

A review of sheet warm forming methods for high-strength 7xxx aluminum alloys

Review Article

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Abstract: The article presents an overview of the warm forming process used to form 7xxx alloy sheets. The literature review covers the characteristics of alloys tested during forming at elevated temperatures: AA7075, AA7020, and a non-commercial alloy with a lower chromium content, higher zirconium content, and higher zinc-to-magnesium ratio than commercial alloys. A diagram of the forming process is presented, taking into account the individual stages and the most important parameters of heat treatment and deformation. An analysis was carried out of the results published to date in the field of basic research, such as tensile tests of alloys in the temperature range of 20–300°C, limiting dome high and limiting drawing ratio tests in the temperature range of 20–260°C, and tests of forming blanks such as a bracket, U-profile, lower part of a B-pillar, and B-pillar. Based on an extensive literature review, it can be concluded that warm stamping with accelerated heating allows for achieving at least 90% of the original strength of the AA7075 alloy. The use of a paint baking process (heat treatment at 180°C for 30 min) after stamping can contribute to a final product strength of up to 85–90% of the strength of the alloy in the T6 state.

Keywords: Aluminum alloys • Aluminum 7xxx • Warm forming • Review

1. Introduction

The increasing popularity of electric vehicles has led to a growing need for solutions that address the issue of limited battery capacity. One way to reduce energy consumption is to minimize vehicle weight by replacing steel body components with lightweight alloys. The “Super Light Car” project was created by a consortium of 38 European organizations and is co-financed by the European Union. In this project, aluminum alloys were selected as they have the greatest potential to replace steel components; using them allows for a weight reduction of up to 50% without compromising the safety of the entire structure. This is due to the high specific strength of aluminum alloys, i.e., the ratio of the alloy’s strength to its density [1].

The aluminum alloys currently used in the automotive industry are the 5xxx and 6xxx series of wrought alloys. The 5xxx series alloys (e.g., AA5182, AA5754) are not heat-

treatable and are typically used for interior panels and structural sheet metal components due to their excellent corrosion resistance and formability. However, they offer relatively low strength (yield strength below 200 MPa), limiting their use in load-bearing or impact-prone areas. In contrast, the 6xxx series alloys (e.g., AA6016, AA6061, AA6082) are currently the most common materials used for body components such as exterior panels, hoods, closures, and subframes. These alloys combine moderate strength (yield strength 200–300 MPa), good corrosion resistance, and excellent weldability. Despite their balanced properties, 6XXX alloys are not suitable for applications requiring both very high strength and increased resistance to stress corrosion cracking – especially in structures or crash reinforcements where low weight must go hand in hand with crash resistance [2].

Among commercially available wrought aluminum alloys, the 7xxx series, whose primary alloying element is zinc, offers the highest strength properties. The favorable mechanical properties of the 7075 alloy (strength up to 600 MPa in the T6 temper and elongation up to 12–14%) allow for better

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energy absorption during side impacts, ensuring high occupant safety. Due to their high specific strength (strength relative to density) and high buckling resistance, the 7xxx series alloys can replace steel in automotive and aircraft structures. Furthermore, this material exhibits high resistance to stress corrosion cracking and high fracture toughness [3,4].

Manufacturing a body entirely made of aluminum alloys would reduce car weight by 70–140 kg, and each 100 kg saved in car weight reduces emissions by approximately 9 g of carbon dioxide per kilometer. The numerous advantages demonstrated by 7xxx alloys led to their widespread introduction in 1950, when they became a frequent subject of research. Initial work on modifying 7xxx alloys was aimed at increasing their strength properties, primarily due to their use in the aviation industry. The main strengthening mechanism of zinc-based aluminum alloys is precipitation hardening, which is caused by the decreasing solid solubility of one or more alloying elements with decreasing temperature [5,6].

The main limitation to the use of high-strength 7xxx alloys is their low deformability at ambient temperature. Therefore, it is necessary to develop an appropriate forming strategy that takes into account structural and mechanical property changes resulting from thermoplastic treatment. Currently, the literature lacks a comprehensive description and summary of the progress made in forming methods for 7xxx alloys, the development of which contributed to their popularization in the automotive industry and military [7]. This article provides a comprehensive review of forming complex components from 7xxx alloys using the warm forming method, taking into account thermoplastic treatment parameters, advantages and disadvantages, and a description of the technological challenges associated with the method. The characteristics of the alloys most commonly used for forming tests are presented. The literature review aims to provide the reader with recommendations for the application of this forming method, present parameters, and outline trends related to aluminum alloy processing.

2. Materials

7xxx series aluminum alloys for plastic forming are alloys in which the main strengthening mechanism is

precipitation strengthening. This mechanism is created as a result of heat treatment consisting of three stages: solution annealing, quenching, and aging. If the treatment is carried out within the permissible ranges of parameters such as temperature, time, and cooling rate, second-phase precipitate particles within aluminum grains will precipitate in the structure, causing lattice distortion and acting as an obstacle to moving dislocations. Dislocations can overcome the obstacle by cutting or bending, and the shear stress required for this causes an increase in strength, the increase of which depends on the size and density of the resulting precipitates [8].

The state in which the heat-treated aluminum alloy exhibits maximum hardness is designated as T6. The most optimal particle size and distribution is achieved through controlled heat treatment called artificial aging, which is carried out at temperatures ranging from approximately 100 to 200°C, depending on the alloy. When particles precipitate spontaneously at ambient temperature, their size and distribution are not as optimal, so hardening does not result in maximum mechanical properties. This process is called natural aging and is designated as T4.

The most popular alloy in the 7xxx series, which has undergone numerous experimental warm stamping tests, is AA7075, currently used for upper wing skins, stringers, and horizontal/vertical stabilizers in the T73 (overaged). The strength of the alloy in T73 is lower than in T6, but corrosion resistance is improved due to increased precipitation (505 MPa in T73 compared to 540–570 in T6). The second most frequently tested alloy is 7020. The chemical composition of the alloys described is shown in Table 1, and the basic mechanical properties in Table 2.

Alloys 7020 and 7075 have similar densities. AA7075 in the T6 condition has one of the highest tensile strengths commercially available, making it highly resistant to mechanical stress. In addition to commercially available materials, researchers are developing their own alloys in order to find a better compromise between strength and corrosion resistance, which would allow for a wider use of high-strength aluminum alloys. For example, Noder et al. [9] tested an experimental alloy with a lower chromium

Alloy	Zn	Mg	Cu	Fe	Cr	Si	Mn	Ti	Zr
7075	5.1–6.1	2.1–2.9	1.2–2	≤0.5	0.18–0.28	≤0.4	≤0.3	≤0.2	0.08–0.25
7020	4–5	1–1.4	≤0.2	≤0.4	0.1–0.35	≤0.35	0.05–0.5	≤0.25	0.12
7xxx_1	7–8	1.2–1.8	1.3–2	0.08	0.04	0.06	0.04	0.06	0.08–0.15

Table 1. Chemical composition of typical aluminum alloys.

Alloy	Density (kg/m ³)	R_m (MPa)	$R_{p0.2}$ (MPa)	A_{50} (%)	Hardness (HV1)
7075 T6	2,810	540–580	460–500	8–12	180–198
7020 T6	2,780	350–380	280–310	8–10	108–115
7xxx_1	2,800	517–525	486	11–16	127–155

Table 2. Mechanical properties of typical aluminum alloys.

content, higher zirconium content, and higher zinc-to-magnesium ratio than the commercial AA7075 (author's designation 7xxx_1 – Table 2) in a warm forming process.

3. Warm forming

3.1 Process diagram and the most important forming parameters

Warm forming of aluminum alloys is a forming method that uses the T6 condition of the material as the starting point. A diagram of the process is shown in Figure 1. The process begins with cutting the appropriate shape out of a sheet (usually using a laser). The blank is then heated in a furnace to a temperature below the solution heat treatment temperature for the time necessary to achieve a uniform temperature distribution throughout the material cross-section. The sheet metal is then transported to the press area and positioned in a tool that is heated to a temperature close to that of the sheet metal. The sheet metal is deformed as the upper tool moves.

The forming process parameters that have the greatest impact on the final properties and quality of the stamping are related to the following stages: heating (temperature, time, velocity), forming (forming velocity, tribological conditions), and cooling rate (Figure 2). As the temperature of the material increases, the yield stress decreases, resulting in an increase in fracture strain of up to 60%. This is related to the phenomenon of thermal activation of linear dislocations and the dissolution of Guinier–Preston (GP) zones, the formation of η' phase precipitates, and the onset of dynamic recovery. In turn, the heating time and

forming time (i.e., the time during which the material is at an elevated temperature) affect the amount of dissolved GP zones. The higher the temperature and the longer the time, the more particles are dissolved, resulting in a decrease in the final strength of the product [10–12]. Therefore, the research area of hot stamping of aluminum alloys includes the optimization of the temperature to which the material is heated so that it exhibits sufficient ductility without losing its strength. Another area is the pursuit of the fastest possible heating of the blank. If the final properties of the product differ significantly from those of the alloy in the T6 state, additional heat treatment – super-saturation and aging – may be necessary.

3.2 Determination of process parameters – sheet metal and tool temperature, time and rate of heating

3.2.1 Isothermal warm tensile tests

In order to determine the optimal parameters for the warm forming process, it is necessary to conduct material tests such as tensile tests at elevated temperatures. Interpretation of stress–strain curves will allow the selection of the appropriate temperature range and heating time to which the sheet should be heated prior to the forming process in order to increase its plasticity. Wang et al. [11] conducted strength tests on the 2 mm-thick 7075 alloy sheet in the temperature range from 20 to 260°C (with increments of 40°C) and a beam velocity of 2 mm/s (strain rate 0.058 s^{-1}). Additionally, for temperatures of 140, 180, and 220°C, the material was stretched at velocities of 0.25 and 0.76 mm/s (0.008 and 0.025 s^{-1}). The curves

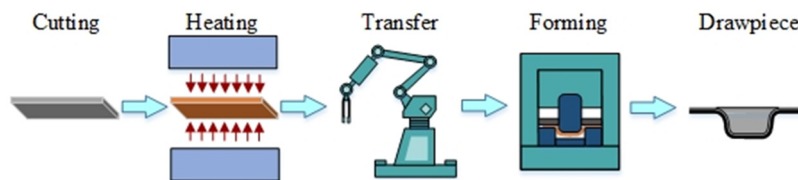


Figure 1. Graphic diagram of the warm forming process (own drawing).

