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Investigation of the Possibility for Compensating the HAZ Softening of AA7075-T6

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Abstract
New generations of high strength aluminum alloys are increasingly used in automotive industry. AA7075 is one of the strongest aluminum alloys in industrial use today. The outstanding strength properties open the possibility to use this alloy in automotive industry as a possible alternative material for car body elements instead of steels. Growing industrial demand of aluminum alloys led to the development new technologies, processes. Solution heat treatment, forming, and in-die quenching is one such technology. In our research work the different parts of the heat affected zone of AA7075-T6 high strength aluminum were examined. The thermal cycle of the heat affected zone was tested at four different temperatures (280 °C, 380 °C, 440 °C, 550 °C) with the help of physical simulation. The aim was to define the softening tendency of the heat affected zone after gas tungsten arc welding. Two heat input values 100 J/mm and 200 J/mm were selected in order to simulate a low and a high heat input welding at the given sheet thickness and welding technology by the application of Rykalin 2D model. Then the most critical subzone was selected for the further investigations. Therefore, the 380 °C temperature was examined in case of five more technical processes, which based on the solution heat treatment, forming, and in-die quenching process. The properties of the investigated subzone were examined by optical microscope and hardness test.

Keywords
AA7075-T6, heat affected zone (HAZ), physical simulation, Rykalin 2D model, HFQ process

1 Introduction

The growing demand for more fuel-efficient vehicles to reduce energy consumption and air pollution is a persistent challenge for the automotive industry [1, 2]. Serials of lightweight metallic materials, e.g., the aluminum alloys, advanced high-strength steels, are more popular and attractive to reinforce the component strength and improve the crashworthiness of vehicle body [3]. The characteristic properties of aluminum alloys, high strength stiffness to weight ratio, good formability, good corrosion resistance, and recycling potential make it the ideal candidate to replace heavier materials (steel or copper) in the car to respond to the weight reduction demand within the automotive industry. The most commonly applied types are the 5xxx, 6xxx and 7xxx groups, for example: 5754, 6082 and 7075, respectively [1, 4]. In Fig. 1 [5] the high strength aluminum alloys in Audi A8 car body are shown.

AA7075 ($AlZn_{5.5}MgCu$) is an aluminum alloy with zinc as the primary alloying element (according to EN 485-2:2016 standard) [6]. This is one of the strongest aluminum alloys in industrial use today with tensile strength above 500 MPa. The alloy derives its strength from precipitation of Mg_2Zn and Al_2CuMg phases [7–9]. AA7075 owns more advantages such as lower density, higher strength to weight ratio with natural ageing characteristics, higher fracture toughness and better resistance

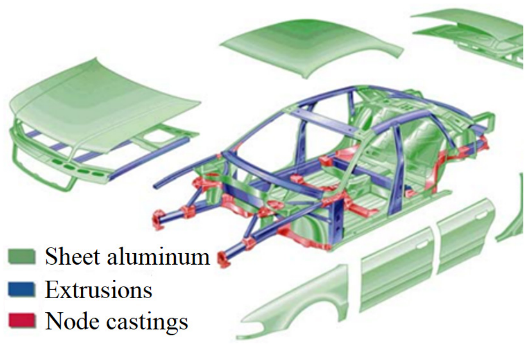

Fig. 1 Aluminum alloys in Audi A8 car body according to [5]

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to stress corrosion. The AA7075 aluminum alloys can be effectively used in lightweight structures; in automotive industry we can meet this alloy in body panels, brake housings, brake pistons, air deflector parts and seat slides [3, 4].

The remarkable positive property of this aluminum alloy is the self-hardening effect thanks to the supersaturated solid solution after air cooling (the solid solution is supersaturated even in slow cooling), then the natural ageing can occur in a couple of months. This characteristic can be advantageous in terms of the production of welded structures, since the acceptably strength can be partially realized without post weld ageing, however this alloy tends to intergranular corrosion [10, 11].

