The interaction between short-term heat-treatment and the formability of an Al-Mg-Si alloy regarding deep drawing processes

M Machhammer and C Sommitsch

Institute Tools and Forming, Graz University of Technology, Graz, Austria

E-mail: michael.machhammer@tugraz.at

Abstract. Research conducted in recent years has shown that heat-treatable Al-Mg-Si alloys (6xxx) have great potential concerning the design of lightweight car bodies. Compared to conventional deep drawing steels the field of application is limited by a lower formability. In order to minimize the disadvantage of a lower drawability a short-term heat-treatment (SHT) can be applied before the forming process. The SHT, conducted in selected areas on the initial blank, leads to a local reduction of strength aiming at the decrease of critical stress during the deep drawing process. For the successful procedure of the SHT a solid knowledge about the crucial process parameters such as the design of the SHT layout, the SHT process time and the maximum SHT temperature are urgently required. It also should be noted that the storage time between the SHT and the forming processes affects the mechanical properties of the SHT area. In this paper, the effect of diverse SHT process parameters and various storage time-frames on the major and minor strain situation of a deep drawn part is discussed by the evaluation of the forming limit diagram. For the purpose of achieving short heating times and a homogenous temperature distribution a one side contact heating tool has been used for the heat treatment in this study.

Keywords: Short-term heat treatment, Al-Mg-Si alloy, storage time, contact heating

1. Introduction
The use of aluminum components in car bodies, powertrains, and chassis offer a high potential of weight saving in the automotive sector [1]. Thus, to increase the number of aluminum parts in the field of car body construction, the material’s disadvantage of a degraded formability compared to deep drawing steel qualities must be improved [2]. A promising method for enhancement of the forming behavior of heat-treatable Al-Mg-Si aluminum alloys (6xxx) is the local reduction of strength, in order to reduce stress in the critical zone, when failures occur during forming processes. This can be achieved by a partial short-term heat-treatment (SHT) on the aluminum sheet in a process state before the actual forming process [3, 4]. The improvement of the formability of 6xxx through SHT depends considerably on the design of the SHT layout, the maximum SHT temperature, and the storage time between the heat-treatment and the forming process. The heat-treatment is mostly applied through conduction by contact plates, or through laser technology. One of the advantages using laser heating technology is a high flexibility regarding modifications of the SHT layout during prototyping. When short SHT process cycle times and homogeneous temperature distributions are required, heating via conduction offers improved performances, as compared to laser heating concepts. The present study shows the modifications of the forming limit diagram (FLD) of a deep drawn 6xxx material through the use of different SHT layouts, SHT temperatures and SHT process times. Furthermore, it illustrates the influence of storage time between SHT processing and forming.

2. Material
The result of natural aging after solution heat treatment and the quenching of Al-Mg-Si alloys is Si- and Mg-atoms grouped in clusters and dispersed within the aluminum lattice. These clusters distort the
material lattice and hinder the dislocation motion [5]. SHT leads to a partial or complete dissolution, depending on the maximum SHT temperature of the MgSi-clusters within the material lattice. To be precise, the initiate softening of the material’s yield strength through the dissolution of the clusters starts at an SHT temperature of 200°C (T) and increases to 400°C. The profile of the yield strength regarding the SHT temperature is not decreasing linear. A renewed increase of strength appears at a temperature near to 300°C and ends shortly after 300°C. In addition to the softening of 6xxx, at the same time a reduction of ductility in the SHT temperature range between 200 °C and 350 °C occurs [6]. In this research an Al-Mg-Si aluminum alloy 6016 in T4 temper (Si - 1.13% Mn – 0.15 Fe – 0.28 Zn – 0.02 Mg – 0.48 Ti – 0.01 V – 0.01 Cu – 0.06 Cr – 0.06) was used in the SHT and during the deep drawing process.

3. Experimental Procedure

3.1. Heating strategy

In this experiment/research a contact heating tool (Figure 1) was used to provide near-series conditions during the SHT process. Moreover, the heat sources of the tool are evenly distributed heating cartridges, integrated in a steel plate. In order to obtain partial modifications of the material’s flange area, the design of the heat-treatment layout was adapted to the shape of the heat plate. In addition, heating nearby the critical zone is achieved through steel cylinders equipped with heating cartridges (Figure 1). The heating cylinders are preloaded with compression springs in order to provide enough contact pressure during the heating process. The upper unit of the tool is lifted with a portal crane, and the closing of the tool can be measured with a position sensor. The pressure that was needed to improve the heat transfer between the heat plate and the blank was applied by an additional weight on the upper tool. Moreover, the 6016 material is placed on an insulating multilayer textile (ThermTex 1100SVG) in the shape of the heat-treatment layout to minimize the heat loss on the bottom side of the blank (Figure 2 and 3).