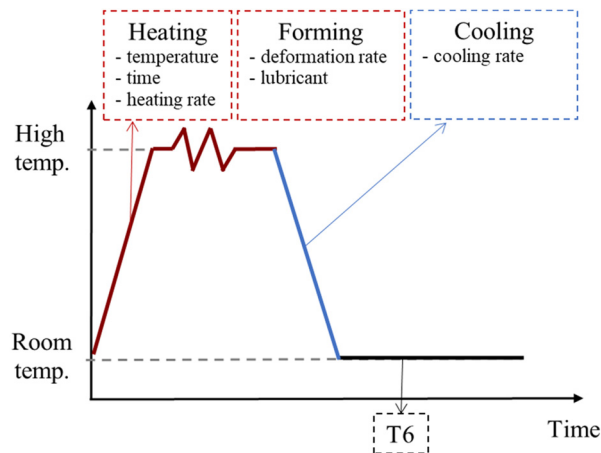


Figure 2. Schematic diagram of the warm forming process in the form of a temperature-time graph (own drawing).

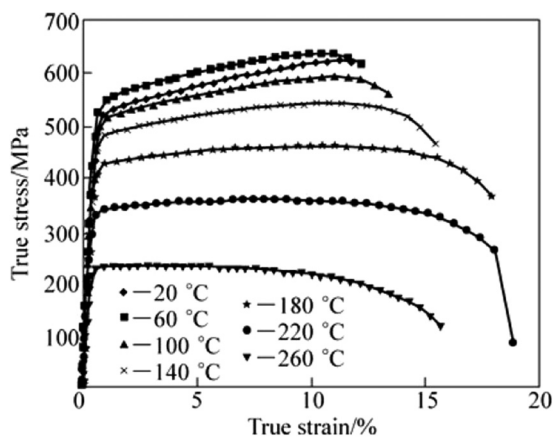


Figure 3. True stress-strain curves of AA7075 at elevated temperatures [11].

obtained by the authors are shown in Figure 3. The tests showed that the true strain and strength of the alloy are at a similar level in the temperature range from 20 to 100°C ($\pm 10\%$). Only exposure of the material to temperatures above 140°C causes a significant decrease in strength (by an average of 15–20%) and an increase in fracture strain (from 6 to 23%). At a temperature of 260°C, there was a sharp decrease in strength (by 38%) and an increase in fracture strain (by 6%), most likely as a result of the dissolution of precipitates and thus the elimination of the T6 hardened state. Moreover, the results indicate that at 220°C, with increasing strain rate, stress increases and total elongation decreases (Figure 4). The strain rate index (m) is 0.02 (for 140°C), 0.04 (for 180°C), and 0.03 (for 220°C).

Huo et al. [13] carried out strength tests of the 7075-T6 alloy in the form of 2.25 mm thick sheet at temperatures of

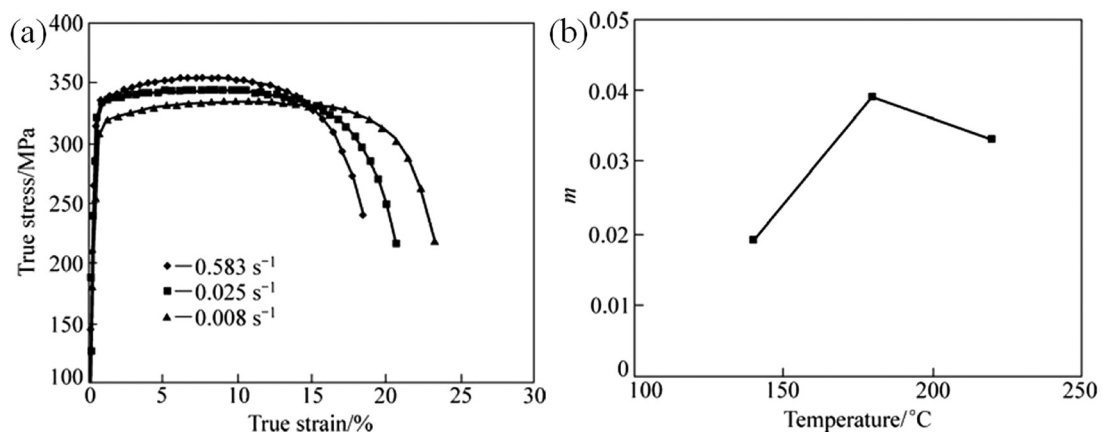


Figure 4. (a) True stress-strain curves of AA7075 at 220°C and (b) strain rate sensitivity parameter (m) [11].

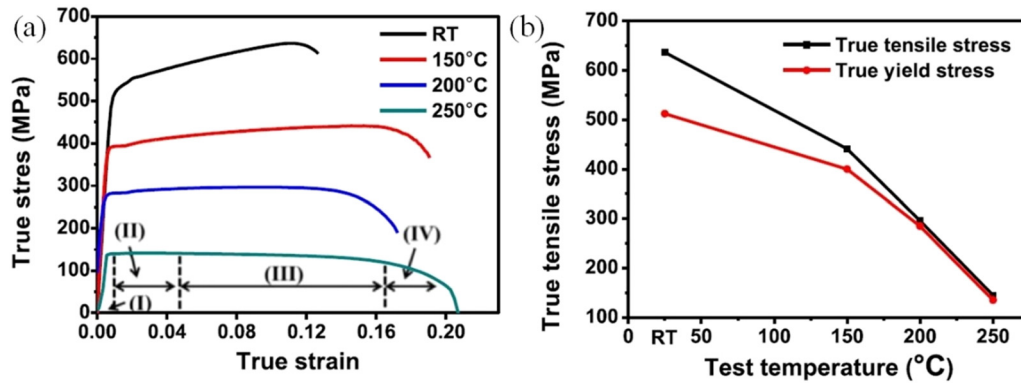


Figure 5. (a) True stress–strain curves and (b) true tensile/yield strength of AA7075 [13].

20, 150, 200, and 250°C. Figure 5 shows the curves obtained by the authors.

Based on the curves obtained by the authors, it was observed that at 250°C, the total elongation increased to 0.24 and was 40% higher than at room temperature. It was also observed that uniform elongation increases at 150°C (relative to room temperature) and then decreases, although the true uniform elongation at 200°C is relatively high and slightly higher than at room temperature.

Polak et al. [14] conducted strength tests and hardness measurements of 7075-T6 alloy in the form of 3 mm thick sheet. The results confirmed that forming the alloy in the temperature range of 200–230°C significantly improves elongation (an increase from 14% in the T6 temper to as much as 24–26%), but the material does not harden – a negative hardening coefficient occurs. This causes a potential problem when forming complex geometries, e.g., for car bodies. The authors also note the important factor of the time of heating the alloy at a given temperature. Heating at 200°C causes a hardness decrease of 5% (at 5 min), 8% (15 min), and 18%

(30 min), while at 250°C the hardness decreases by 18% (at 5 min), 29% (15 min), and 35% (30 min).

Zhang et al. [15] carried out strength tests of AA7075-T6 in the form of 1.6 mm thick sheet on the MMS-200 thermal simulation machine. The sheet was heated to a given temperature (200, 250, 300, 350, and 400°C) at a rate of 10°C/s and held for 3 min, and then stretched at a strain rate of 0.01, 0.1, 1, and 10 s⁻¹.

Based on the results presented in Figure 6, it can be concluded that the strain hardening effect increases with increasing strain rate, and the alloy's ductility increases with decreasing strain rate. Furthermore, the measured alloy elongation at a strain temperature of 200°C reaches 21%, which is the effect of the partial dissolution of precipitates and the dynamic recovery effect. Compared to the results in the literature [13], the stress levels at temperatures of 200 and 250°C are significantly higher – 400 vs 300 MPa at 200°C and 250 vs 150 MPa at 250°C.

Behrens et al. [16] conducted isothermal tensile tests of alloys 7075 and 7022 in the T6 temper at elevated

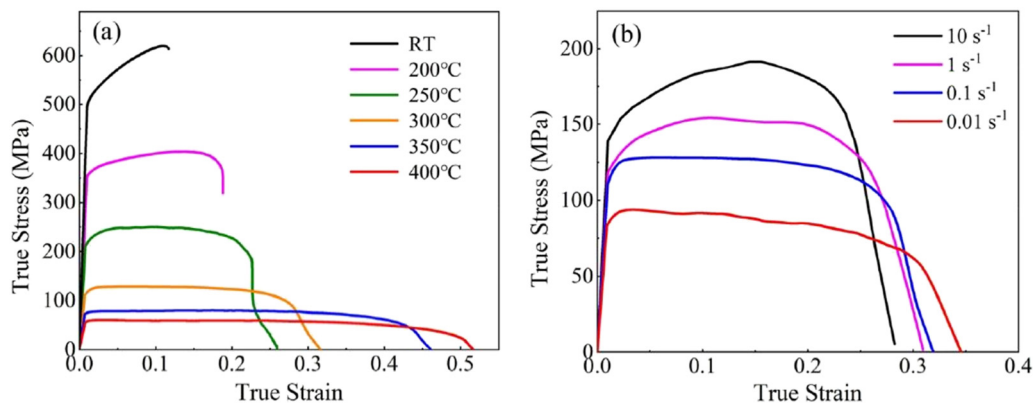


Figure 6. The true stress–strain curves of the AA7075-T6 alloy under (a) different temperatures with a strain rate of 0.1 s⁻¹ and (b) different strain rates with a temperature of 300°C [15].

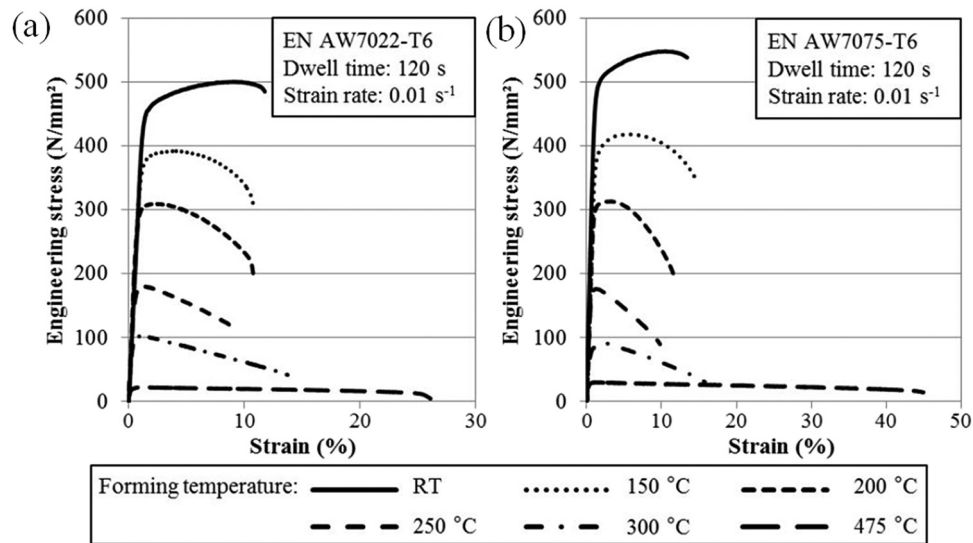


Figure 7. Influence of the forming temperature on the formability in the warm and hot forming of (a) EN AW7022-T6 and (b) EN AW7075-T6 [16].

temperatures within the warm forming range: 150, 200, 250, and 300°C at a strain rate of 0.01 s⁻¹. Based on the obtained results (Figure 7), the authors observed that at 150°C, the EN AW7075-T6 alloy has a higher engineering stress than the EN AW7022-T6 alloy, although this difference decreases with increasing forming temperature.

