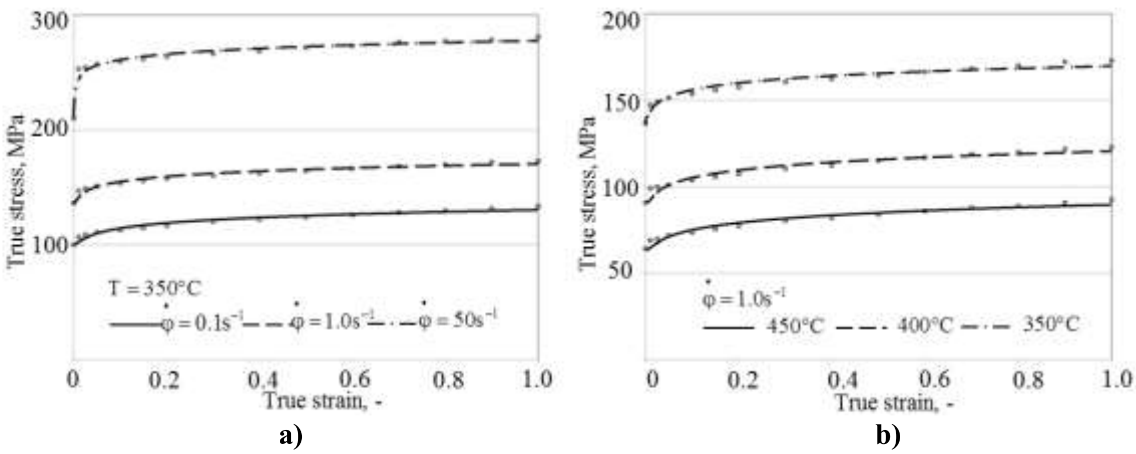

Figure 3. (a) Flow curves of AA2060 at different strain rates at T=350°C
(b) flow curves of AA2060 at different temperatures with $\dot{\varphi} = 1s^{-1}$

2.1.2. Yield surface
For the mathematical description of the Yield surface which will define the occurrence of plastic deformation, we used the Barlat-89 model [9]. The *Barlat-89* model is formulated in stress space. The yield surface is assumed to be a non-quadratic function. The yield surface is defined using three r values $r_{0°}$, $r_{45°}$ and $r_{90°}$ and the *M* value. The Barlat-89 model is especially developed for the description of the yield surfaces for aluminum alloys. The default *M* value of 8 typically gives a good representation of the aluminum behaviour.

The temperature dependence of Yield surface can be taken into consideration by specifying the temperature dependence of anisotropic coefficients. To get these values, the n-r tests must be performed at the given temperatures. In Table 2. the temperature dependence of normal anisotropic coefficients and biaxial anisotropic coefficient are given in the different directions relative to the rolling direction [8]. Using these parameters, the Yield surfaces for each temperature can be determined (Figure *4*.a).

Table 2. Temperature dependence of r-values in different directions

Temperature	r_0	r_{45}	r_{90}	r_b
350°C	0.710	1.080	0.730	0.937
400°C	0.630	0.970	0.660	0.893
450°C	0.630	0.970	0.660	0.893

2.1.3. Process parameters

In the forming process, the tool elements and their position are shown in Figure 4.b. Accordingly, the forming process performed with the following schedule using the markings of the figure:

- First, the *Blank* (1) with the temperature corresponding to the SHT temperature (450 °C) of the material to be formed positioned on the *Bottom die* (4). The *Bottom die* is on room temperature.
- Subsequently, when the Top Blankholder (2) and the Top punch (3) together with the Blankholder (2) are closed on the Bottom die (4), thus the Blank to be formed is strongly hold by the Blankholder (2).
- The so-called *Top punch* (3) forms the characteristic U-shape of the component, while during its movement the forming of the U-shape is done by the *Bottom blankholder* (5).
- At the end of the forming process, the *Bottom punches* (6) will form the square and triangular ribs (shown in Figure 2.) moving into the blank in backward direction.

The further technological settings of the forming process are shown in Table 3.

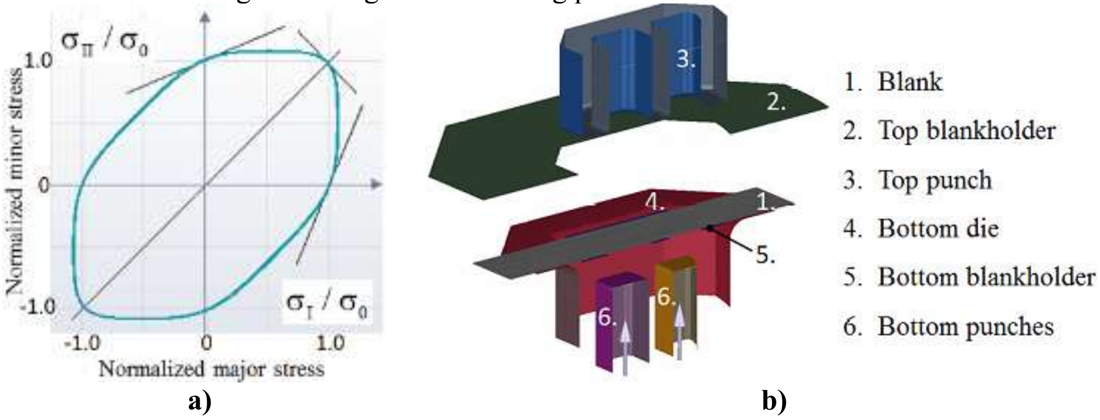

Figure 4. (a) Temperature dependence of yield surface **(b)** Schematic drawing of tool elements

Table 3. Process parameter of forming the wing stiffener component

Process parameter	Value
Initial blank temperature	450°C
Initial tooling temperature	20°C
Forming speed	250 mm/s
Blankholder force	15kN
Gas spring stiffness	1kN/mm
Friction coefficient	0.2

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3. The comparison of the result of the HFQ™ modelling

The results of the numerical modeling were examined by measuring the thickness distribution along defined sections. The reason for this is that a relatively large number of result variables of mathematical modeling, therefore it is advisable to choose such a measurable parameter that can be measured on the physical workpieces. Furthermore, the results of the chosen forming process were compared with the results of the modelling done by the PAM STAMP system and in this case the result variable was also the thinning. Therefore, the results of the AutoForm modeling were compared with this result. On the physical workpiece, the degree of thinning was measured on the basis of distorted grids using optical measuring principle applying the GOM ARGUS system [5].