A major problem with this alloy is that it is extremely sensitive to weld solidification cracking as well as heat affected zone (HAZ) liquation cracking due to the presence of copper. Furthermore, oxidation and/or vaporization of zinc present several problems during welding, such as porosity, lack-of-fusion, and hazardous fumes. Therefore, use of alloy AA7075 is currently limited to applications that do not involve welding [8].

2 Solution heat treatment forming and in-die quenching

Since one of the major obstacles to use high strength aluminum sheets in automotive industry is their limited formability; therefore, advanced forming technologies are also being investigated to form complex shaped parts from these alloys [4]. Solution heat treatment, forming, and in-die quenching (HFQ) is one such technology. In this process, the blank is first heated up to its solution heat treatment temperature. At this elevated temperature, the solid solubility is increased and the alloying elements, or precipitates, fully dissolve into the aluminum matrix. Consequently, the yield stress is reduced, and the material becomes more ductile due to the fewer obstacles to dislocation movement, enabling more complex shapes to be formed. The blank is then transferred to a cold die, formed at a high speed, and held in the cold tool to achieve a rapid cooling rate to room temperature. The fast pace of the process allows a supersaturated solid solution to be obtained [12]. After the successful pressing process, the car body elements should be joined to each other. Finally, the assembled car body is generally moved to the paint shop, where the formed and joined aluminum sheets get a heat input according to the heat cycle during the paint bake. This heat input can be partially used for ageing in order to reach the demanded mechanical properties. It means that the aluminum sheets are joined in a solution annealed (softened) and formed condition. Although it might be considered that the sheets are basically joined at the less deformed parts of the car body elements. Since the artificial ageing is partially connected to the painting of the car-body; therefore, the joint connections should be prepared before. It means that joints are heat treated as well, which might influence the mechanical properties of the weld metal and the HAZ. However, the paint bake cycle is not sufficient for the overall ageing due to the relatively short time (180 °C for 30 min); therefore, another ageing cycle can be implemented into the production chain. The whole process can be seen in Fig. 2 [4, 13].

3 Materials, methods, and experimental background

The chemical composition of the investigated alloy in weight percent is summarized in Table 1, and the typical mechanical properties in T6 condition are presented in Table 2.

3.1 The characterization of the softening tendency of the heat affected zone

During our research, the tests were divided into two parts. In the first phase of testing period the different parts of the HAZ of the investigated AA7075-T6 were examined. The thermal cycle of the HAZ was examined at four different peak temperatures (280 °C, 380 °C, 440 °C, 550 °C) with the help of physical simulation. The four different temperatures were defined based on the different phase transformation methods in the material [14].

In this phase of the research work the aim was to define the softening tendency of the HAZ after gas tungsten arc welding. On the investigated high strength aluminum

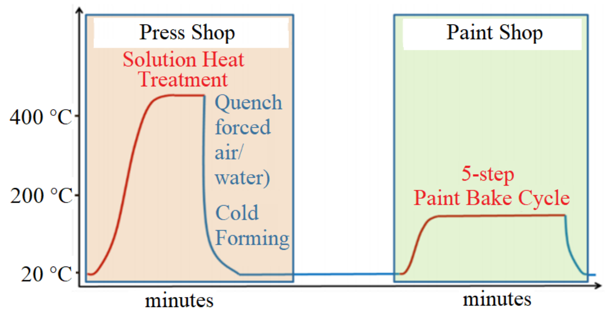

Fig. 2 The whole cycle of HFQ process according to [13]

Table 1 Typical chemical composition of AA7075-T6 (in weight%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.4	0.5	1.2–2	0.3	2.1–2.9	0.18–0.28	5.1–6.1	0.2