Until the temperature reaches 300°C, the maximum strain begins to increase for both alloys. The tests were conducted on a small scale (sample gauge width 2 mm), and the graphs show the conventional engineering stress instead of the true stress; therefore, it is difficult to compare them to the tests discussed earlier.

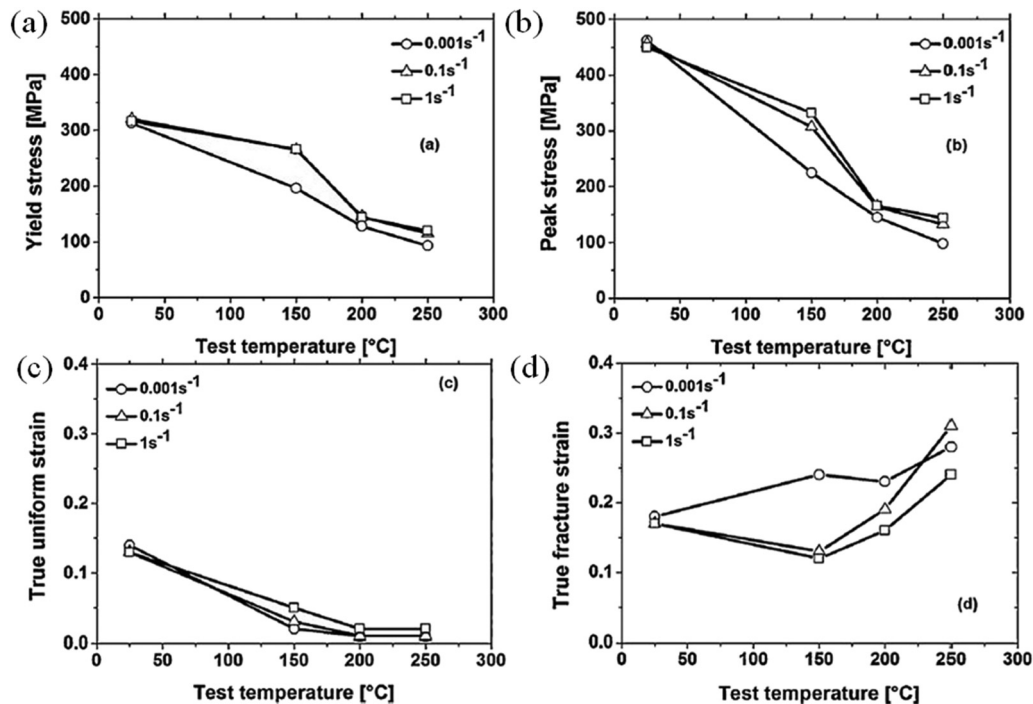


Figure 8. (a) YS, (b) peak stress, (c) true uniform strain, and (d) true fracture strain of AW-7020-T6 [10].

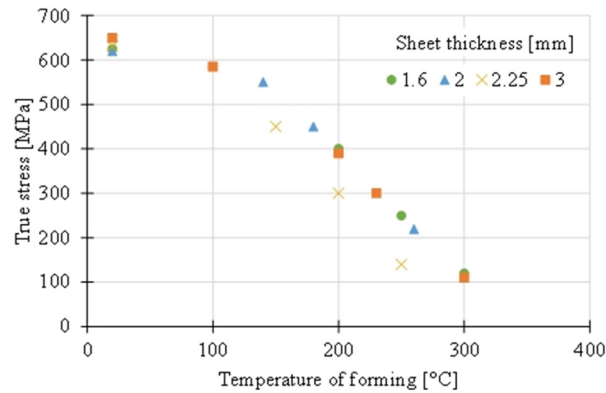


Figure 9. Influence of forming temperature on strength AA7075 T6 taking into account the sheet thickness (own drawing).

Tensile tests at elevated temperature of the AA7020-T6 alloy were carried out by Kumar et al. [10] (sheet thickness 2 mm). Samples with a gauge length of 10 mm were stretched using an A/D Bähr 805 strain dilatometer. The samples were heated for 6 s and annealed for 4 s at a given temperature in the range of 20–250°C, and then deformed at a strain rate of 0.001, 0.1, and 1 s⁻¹.

Based on the stress–strain curves (Figure 8), the authors of the publication determined the relationship between true stress and test temperature and between true strain and test temperature. Based on the determined relationships, the researchers drew the following conclusions: the deformation rate has a negligible effect on the strain hardening rate at ambient temperature, at a strain rate of 0.001 s⁻¹ and a temperature of 150°C, the strain hardening rate and true stress are significantly lower compared to higher strain rates at the same temperature, and as the test temperature increases to 250°C, the strain hardening rate and true stress decrease. Furthermore, increasing the strain rate from 0.001 to 1 s⁻¹ at temperatures of 200 and 250°C results in only a slight increase in

true stress strain. Furthermore, the true stress after initial plasticization reached a steady state, suggesting the presence of a thermally activated softening mechanism at these temperatures, and the shape of the curve indicates that this is dynamic deformation.

Based on the analysis of the stress–strain curves discussed above, it can be concluded that the temperature range of 150–230°C is favorable due to the increase in the formability of the aluminum alloy above 20%. The effect of the forming temperature of AA7075 T6 on the final strength depending on the sheet thickness (1.6 mm [15], 2 mm [11], 2.25 mm [13], 3 mm [17]) is shown in Figure 9. The lower the forming temperature of the material, the smaller the decrease in its original strength. Narrowing the forming temperature to the range of 200–230°C is a compromise between improving plasticity and losing hardness and strength, which should be taken into account when designing hot forming processes for high-strength 7xxx series aluminum alloys. The effect of forming temperature on the strength of AA7020 T6 in the form of a 2 mm thick sheet [10,16] is shown in Figure 10.

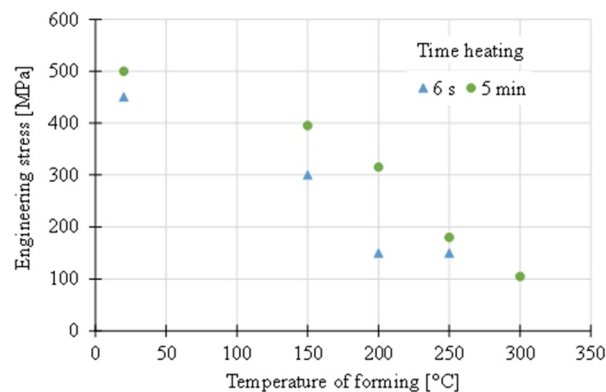


Figure 10. Influence of forming temperature on strength AA7020 T6 taking into account the heating time (own drawing).

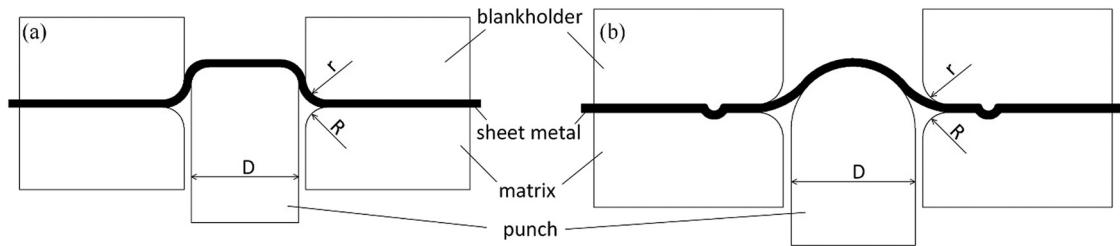


Figure 11. Geometry of shaping tools in tests (a) LDH and (b) LDR (own drawing).

3.2.2 Limiting dome high (LDH) and limiting drawing ratio (LDR) tests

In order to accurately determine the susceptibility of the material to the plastic forming process (stamping), LDH and LDR tests are performed. The cross-section of the forming tools (die, punch, blankholder) is shown in Figure 11. The tests include various deformation modes, such as in-plane stretching (in the cup wall), bending (in the corners of the punch and die), biaxial stretching (in the cup bottom), and pure shearing (in the flange). The LDH test evaluates the ductility of the material by measuring the maximum height that the blank can reach before it cracks. The LDR, on the other hand, is the ratio of the last sample tested before cracking occurs and is defined as the ratio of the initial blank diameter to the punch diameter. In this test, the initial diameter of the blank is systematically increased until cracks appear in the stamped cup.

Wang et al. [11] determined the LDH and LDR for 7075 aluminum alloy in the form of 2 mm-thick sheet metal at

elevated temperatures and under isothermal conditions. The diameter of the punch in both tests was 100 mm. The sheets were heated to temperatures of 140, 160, and 220°C, then transferred to tools heated to the same temperature as the sheet and deformed under isolated conditions. The punch velocity was constant at 5 mm/s. The initial diameter of the blank during the LDR tests was 160 mm, and then, it was increased by 10 mm until it was impossible to produce an embossed part. There is no significant change in the LDH in the range from 20 to 100°C. The dome height increases in the range from 140 to 220°C, and at temperatures above 220°C, the dome height of AA7075 is greater than that of AA5182-O at room temperature (the dashed horizontal line indicates the alloy AA5182-O that has the best workability at ambient temperature). The LDR experimental results (Figure 12) show that at temperatures below 100°C, the formability of AA7075 is poor and 160 mm diameter blanks cannot be formed. Only above 140°C does the LDR increase significantly, reaching a value of 2.0 at 180°C (equivalent to the value of AA5182-O at room

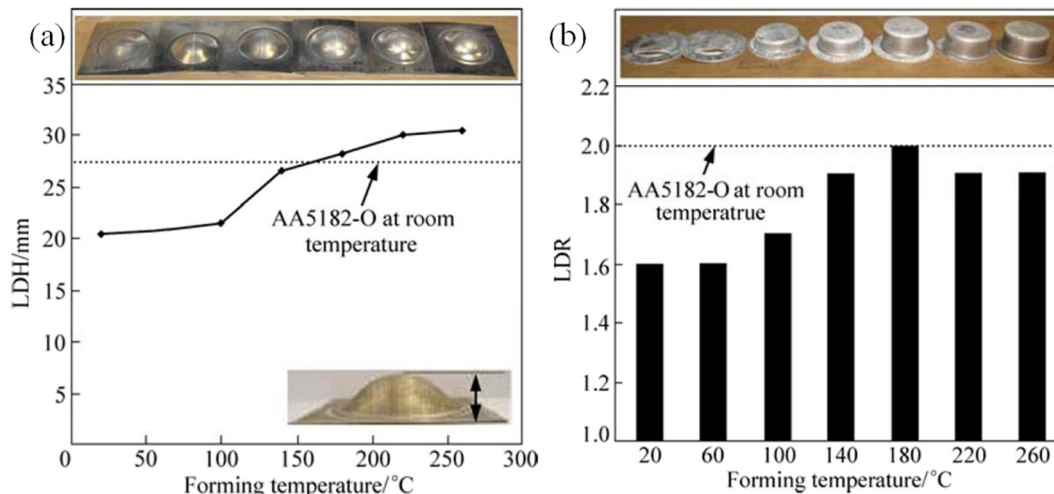


Figure 12. Dependence of (a) LDH and (b) LDR of forming temperature (the dashed horizontal line indicates the alloy AA5182-O that has the best workability at ambient temperature) [11].