In Figure 5, the thinning distribution of the workpiece is shown for a relevant section (X-Y) of formed component. It can be seen that both numerical simulation follow the measurement points with an acceptable error relative to the physically measured thinning. It is also common to say that the differences between the results of two software are not significant concerning both their nature and their actual values. The deviations do not exceed the pre-defined range of thinning applying optical measuring principle. Similar statements can be made for the section V-Z shown in Fig. 6.

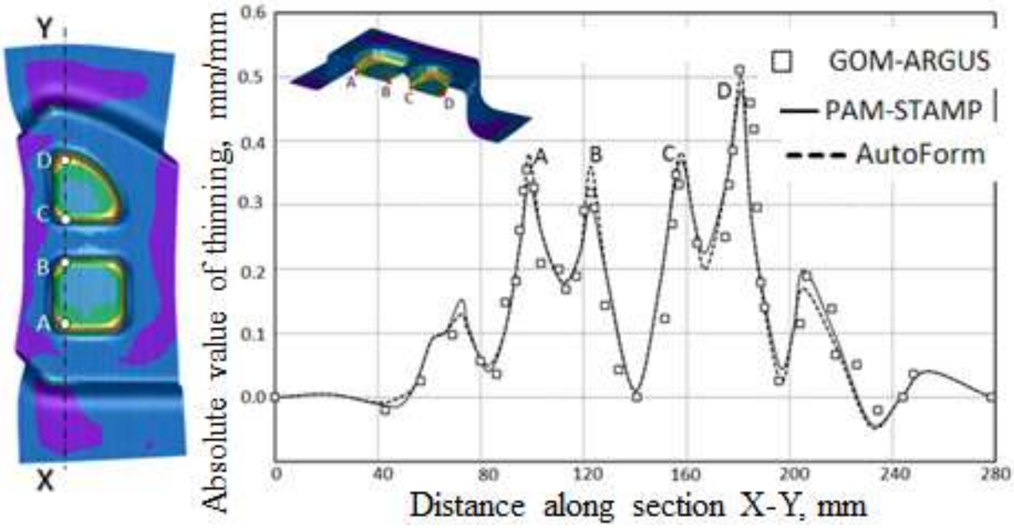

Figure 5. Comparison of thinning distribution through X-Y section

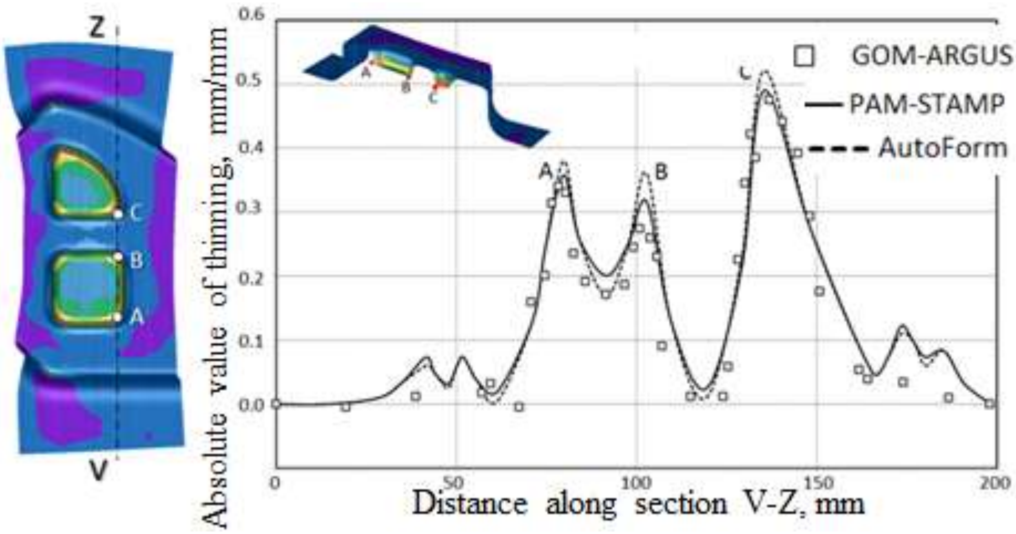

Figure 6. Comparison of thinning distribution through V-Z section

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4. Conclusion

In this paper, we have presented a relevant field of research for the production of sheet metal parts made of high strength aluminum alloy (AA2060) for weight reduction of vehicles (HFQ™). The technological and tool design of automotive sheet parts is nowadays unimaginable without the use of integrated software packages capable of designing the full process cycle.

Therefore, with the help of a market leader software package in this field, we have examined the modeling ability of AutoForm software through a numerical modeling of a specific industrial part and process. As an overall result we can state that the process presented is acceptable for both process and design engineers in terms of the thinning as a parameter essential to the success of forming.

Acknowledgment
The authors express their grateful thanks to the European Commission for their support on the H2020 project „Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles (LoCoMaTech)" , Grant No: H2020-NMBP-GV-2016 (723517)

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