3.2. SHT process settings

To investigate the influence of different SHT temperatures on the forming limit diagram (FLD) of a deep drawn part, the SHT layout 1 shown in figure 4 was used. In this test series maximum temperatures in a temperature range of 200°C to 360°C were conducted during the SHT process. The modification of formability, caused by the design concept of the heat treated area, was evaluated with the SHT layouts presented in figures 4, 5 and 6. Therefore, a maximum SHT temperature of T + 70°C was used for each layout.
In brief, not only the maximum SHT temperature and the design of the SHT layout, but also the time-temperature profile affect the forming behavior. Due to the aim of dissolving the MgSi-clusters, and not enlarging them, the heating and holding time should be as short as possible [7]. In this study an SHT process time of eight seconds was mainly used. The time temperature profiles for each target temperature were evaluated in preliminary tests with blanks which have been equipped with thermocouples (figure 7). To analyze the influence of the heating time on formability, a test series with SHT process times (tx, ty, tz) between 2 and 14 seconds were conducted at the SHT process. In order to achieve fast heating times (tx) of a maximum SHT temperature of T + 70°C, the settings of the SHT process with an SHT temperature of T + 160°C was used (figure 7).

Figure 7. Profiles of the temperature over time measured in the blank for different heating configurations

3.3. Deep drawing
The performed deep drawing processes were conducted with a rectangular shaped tool with different radius combinations and an additional stamping on the bottom side (figure 4). The forming process was controlled with distance plates (thickness = 1.15mm) and a blankholder force of 200 kN. With reference to the coefficient of friction between tool and blank, former investigations have identified that dry lubricants are changing tribological properties by the use of SHT [8]. Thus, the applied dry lubricant, on the material’s surface during manufacturing, was completely removed before SHT processes. Thus, to minimize adhesive wear, galling, and abrasion of the tool, an oil-based lubricant (WISURA ZO 3107/180) was applied on both surfaces of the blank after the SHT process. Considering natural aging of the SHT area, it has to be pointed out, that the forming processes of SHT layouts 1, 2 and 3 were achieved shortly after the heat treatment. In the analyses of how the storage time in process cycle effects the deep drawing process, the forming of SHT layout 2 (figure 5) was performed after additional time frames of 16, 40, 100 and 164 hours. To evaluate the potential of SHT in a manufacturing process, a die with a maximum drawing depth of 115 mm was used. Moreover, to minimize wrinkling the blank outline of the 6016 was optimized and a blank holder force of 420 kN was applied during the deep drawing process.

3.4. Deep drawing Measurement and evaluation of formability
In order to assess the deep drawing results the major and minor strain distribution on each test part was measured with the optical forming analysis ARGUS. Figure 8 shows the measured area in this analysis. Also, to present the improvement and potential of the SHT on deep drawing processes, a
forming limit curve (FLC) of the 6016 material in T4 and SHT (T + 70°C) state was determined through the Nakajima test.

**Figure 8.** Area of measured strain situation

### 4. Results

#### 4.1. Deep drawing of SHT layout 1 – SHT temperatures T+25°C, T+70°C, T+160°C – ty

Figure 9 clearly shows the influence of SHT before the forming process in regard to the material failure. In a manufacturing process, without SHT, the material cracks at a drawing depth of 73 mm. A drawing depth of 85 mm could be produced, without crack deformations, by including SHT in the process chain with temperatures of T + 25°C, T + 70°C, T + 160°C and a SHT process time of ty (figure 9).

**Figure 9.** Deep drawn test part with and without SHT (drawing depth 85mm)

As illustrated in figure 10, the critical zone in the radius area reaches the minimum of resistance to necking at the deformation mode near plane strain tension, by the use of the SHT temperature of T + 25°C. Due to the increase of the SHT temperature from T + 25°C to T + 70°C, the strain distribution in the critical zone was lowered to the FLC’s safety margin of 20 % (figure 11). A further increase of the SHT temperature from T + 70°C to T + 160°C, leads to the highest decrease of major strain in the critical zone (figure 12).

**Figure 10.** SHT temperature T + 25°C

**Figure 11.** SHT temperature T + 70°C
4.2. Deep drawing of SHT layout 1, 2, 3 – SHT temperature T+70°C – ty

Figures 11, 13 and 14 show the modification of the forming limit diagrams caused by SHT layout 1, 2 and 3. The SHT process was performed with an SHT temperature of T + 70°C and an SHT process time of ty. Thereby, deep drawing without material failure was achieved by layout 1 and layout 2.