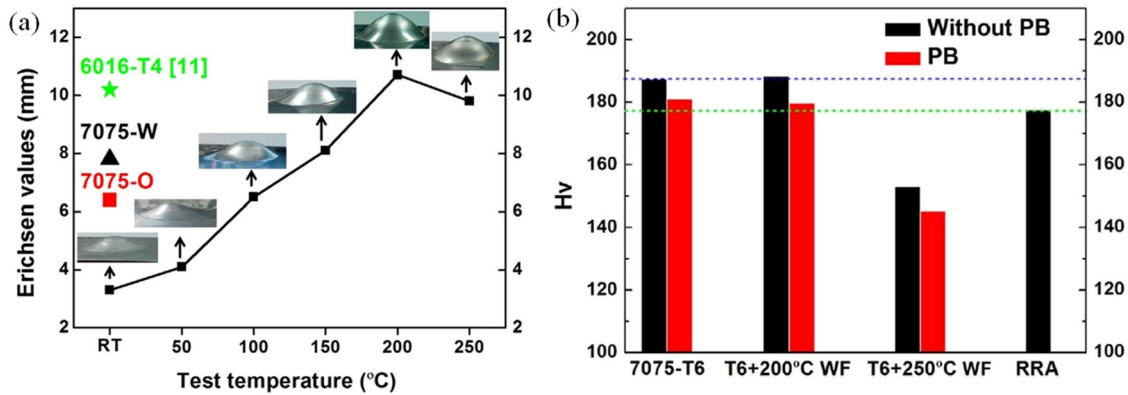


Figure 13. (a) Erichsen values of 7075-T6 as a function of test temperatures and (b) Vickers hardness of 7075 (PB – paint baking) [13].

temperature). At temperatures of 220 and 260°C, the LDR value drops to 1.9, which means that the AA7075 alloy achieves its best deep drawing properties at a temperature of 180°C.

Huo et al. [13] tested the formability of 2.25 mm-thick 7075-T6 alloy sheet on a BCS-50AR universal sheet metal testing machine equipped with a resistance furnace and heated tool set. The input sheet size was 90 mm × 90 mm, and the tools were equipped with a clamp, a die ring, and a punch (punch radius: 10 mm). After heating the sheet to the set temperature (in the range of 20–250°C), it was maintained for 30 min and then deformed at a punch velocity of 5 mm/min. A clamping force of 15 kN was applied. Some samples were subjected to additional heat treatment at 185°C for 20 min to simulate conventional automotive paint baking (T6 + WF + PB) and the retrogression and re-aging (RRA) heat treatment process (T6 + 200°C/10 min + T6).

Based on the graph obtained by the authors (Figure 13a), it was observed that as the test temperature increases, the Erichsen value increases, and thus the deformability. This trend occurs in the temperature range from 20 to 200°C (50°C step). The height of the cup increased from 3.5 mm at ambient temperature to 8 mm (at 150°C) and 10.7 mm (at 200°C), which is more than a two- and threefold increase. Only at 250°C does it decrease to 9.8 mm, which still represents high formability. The authors of the publication also examined the effect of the paint baking (PB) process on the final hardness of the material (HV). For this purpose, the embossed parts (after the warm forming process and in the T6 state as reference samples) were subjected to additional treatment simulating PB (temperature of 185°C, time of 20 min).

Based on hardness measurements, it was observed that the amplitude of the hardness decrease caused by PB is constant and amounts to approximately 7 HV,

regardless of the condition of the material before baking (Figure 13b). Furthermore, the hardness of the sample formed at 200°C after PB is the same as the hardness of the initial 7075-T6 sheet (after PB) and slightly higher than that of the material after RRA treatment. The hardness of the material formed at 250°C is approximately 153 HV and is significantly lower than the others – 187 HV. The final hardness of the extrusions results from structural changes. In the case of 7075-T6, the matrix precipitate (MPt) particles had an average size of approximately 5 nm and were evenly distributed, the average grain boundary precipitate (GBP) size was approximately 20 nm, and the precipitation-free zone (PFZ) width was approximately 25 nm. Warm forming led to thickening of MPt and GBP: approximately 8 and 40 nm (for 200°C) and approximately 55 and 95 nm (for 250°C, which is caused by severe aging). The width of the PFZ zone was approximately 70 and 95 nm, respectively, for T6 + 200°C WF and T6 + 250°C WF. The tests showed that the effect of PB on particle size and PFZ zone was negligible – in the case of 200°C treatment, only GBP was larger by 20 nm, and in the case of 250°C, the differences were max. 10 nm.

Kumar et al. [10] determined the LDR and LDD for the AW-7020-T6 alloy (sheet thickness 2 mm) on a universal sheet metal testing machine Erichsen Model 142-40-Basic in a cross-drawing test. The part formed at room temperature broke after being drawn to about half the drawing depth, while the part formed at 200°C was in good condition. The limit drawing coefficients obtained by the authors are shown in Figure 14 – an increase in the drawing coefficient was observed with an increase in temperature from 170 to 250°C. A similar relationship was obtained for the limit drawing depth (LDD) with increasing temperature in the range from 150 to 200°C. Above 200°C, only a moderate increase in LDD is observed.

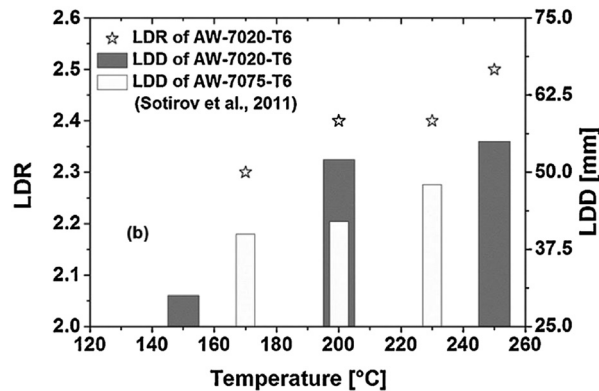


Figure 14. LDR and LDD value at elevated temperature [10].

Compared to AW-7075-T6, the deep drawability of AW-7020-T6 steel is better at elevated temperatures, especially 200°C. The authors also determined the strength of the alloy after deep drawing – at temperatures of 200 and 250°C, there was a 20% decrease in strength compared to the T6 condition. In addition, the strength after the forming and PB process was determined – in this case, there was an 11% decrease (for 200°C) and a 20% decrease (for 250°C) in strength compared to the T6 state.

The authors performed differential scanning calorimetry (DSC) tests on samples pressed at 200 and 250°C. Three main peaks appear on the DSC curve of the tested AW-7020-T6 sheet. Peak 1 (150°C) is an endothermic peak, which refers to the dissolution of GP strengthening zones and η' precipitates, while peak 2 (225°C) is an exothermic peak, which refers to the precipitation of thick η' and η phases. A broad endothermic peak 3 appears at 315°C, which refers to the dissolution of all phases. The height of peak 1 decreases during deep warm stamping, which can be associated with the dissolution of GP zones and η' precipitates. The endothermic peak 1 completely disappears on the DSC curve of the paint sample baked after deep hot stamping. This shows that the η' precipitation thickens and turns into η precipitation. This is clearly visible after the appearance of a broad endothermic peak 3 at 315°C. Compared to heat forming at 200°C, the width and height of endothermic peak 3 decreased and increased, respectively, in the sample baked with paint after deep warm forming at 250°C (more pronounced thickening effect).

Noder et al. [9] studied the tribological conditions during warm deep drawing of an experimental 7xxx series alloy in the T76 condition (author's designation 7xxx_1 – Table 2). The tested material was in the form of a 2 mm thick sheet. The researchers tested four commercially available lubricants: Fuchs FORGE EASE AL 278®

(synthetic lubricant, diluted with alcohol in a 4:1 ratio), OKS 536® (water-based coating, graphite-bonded), PTFE LPS® Dry Film lubricant (liquefied gas supplied in a pressurized container), and Teflon® PTFE coating (dry, synthetic fluorocarbon-based polymer coating with a thickness of 0.1 mm). The tests were carried out using tools as shown in Figure 10a, consisting of a punch with a diameter of 101.9 mm and a rounding radius of 12 mm, a die with an entrance diameter of 110.6 mm (rounding radius equal to 12 mm) and a blankholder. The initial diameter of the sheet metal disc was 203.2 mm, the embossing depth was 55 mm, and the punch velocity was 1 mm/s. The tests were carried out under isothermal conditions at a temperature of 170°C.

The tribological analysis conducted by the researchers included an assessment of the quality of the side surface of the blanks, as it represents the part of the material that slides between the blankholder and the die when the punch pulls the material inward. The cups formed using PTFE spray (Figure 15d) adhered to the die and had to be pulled out with force, while the others could be easily removed from the tool (Figure 15a–c). The side wall of the Teflon®-coated cup had an impeccable surface quality with no visible traces of contact with the tool. Another parameter for assessing the tribological conditions of the stamping process is the force exerted by the punch. The trend was consistent with the previous assessment of the quality of the stampings – for Teflon, Fuchs, and OKS, the maximum force ranged from 180.8 to 187.7 kN (maximum difference of up to 4% – Figure 16). The highest force value was recorded for PTFE lubricant (207.7 kN, which was an increase of more than 13% compared to the other lubricants).