Table 2 Typical mechanical properties of AA7075-T6

R_m, MPa	$R_{p0.2}$, MPa	A_5, %	HV
572	513	11	180

alloy, the HAZ simulations were performed with a Gleeble 3500 physical simulator in the Institute of Materials Science and Technology at the University of Miskolc. Physical simulation of materials processing involves the exact reproduction of the thermal and mechanical processes in the laboratory that the material is subjected to in the actual manufacturing or end use. The Gleeble thermomechanical simulator offers considerable flexibility both in thermal cycles and loads that can be applied to a number of different sample geometries. One of the most popular types of welding research conducted on the Gleeble is HAZ simulation. The real parts of the HAZ have small existence, thus their examination is limited. With the help of Gleeble 3500 physical simulator every part of the HAZ can be created to an optimal size for the different material tests. The HAZ simulation with Gleeble can be performed on $F(s,d)$ thermocouple measurement (where s = time, sec.; d = distance from the weld centerline, cm) or heat cycle models including Hannerz, Rykalin 2D, Rykalin 3D, Rosenthal and exponential options [15–18]. During our investigations, heat cycles were determined according to the Rykalin 2D sheet model by considering the 1.5 mm sheet thickness. The thermomechanical properties of the investigated alloy were used for the model. Two heat input values 100 J/mm and 200 J/mm were selected in order to simulate a low and a high heat input welding at the given sheet thickness and welding technology.

At temperatures above 450 °C the melting of the thermocouples can happen, therefore in case of 440 °C and 550 °C examination temperature the thermocouples were protected with cement cover.

In the Fig. 3 the structure of the workspace of Gleeble and the previously described specimen is presented. The physical simulation can provide 5–6 mm wide, homogeneous parts of the HAZ, which width depends on the clearance between the jaws and the test parameters.

The HAZ simulations were performed in 4–4 specimens on every peak temperature. Therefore, hardness tests were performed on 16 specimens after the physical simulations. In the cross section of every sample five hardness indentations were produced whit the help of Mitutoyo micro hardness tester. Vickers harness values (HV0.2) are presented in the Fig. 4 depend on the previously used peak temperatures.

In order to compare the original and the heat-treated material, the hardness tests had to be done also on the base material and according to the EN ISO 15614-2:2005 [19] standard the hardness requirements were calculated. The standard does not include any requirement for the hardness of the welded joints in case of aluminum alloys, but the strength level can be characterized by the hardness, since there is a correlation between the hardness and the tensile strength. The examined aluminum alloy belongs to the 23.2 group according to the MSZ CEN ISO/TR 15608:2021 [20] standard; therefore, the tensile strength of the joint has to reach 75% of the tensile strength of the base material, according to the EN ISO 15614-2:2005 standard [19]. Related from the previous statement, because the hardness of AA7075-T6 is 180 HV0.2, the required hardness is 135 HV0.2.

The results show, that due to the welding heat input the tested aluminum alloy is significantly softened in the HAZ. As the heat input is growing, the hardness of the aluminum is reducing. The rate of softening was the highest in case of 380 °C part of HAZ. Generally, the hardness of the parts of HAZ are smaller than the required harness according to the standard (besides only one exception).

3.2 Effect of HFQ process on HAZ characteristics

The aim of the second phase of the experiments was to analyze the possible benefits of the HFQ process on the HAZ properties of AA7075-T6 alloy. At the end of the previous measurement period, based on the principle of the weakest chain link the temperature, which usage generated the lowest hardness of specimens, was chosen for the following