The forming results when using layout 3 show two parts at a number of three tests with material failure and different oriented crack formations, compared to manufacturing processes without SHT (figure 9 and 15). This outcome can be explained by considering the reaction forces along the load path (figure 8) and consequently the stress situation nearby to the critical zone (figure 9). It is vital to point out that literature argues that a reduced averaged flow stress in flange sections leads to a reduction of the maximum drawing force [9]. Furthermore, the drawing force affects the reaction forces along the load path and therefore the stress within the SHT areas of layout 3. To be more specific, figure 16 shows the measured strain margin \( \Delta \varepsilon \) to the FLC (T4 - state) along the path marked in figure 8. The use of layout 3 shows that the determined strain margin \( \Delta \varepsilon \) is distinctly smaller within the part’s bottom SHT area than when using layout 1 or 2 (figure 16). The smaller \( \Delta \varepsilon \) is related to the reduced flow stress through SHT and a simultaneous larger stress situation due to the untreated flange section. Also, important to mention is that the lower forming limit in SHT state (figure 14 and 16) provides an earlier beginning of necking during deep drawing. Accordingly, the crack formation starts on the part’s bottom SHT area and can be also detected by the beginning of local necking, at the only test part, conducted with layout 3, without material failure. Even though cracks occurred in the SHT area of layout 3, also a reduction of the plane strain in the critical radius could be measured, as shown.
in figure 14 and figure 16. Hence, it can be concluded that the combination of layout 1 (reduction of drawing force) and layout 3 (local reduction of strain through soft zones) provides the most desired result in formability.

4.3. Deep drawing of SHT layout 1 – SHT temperature $T + 70^\circ C$ – $t_x$, $t_y$ and $t_z$

In the following section, the influence of SHT process times on deep drawing processes was analyzed. The material, used in this study was heated up with SHT layout 1, at a temperature of $T + 70^\circ C$ and SHT process times of $t_x$, $t_y$ and $t_z$. The outcome of the measured forming limit diagrams in figure 11, 17 and 18 show a marginal deviation of the strain distribution with regard to the SHT process times. Moreover, figure 19 illustrates the strain margin $\Delta \varepsilon$ to the FLC depending on the particular SHT process time applied.
4.4. Natural aging – SHT layout 2 – SHT temperature T+70°C – storage time 0, 16, 40, 100, 164 hours – ty
To investigate the effect of natural aging on the formability of 6016, the blank was heat treated with layout 2, T + 70°C SHT temperature and ty SHT process time. This is illustrated in figure 20, which shows an increase of 5.5 % plane strain at a storage time of 16 hours compared to a continuous manufacturing process (0 hours storage time, figure 13). Additionally, figure 21 shows a considerable increase of major strain in the FLD when a storage time of 164 hours is applied. The distance between the maximum plane strain and the FLC of the analyzed storage times is presented in figure 22.

![Figure 20. Natural aging 16h](image1)
![Figure 21. Natural aging 164h](image2)
![Figure 22. Distance to FLC](image3)

4.5. Deep drawing 115mm – SHT layout 2 – SHT temperature T+70°C – ty
To achieve the deep drawing depth of 115 mm, the SHT process was conducted with layout 2, the SHT temperature of T+70 °C and the SHT process time of ty. During the manufacturing process without SHT, cracks occurred at a certain drawing depth of 63mm (figure 23). Due to SHT, the target depth of 115 mm was reached without any material failure (figure 23).

![Figure 23. SHT layout 2 and T4 (drawing depth 115mm)](image4)
5. Conclusion
Summing up the results, it can be concluded that:

- Short-term heat-treatment (SHT) with the objective of modifying the formability of heat-treatable Al-Mg-Si aluminum alloys (6016) can be successfully performed through conduction heating.
- Varied SHT process times showed marginal deviations in the forming limit diagram (FLD).
- The SHT process temperature of T + 160°C showed a much greater decrease of plane strain in the critical area compared to an SHT process temperature of T + 70°C.
- The design of the SHT layout plays an essential role in terms of a robust forming process. Therefore, the findings suggest a combination of a reduced drawing force through SHT in flange sections and the reduction of strain in the critical areas due to soft zones.
- The storage time between heat treatment and forming process has a significant impact on the deep drawing result. In fact, storage times higher than 16 hours showed considerable changes in the forming limit diagram.

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