The greater the forming force, the greater the resistance to material movement between the die and the blankholder and the lower the material flow. PTFE recorded

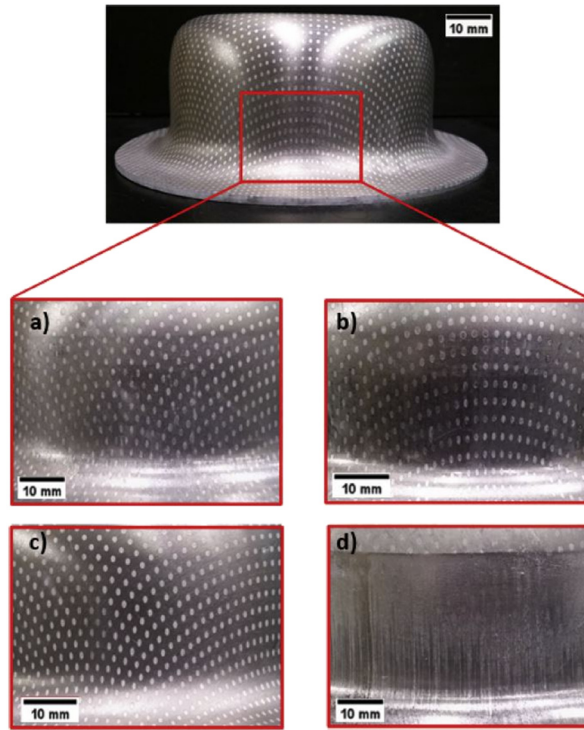


Figure 15. Visual inspection of the part sidewall isothermally formed at 204°C for (a) Fuchs, (b) PTFE Spray, (c) OKS, and (d) at 233°C utilizing the Fuchs lubricant [9].

the highest punch force, which is consistent with the largest circumference of the embossed cup flange (492.4 mm – Figure 17a). In turn, the smallest circumference was observed for Teflon[®] (485.2 mm), which also had the lowest forming force (180.8 kN). The circumference of the other cups (Fuchs and OKS) was slightly larger than that of Teflon (within the standard deviation of ± 2.6 mm).

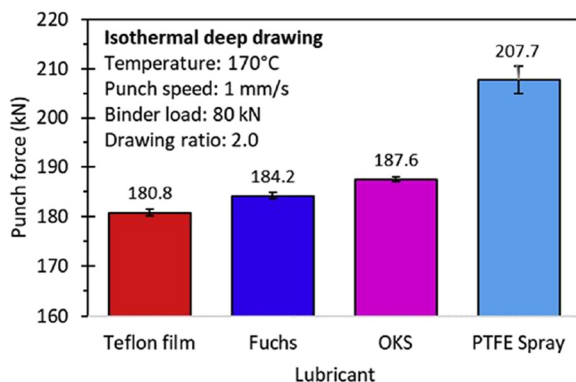


Figure 16. Peak values during isothermal cup drawing at 170°C utilizing different lubricants [9].

The more effective the lubricant, the lower the resistance to material flow and the greater the material pull-in length. The average material pull-in values obtained showed the same trend as the parameter related to the stamp force (Figure 17b). The material was drawn in the most when Teflon[®] was used. The maximum difference of 4.2 mm between PTFE and Teflon shows that the draw length is not as sensitive to the type of lubricant as the circumference or stamp force.

Based on the literature review, it can be concluded that increasing the temperature of the 7075-T6 alloy to 180–200°C during forming allows for a limit die ratio of 2.0 to be achieved. Annealing 7075-T6 sheet at 200°C for only 15 min results in a decrease in tensile strength from 560 to 580 MPa (for the T6 condition) to 345 MPa and hardness to approximately 177 HV0.1, which is over 88% of the T6 condition hardness. Further increasing the temperature of the shaped sheet to 220°C allows for deformation of 0.2. The deformability of the material at this temperature is greater than that of the cold-formed 5182-O alloy, which has excellent plasticity. According to the literature, the most favorable forming temperature for 7xxx alloys is 250°C, as this dissolves the inclusions that are responsible for high strength and low plasticity. The decrease in

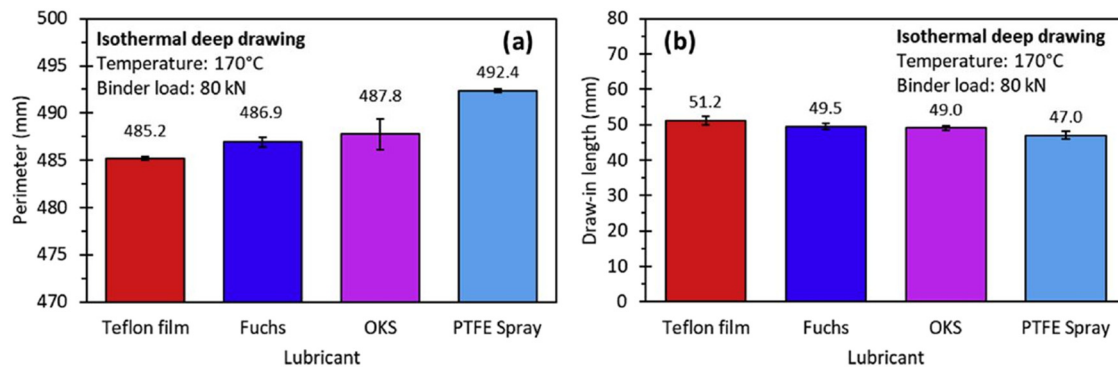


Figure 17. Comparison of perimeter (a) and draw-in length and (b) of cups drawn under isothermal conditions utilizing different lubricants [9].

strength properties caused by even short annealing of the material at 250°C can theoretically be compensated for by combining the artificial aging process with baking the paint on the deformed finished product, which can restore the strength of the alloy to values similar to those in the T6 state. Exceeding the forming temperature limit of 260°C causes a restructuring of the microstructure and dissolution of metastable precipitates, resulting in a deterioration of the deformability and mechanical properties of the material.

3.3 Forming tests

The first tests similar to the warm forming process of alloy 7075 were conducted by Wang et al. [11]. The authors simulated the process of heat treatment without deformation. The test procedure included: heating the material in a furnace to temperatures of 140, 180, 220, 260, 300°C

(heating to the set temperature for 1.2 min, holding at temperature for 300 s), cooling in ice water, heating of sample parts to 177°C for 30 min (simulation of the PB process), and cooling on a 25 mm aluminum plate (simulation of air cooling). After this cycle, the authors measured the hardness using the Rockwell method and performed strength tests in accordance with ASTM E8.

The results obtained by the authors indicate that heat treatment below 180°C does not cause a decrease in the strength or hardness of the material; only above 180°C do both parameters decrease. The effect of PB for heat treatment below 180°C results in an approximately 8% decrease in strength, and in the range from 180 to 260°C, PB mitigates the strength losses resulting from heat treatment. Above 260°C, PB does not cause further degradation of strength. Based on the results obtained, the authors conclude that in order to maintain high strength during hot forming of AA7075 without the need for additional heat treatment, the forming temperature should not exceed 260°C. Structural studies of material exposed to 300°C for 300 s indicate a significant increase in precipitates at grain boundaries, which results in a 44% decrease in yield strength compared to the initial state. In addition, during the re-aging process, the microstructure forms very dense precipitates inside the grains. Material subjected to PB and heat forming at 20–260°C does not significantly change its properties or microstructure during 150–300 s.

The first attempts at warm pressing 7075-T6 aluminum alloy in the process of manufacturing a car body component (bracket – Figure 18) were carried out by Polak et al. [14]. For the forming process, the authors used 3 mm-thick 7075-T6 alloy sheet, which was heated by contact (using forming tools at a temperature of 240°C) for 20 min. The sheet was then shaped at a punch speed of 2 mm/s. The resulting stampings were tested for strength and hardness. The strength of the material after thermoplastic

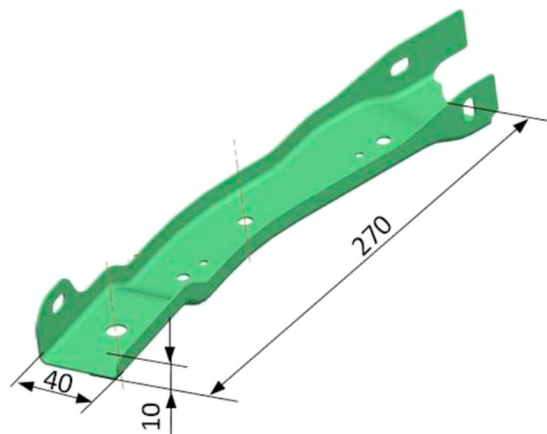


Figure 18. CAD model of car bracket [14].

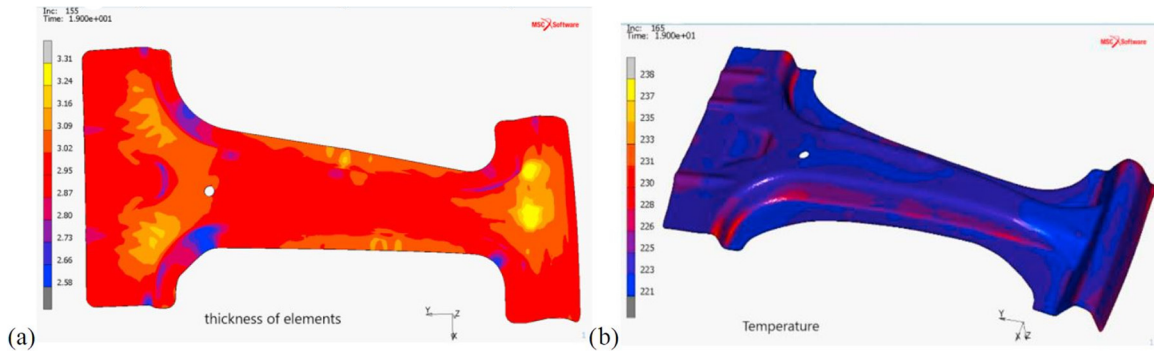


Figure 19. FEM of a formed B-pillar (a) thickness deformation and (b) temperature distribution [18].

processing decreased by about 10% (from 580 MPa in the T6 state to 520 MPa). A similar decrease occurred in the case of hardness – approximately 14% (from 192 HV in the T6 state to 165 HV).

Gronostajski et al. [18] performed numerical simulations of the stamping of a B-pillar made of the 7075-T6 aluminum alloy in a 3 mm-thick sheet metal forming process at a temperature of 230°C. Numerical analysis showed that the greatest deformations and risk of aluminum cracking occur in the corners of the B-pillar foot (Figure 19), which is why the authors conducted the stamping tests on a simplified shape.