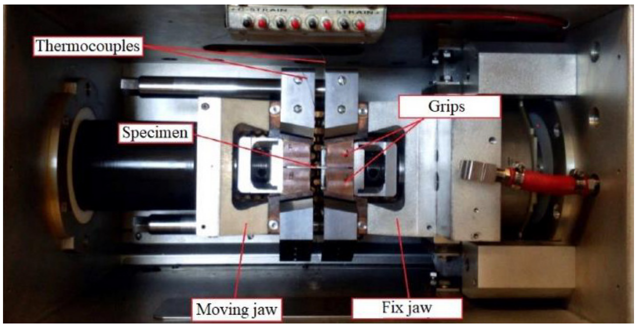

Fig. 3 The structure of the test chamber of Gleeble 3500

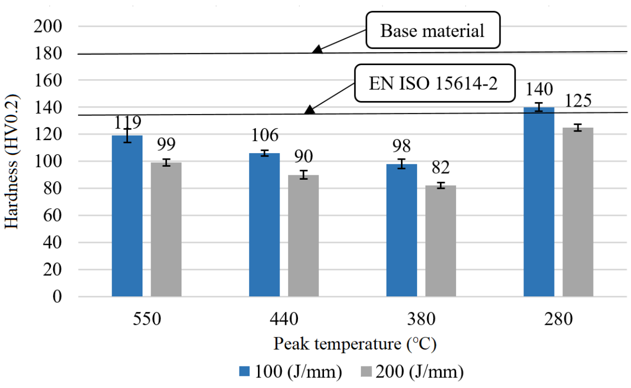

Fig. 4 Average hardness values in HAZ

tests. Therefore, the 380 °C peak temperature was examined in case of five more technical process, which based on the HFQ process. The physical simulations of the five different processes were prepared on 4–4 specimen with two different heat input (100 J/mm and 200 J/mm) and two directions according to the machining direction. It is important to note, that during the experiments just the different heat treatment passes were considered, and the experiments do not involve the examination of the effect of metal forming.

In the first and the second process two possible usage of HFQ processes will be presented. The first process is made up from annealing and a fast cooling, pre-ageing, HAZ heat cycle with 380 °C peak temperature, and post ageing (in connection with paint bake). The examination parameters of the II. and the III. processes are the same as the I. process with the difference, that during the II. process the pre-ageing period is skipped, and the III. process is only made up from HAZ heat cycle and post ageing. The IV. process similarly to the I. process is made up from annealing and a quick cooling, pre-ageing, HAZ heat cycle with 380 °C peak temperature, and post ageing. The examination parameters of the V. process are the same as the IV. process with the difference, that during the V. process the pre-aging period is skipped. The exact parameters of the different heat cycles of the processes are shown in Table 3, respectively.

Table 3 The exact parameters of the different heat cycles of the processes. The unit of heating and cooling speed is °C/min, the unit of the time is min, and the unit of the temperature is °C in every case

Heat treatment			Process				
			I.	II.	III.	IV.	V.
Preheating	heating speed		780	780	-	780	780
	holding	temperature	150	150	-	150	150
		time	5	5	-	5	5
	cooling speed		780	780	-	780	780
Annealing	heating speed		289	289	-	300	300
	holding	temperature	535	535	-	485	485
		time	1	1	-	1	1
	cooling speed		2888	2888	-	3000	3000
Pre-ageing	heating speed		273	-	-	300	-
	holding	temperature	220	-	-	130	-
		time	5	-	-	30	-
	cooling speed		273	-	-	300	-
HAZ cycle maximal temperature			380	380	380	380	380
Post ageing	heating speed		53	53	53	53	53
	holding	temperature	180	180	180	180	180
		time	30	30	30	30	30
	cooling speed		267	267	267	267	267

The temperature-time diagrams of the five different processes are presented in Fig. 5 (a)–(e), respectively. The application of 150 °C preheating was also necessary to fix the cement on the thermocouples.