The researchers heated the sheet metal in an oven at 260°C for 30 min. The temperature of the tools was 240°C. The resulting stampings had a defect in the form of a crack in the material at the radius. For this reason, the scientists increased the gap between the upper and lower tools in the closed position of the stamping die by placing 0.5 and 1 mm-thick spacers under the lower clamps, which reduced the pressure. However, this method did not eliminate the cracks. Only by raising the tool temperature to 250°C was it possible to stamp the sheet metal without

cracks. Strength tests on samples cut from three locations on the pillar (side, flange, front – Figure 20) showed that due to the high temperature of the tools and the sheet and the annealing time, there was a 20% decrease in the mechanical properties of the 7075 alloy compared to the T6 state (145 HV and 450 MPa after stamping vs. 190 HV and 580 MPa in the T6 state).

In order to reduce the annealing time of the alloy, which has the greatest impact on the loss of final strength of the stamping, the authors used an increased furnace temperature of 350°C. This reduced the time needed to heat the sheet to the required temperature of 240°C to 6.5 min. The change in the sheet heating strategy resulted in an increase in the final strength of the stamping to 531–537 MPa in the face and flange areas and to 500 MPa in the side area (Figure 20), which could have been caused by a local increase in temperature resulting from the friction of the material against the edge of the tool. These values represent 86–92% of the strength of the material in the T6 state. Similarly, in the case of hardness, there was an increase to 176–178 HV in the three areas of the B-pillar considered.

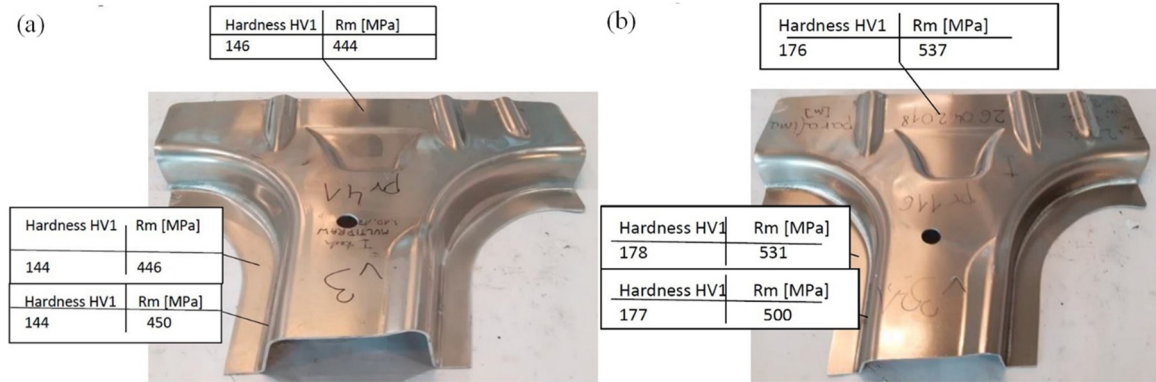


Figure 20. Mechanical properties of the drawpiece manufactured (a) conventionally and (b) by accelerated heating [18].

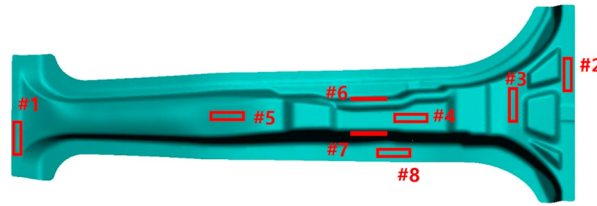


Figure 21. Model of the formed component (B-pillar) [15].

Zhang et al. [15] attempted warm stamping of 7075 alloy in the form of 1.6 mm-thick sheet metal in the process of forming a car B-pillar (Figure 21). For this purpose, a suitably cut sheet was heated to temperatures of 200, 250, 300, 350, and 400°C and held for 5 min. The sheet was then transferred to cold water-cooled tools and formed at a punch velocity of 400 mm/s. Graphite was used as a lubricant. Samples for strength and structural testing were cut from the formed blank.

The three-dimensional shape of the B-pillar without cracks was obtained during forming at temperatures ranging from 200 to 400°C, which indicates that in this range, there is a sufficient improvement in the deformability of the AA7075-T6 alloy to form a complex shape. Figure 22 shows the distribution of mechanical properties. The strength of the component formed at 200°C ranges from 510 to 532 MPa, thus retaining 88–92% of the tensile strength in the T6 condition. As the forming temperature increases, the tensile strength of the formed component decreases from 517 to 391 MPa, and the yield strength decreases from 472 to 207 MPa, but this decrease is not monotonic – the component formed at 300°C has the lowest strength.

The stamping produced at 250°C contains a large number of plate-like precipitates with a size of approximately 10–20 nm, corresponding to a well-developed η' phase, and small amounts of plate-like precipitate with a size of approximately 40 nm, indicating a transformation

of the η' phase into the η phase. The high strength of the sample results from the presence of many dislocations in the microstructure. Due to the short time and low temperature of the heating process, complete dynamic softening did not occur. The sample formed at 300°C exhibits a large number of thick precipitates with a size of approximately 100 nm, corresponding to the η phase. Both plate-like and strip-like precipitates are present in the microstructure of the sample formed at 350°C, with sizes of approximately 10–20 nm to approximately 60 nm, which represents the coexistence of the η' phase and the η phase. In addition, the widths of the PFZs are 44, 124, and 161 nm for samples formed at 250, 300, and 350°C, respectively.

Noder et al. [9] studied the tribological conditions during warm stamping of a U-shaped structural element (with dimensions as shown in Figure 23) made of an experimental 7xxx series alloy in the T76 condition (author's designation 7xxx_1 – Table 2). The tested material was in the form of a 2 mm thick sheet. The researchers tested four commercially available lubricants: Fuchs FORGE EASE AL 278®, OKS 536®, and PTFE LPS® Dry Film Lubricant. The tests were conducted under isothermal conditions at temperatures of 204 and 233°C. The forming tools consisted of a punch with a radius of 5.8 mm, a die with a radius of 7.9 mm, and a blankholder with a radius of 4.8 mm and a clearance of 10%. The die moved at a velocity of 50 mm/s.

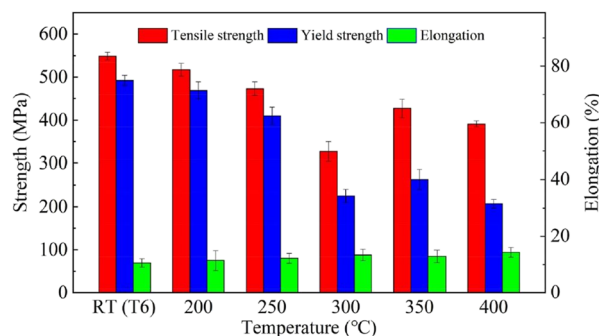


Figure 22. Mechanical properties of warm-stamped components [15].

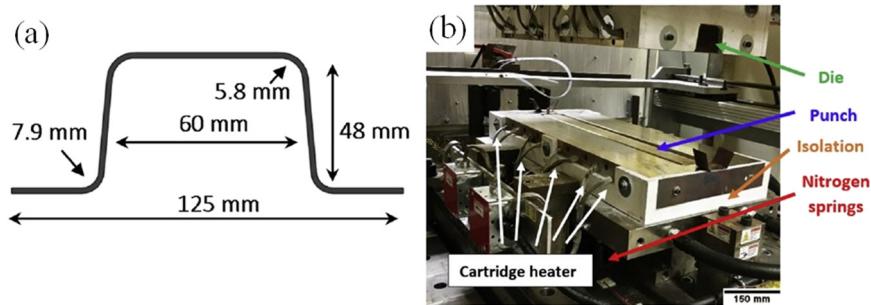


Figure 23. U-profile (a) geometric dimension and (b) forming tools [9].

The force–displacement curve during pressing at a temperature of 204°C obtained by the authors is shown in Figure 24. For the first 10 mm, all three lubricants required similar forces, then higher forces occurred during forming with OKS and PTFE Spray. With a punch stroke of 40 mm, OKS and PTFE Spray required approximately 28.6 and 21.6% higher process forces compared to Fuchs. When pressing with OKS and PTFE Spray, it was necessary to polish and clean the die each time due to the breakdown of the lubricant.

Figure 25 shows pictures of the side walls of the U-profile made using each of the tested lubricants. The stamping formed using Fuchs (Figure 25a) was characterized by good surface quality. However, scuffing was observed in parts formed using both PTFE Spray and OKS (Figure 25b and c). Additionally, a test was performed for Fuchs lubricant at 233°C, and the side wall with occasional scratches is shown in Figure 25d.

The use of Fuchs lubricant both during the pressing of blanks in the LDR test (temp. – Figure 15a) and during the pressing of the U-profile (Figure 25a) allowed for the production of products with high-quality side surfaces

(without scratches visible to the naked eye). Increasing the forming temperature to 233°C during U-profile stamping resulted in a deterioration in surface quality and the appearance of scratches (Figure 25d). The use of OKS during the LDR test allowed for the production of an embossed part without scratches (Figure 15b), while the use of this lubricant during the production of the U-profile resulted in very deep scratches on the side surface of the embossed part (Figure 25c). In the case of PTFE spray, on the other hand, deep scratches appeared on the side surface both during deep cup stamping (Figure 15d) and U-profile stamping (Figure 25b).

Jaśkiewicz et al. [17], Sun et al. [19], and Ma et al. [20] conducted a series of tests on the warm forming of a real object, taking into account various strategies for heating the feed material. Jaśkiewicz et al. [17] pressed a 3 mm thick sheet of 7075 alloy in the process of manufacturing a U-profile (Figure 26a) and the lower part of a B-pillar (Figure 26b). The first material heating strategy involved free heating of the sheet in a chamber furnace heated to 240°C by free convection and thermal radiation. The sheets were heated sequentially to temperatures of 100, 150, 200,

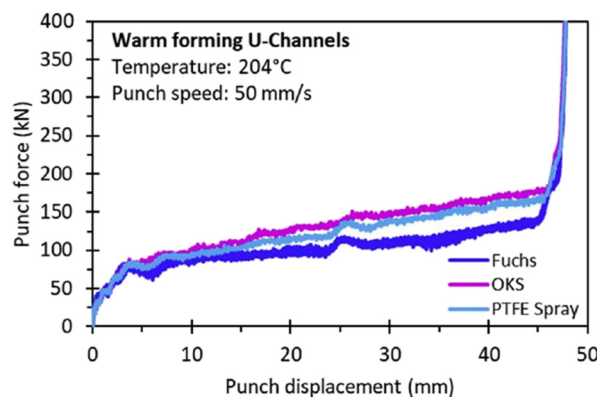


Figure 24. Force evolution as a function of the punch stroke for isothermal warm forming of the structural U-profile at 204°C utilizing different lubricants [9].

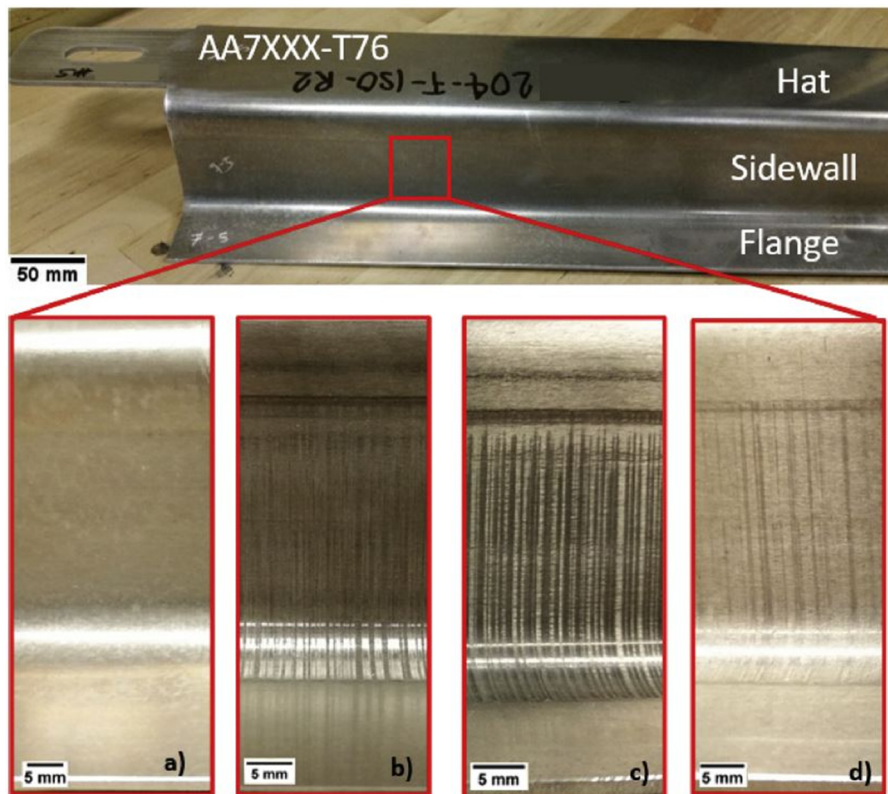


Figure 25. Visual inspection of the part sidewall isothermally formed at 204°C for (a) Fuchs, (b) PTFE Spray, (c) OKS, and (d) at 233°C utilizing the Fuchs lubricant [9].

and 240°C (the time to reach 240°C was 30 min, the sheet heating rate was 0.1°C/s), and then transferred to forming tools heated to 220°C. The sheets were shaped at a punch velocity of 10 mm/s. The second strategy consisted of heating the sheets to the same temperatures, but in a furnace heated to 350°C, which significantly reduced the heating time (to 6.5 min at a sheet heating rate of 0.5°C/s).

The third strategy involved heating the sheets to the set temperatures using steel plates preheated to 350°C. Changing the heating method to conduction allowed for an even greater reduction in heating time (to 2 min, at a heating rate of 1.8°C/s). The literature analysis conducted on strength tests at elevated temperatures (Section 3.1) showed that shortening the heating time of the sheet

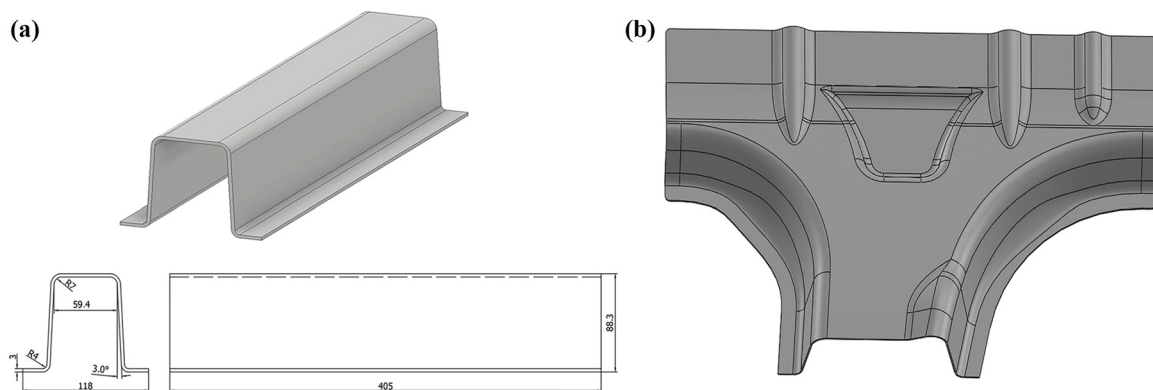


Figure 26. Model of manufactured elements (a) U-shape profile and (b) the B-pillar's foot [17].

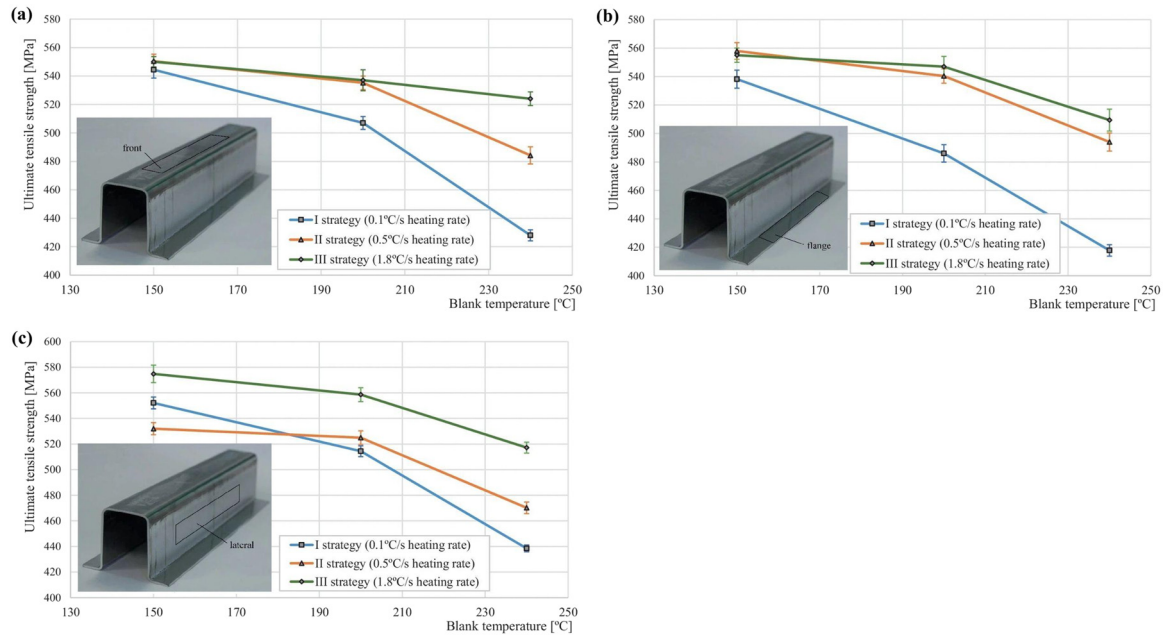


Figure 27. The influence of the heating strategy on the strength of the U-profile (a) front, (b) flange, and (c) lateral [17].

may have a beneficial effect on the final strength properties of the sheet due to the non-dissolution of the alloy strengthening phases.

In the case of the U profile, a strength of over 540 MPa was achieved for all three heating strategies: for heating strategy 1, for an initial sheet temperature of 150°C, and for strategies 2 and 3, and for sheet temperatures of 150 and 200°C (Figure 27). Products manufactured according to strategies 1 and 2 were characterized by excessive springback after stamping, resulting in a deviation in product geometry exceeding the permissible value of ± 1 mm (Figure 28). Only

the third heating strategy allowed for obtaining a product that met both strength and geometric requirements (for an initial semi-finished product temperature of 200°C).

In the case of the lower part of the B-pillar, pressing the blank according to strategy 1 (blank temperature 240°C) did not ensure sufficient strength of the finished product – hardness 140–150 HV1 and tensile strength 450 MPa (Figure 29). Only the use of heating strategy 2 allows for significantly higher strength parameters to be achieved (for sheet metal heated to 240°C, the hardness was 151–158 HV1 and the strength was 470–492 MPa, for

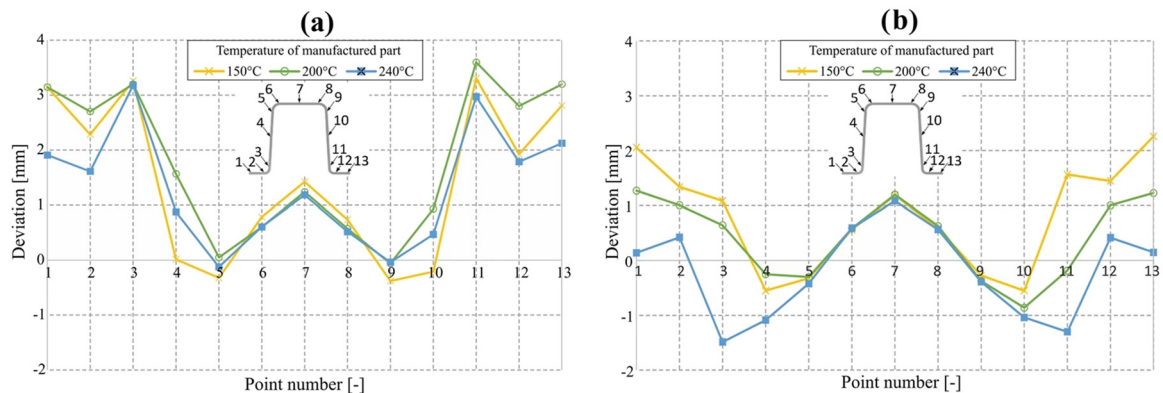


Figure 28. Shape deviations measured in the cross-section of the U-shape (a) second strategy and (b) third strategy [17].

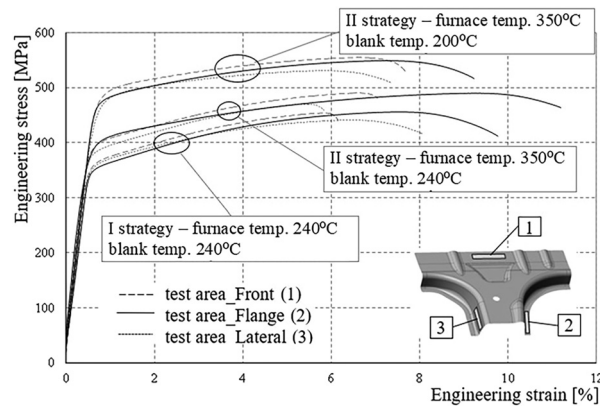


Figure 29. The influence of the heating strategy on the stress–strain curves of different areas of the B-pillar's foot [17].

sheet metal heated to 200°C, the hardness was 170–178 HV1, and the strength was 540–554 MPa).