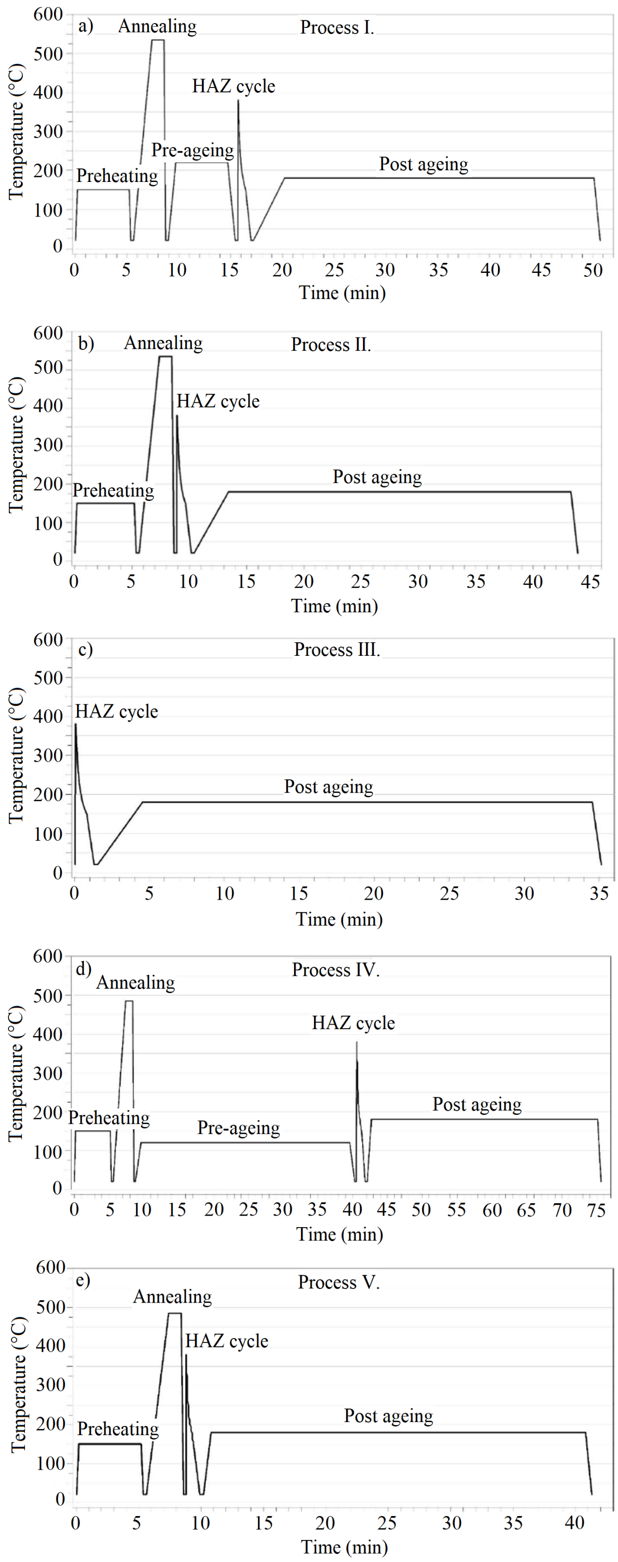

Fig. 5 Temperature-time diagrams for the different processes

3.3 Microstructure and hardness tests

The physical simulations were followed by the optical microscopic tests by a Zeiss Axio Observer D1m. The samples were prepared with Barker-etching (5 g HBF_4 + 200 ml water) which is recommended for aluminum alloys [21]. During this process, an oxide layer forms on the surface with different speed, thus during the examination with polarized light the different orientated grains are seen with different colors through microscope and same orientated grains have the same color.

In the Fig. 6 microscopic images are presented about the grain structure of the investigates subzones. In case of the I. (Fig. 6 (a)) and III. (Fig. 6 (c)) processes the grains have basically elongated structure, while after the II. (Fig. 6 (b)) process the grains were larger and more spherical.

The results of the hardness tests are presented in the Fig. 7. As it was expected the usage of 100 J/mm heat input results higher hardness values, than the usage of 200 J/mm. The diagram shows that all of the investigated processes increase the hardness of the softened base material compare with the results of the simulations with HAZ thermal cycle. On the other hand, these results are still not reached the hardness of the original base material. The most outstanding result was generated by the II. process, thus in case of the examined AA7075-T6 pre-ageing is negligible. Moreover, the hardness results in the first three processes were higher, then in the last two, thus the higher temperature annealing is more favorable.