The deviation in the geometry of the lower part of the B-pillar was a maximum of ± 1.34 mm. This requires further quality and optimization work, including automation of blank transport and minor adjustments to the forming tools. Microscopic observations showed that heating the material to 200°C for 6.5 min using the rapid heating method (second strategy, furnace temperature of 350°C) does not change the grain size of the material. In contrast, electron microscopy showed that neither the number nor the size of the reinforcing particles (MgZn_2 , $\text{Al}_{18}\text{Mg}_3\text{Cr}_2$) change as a result of heat treatment, which ensures the high strength of the 7075 aluminum alloy.

Sun et al. [19] tested 2 mm-thick 7075 aluminum sheet in a warm stamping process using a contact heating (CH) method between plates. After the forming process, the product was subjected to a PB process to simulate the

actual process of applying a protective coating to automotive components. The sheet was heated to 200°C using steel plates with a pressure of 5 MPa, which reduced the heating time from 690 s (convection method, heating rate 0.29°C/s) to 11.5 s (conduction method, heating rate 17.5°C/s). The stamped products were baked at 180°C for 30 min, which is consistent with the industrial PB process.

The change in material hardness depending on the treatment is shown in Figure 30a. The material in the T6 state showed a hardness of 199 HV0.1, which was used as a reference. Warm stamping of the alloy with conventional sheet heating (FH) causes a decrease in hardness to 175 HV0.1 (88% of the T6 value), and with CH to 184 HV0.1 (92.4% of the T6 value). In turn, the PB process caused a further decrease in hardness: to 170 HV0.1 for conventional heating and to 184 HV0.1 for plate heating.

Strength tests showed that the strength of the 7075 alloy in the T6 condition reaches 585 MPa (Figure 30b),

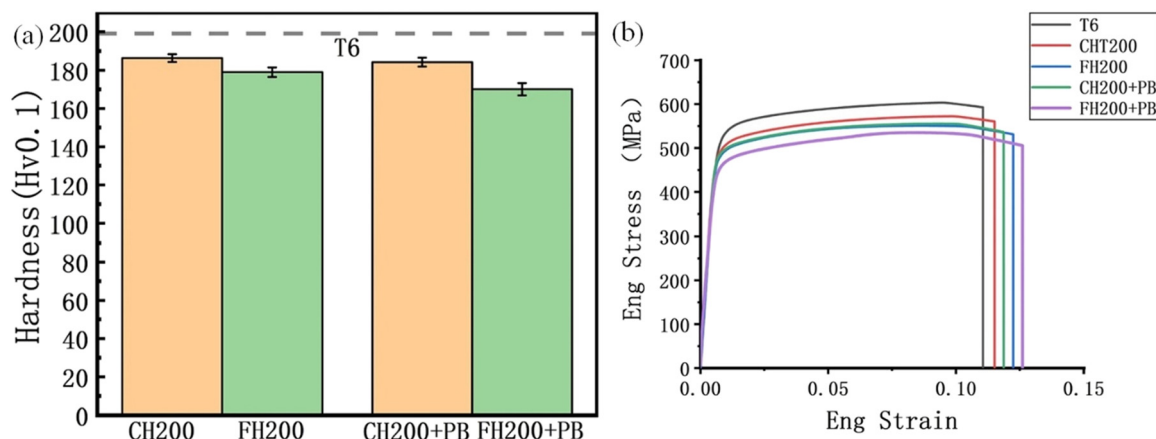


Figure 30. The influence of the sheet metal heating method on (a) hardness and (b) stress–strain curves, FH – conventional sheet heating, CH – contact heating, PB – paint baking [19].

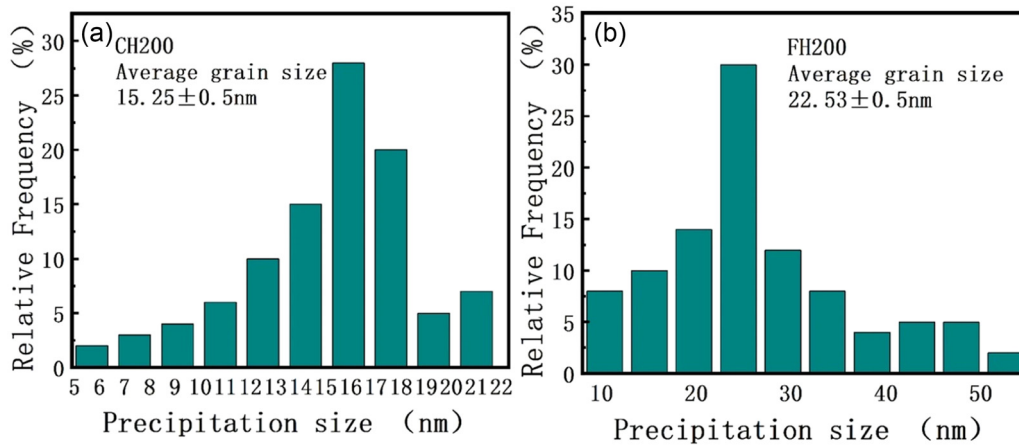


Figure 31. Precipitation size distribution after (a) CH200 and (b) FH200 treatment [19].

while after hot stamping, the strength drops to 545 MPa (93% of the original strength) and to 560 MPa (96% of the original strength). After PB, the tensile strength drops to 510 MPa (conventional heating) and 547 MPa (plate heating), reaching 87 and 94% of the T6 strength, respectively.

Structural TEM studies conducted by the authors showed that CH to 200°C caused a slight increase in matrix precipitates, and finely dispersed precipitates can still be observed in the matrix. The precipitates at the grain boundaries have an increased size of approximately 40 nm (in the T6 state it is 15 nm), and their chain distribution is interrupted, with a distinct PFZ appearing. In the case of conventionally heated samples, the size of the precipitates at the grain boundaries increased to about 70 nm, and their number density decreased significantly. The

segregation enhancement effect of the sample heated between plates was 1.4 times greater than that of the conventionally heated sample, taking into account the average size of the segregations (Figure 31).

The PB process caused an increase in the size of the precipitates in both samples. In the case of heating in plates, the size of most precipitates is less than 20 nm, and only a few coarse particles reach 50 nm (Figure 32a). In the case of conventional heating, the size of the precipitates increases, accompanied by a decrease in the density of the precipitated phase (Figure 32b).

Ma et al. [20] conducted tests on the effect of heating temperature (186–216°C), heating time (10–22 s), and pressure force (10–15 MPa) on the final hardness of the material (after aging) and the springback angle of the U-profile. For forming temperatures above 200°C, all springback

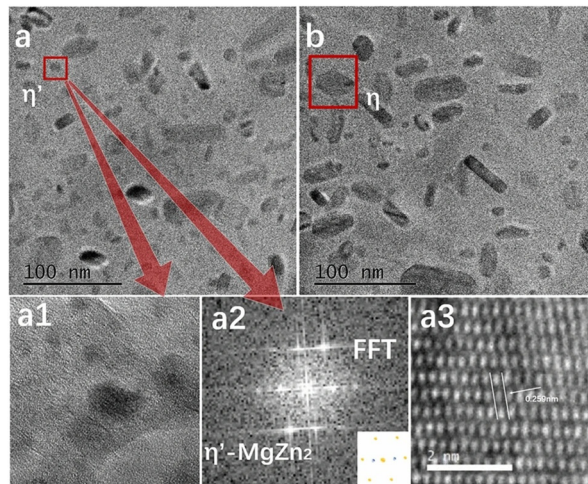


Figure 32. TEM images of samples (a) CH200 + PB and (b) FH200 + PB [19].

angles are less than 0.5°, which meets the quality requirements for drawpieces. Regardless of the forming parameters, the hardness of all parts was higher than 90% of the T6 hardness value. As the forming temperature increased, there was a decrease in hardness due to an increase in the degree of aging.

3.4 Summary

The method of hot forming 7xxx aluminum alloys has been extensively tested both in laboratory conditions (tensile test, LDR and LDH tests) and during the forming of real structural products (U-profile, car bracket, lower part of the B-pillar, and B-pillar). Verification of the method during the production of actual car body components demonstrates its great potential for use in the automotive industry.

A literature review has shown that hot stamping of 7075 and 7020 alloys at temperatures of 150 and 180°C allows the production of complex products free of cracks while retaining up to 90% of the original strength of the material (in the T6 state) – according to Wang et al. [11]. However, the authors did not verify this thesis in a real experiment, but only through simulations of the hot warming process on undeformed sheets.

Due to the significant decrease in alloy strength after heating and deformation, it is necessary to use accelerated methods of heating the initial sheet. Heating the sheet to 200°C using the contact method allows to reduce the time the material spends at high temperature to be reduced several times. Then, most of the η' precipitates responsible for its strengthening are retained. According to Jaskiewicz [17], Gronostajski [18], and Sun [19], warm stamping with accelerated heating (over 2°C/s) allows for obtaining at least 90% of the original strength of the 7075 alloy after stamping. In addition, studies have shown that performing a PB process (heat treatment at 180°C for 30 min) can contribute to the final strength of the product reaching 85–90% of the strength of the alloy in the T6 state. Achieving these parameters allows the final products to be used as car body components [14].

Shaping sheet metal at elevated temperatures is associated with the phenomenon of sheet metal springback. One way to reduce the effect of sheet metal warping by up to 10% is to shape it under strictly isothermal conditions, which is difficult to achieve in industrial conditions [21,22]. The velocity of the punch movement has a significant impact on the amount of springback. The higher the velocity, the more favorable the forming conditions due to

less dynamic recovery, which increases the stability of deformation and springback. In warm forming processes, due to the different temperatures of the tools and the sheet metal being deformed, an important aspect in the analyzed process is the thermal conductivity coefficient and the heat transfer coefficient in the contact between the sheet metal and the tool [17].

When selecting the forming temperature, it should be remembered that as the forming process temperature increases, the sensitivity of the material to the deformation rate increases, and the coefficient of friction between the surface of the formed material and the surface of the forming tools increases. According to Noder et al. [9], the use of Teflon® coating gave the best results – the lowest punch force, the smallest cup circumference, the longest material draw-in length, and perfect surface quality. According to Jaskiewicz et al. [17], paraffin oil is also a good lubricant.

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Conflict of interest statement

Author states no conflict of interest.

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