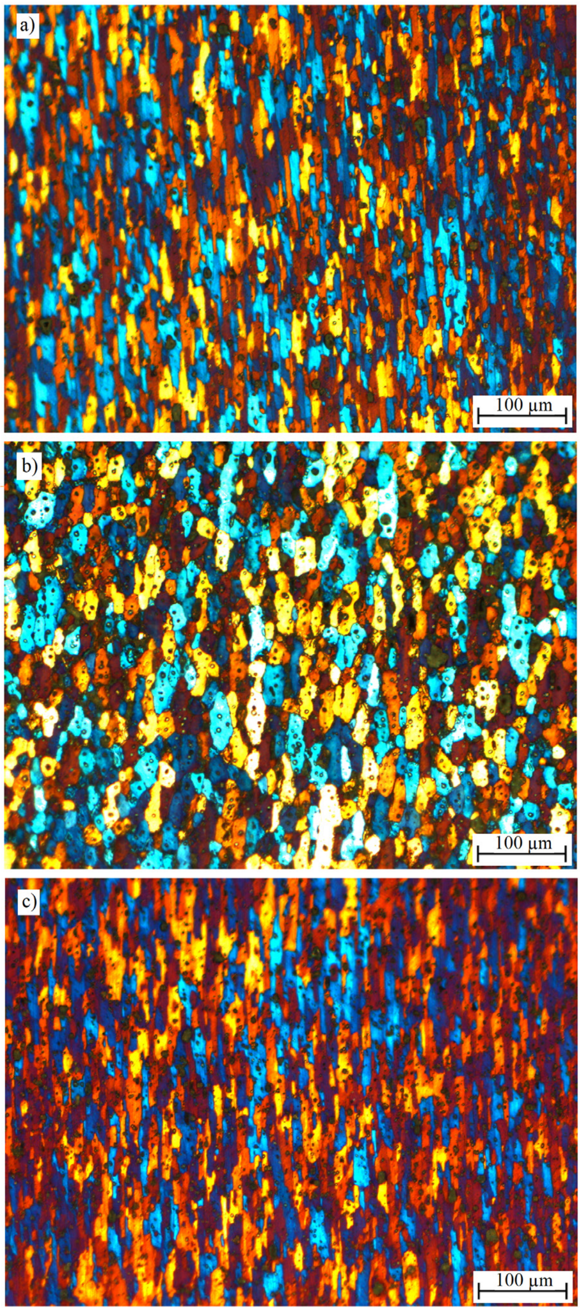

Fig. 6 Optical microscopic pictures in case of I., II. and III. process

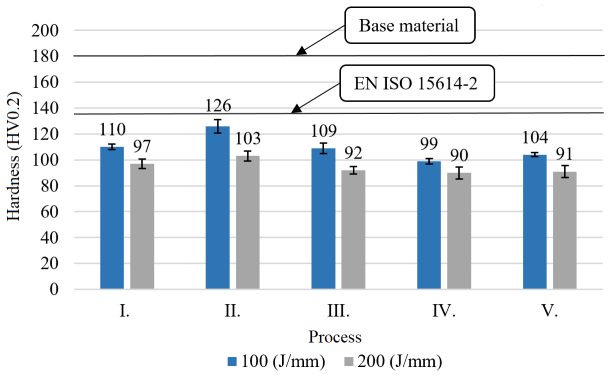

Fig. 7 Hardness of 380 °C subzone in case of different processes

4 Conclusions

The reproduction of different parts of HAZ of AA7075-T6 (in case of gas tungsten arc welding) were successfully performed, using the Rykalin 2D model in the Gleeble 3500 physical simulator. Afterwards, the most critical subzone (380 °C peak temperature) was selected for the further investigations. Five different processes were tested based on the HFQ process. Overall, all five processes have positive effects on the specimens' hardness. The most outstanding of them is the II. process that consists of annealing, HAZ heat cycle and post ageing. Therefore, on the basis of the results, the pre-ageing of the tested alloy type can be omitted as this way it managed to achieve an almost 30% increase regarding its hardness compared to the hardness state after the simulation process consisting solely of welding.

On the basis of the results, it can also be stated that the higher annealing temperature is more favorable in terms of hardness. The article also highlighted that with 100 J/mm heat input generated higher hardness values for each specimen, so it is more appropriate to choose this value compared to the 200 J/mm heat input when selecting the welding parameters. The characteristics of microstructures also confirmed that the mentioned II. method is substantially different from the others, because the otherwise elongated grains took a spherical shape due to the heat treatment applied in this case.

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