Evaluation of hot and warm forming of age-hardenable aluminium alloys into manufacturing of automotive safety critical parts

MYROLD Benedikte[1,a *], JENSRUD Ola[1,b] and HOLMESTAD Jon[1,c]

[1]SINTEF Manufacturing, Box 163, 2831 Raufoss, Norway

[a]benedikte.myrold@sintef.no, [b]ola.jensrud@sintef.no, [c]Jon.Holmestad@sintef.no

Keywords: Hot and Warm Forming, Formability, Hardening of Aluminium Alloys

Abstract. Lightweight solutions will become increasingly necessary for the next generation of passenger cars. Applications of age-hardenable high strength aluminium material can be superior to traditional low strength alloys, especially if the processing of the parts itself is cost effective. Sheet forming of aluminium at elevated temperatures has been addressed in the current work. Warm forming directly after solution heat treatment can eliminate several process steps and reduce cycle time in the production of light weight load bearing car components. However, this is not straight forward as 6xxx alloys need minimum critical cooling rate to achieve the full potential of precipitation hardening. The technical forming methods must take this into the thermomechanical setup during the process steps of handling, lubrication, deformation, and final ageing. Elevated forming temperatures, more likely warm than hot show high formability of the alloys. Further, a short artificial ageing time demonstrate required strength and fatigue capacity in real components. Reduction of the deformation temperature to below 300°C is still favourable when lubrication for serial production is the issue. The modified thermomechanical method is appropriate for achieving accurate geometrical tolerances, uniform properties, and high productivity for aluminium automotive parts. The paper describes a feasibility study and method development for forming of sheet material of hardenable aluminium alloys at intermediate temperatures.

Introduction

Forming at elevated temperatures (>500°C) has been demonstrated earlier by reference [1] and [2] and showed advantages compared to traditional cold forming with respect to spring back, formability, and microstructural control. Forming of aluminium blanks is commonly carried out cold in soft annealed temper (O-temper), which provides very good and tight tolerances. Annealing for O-temper is time consuming and thus requires high energy consumption. Additionally, O-temper parts needs new heat treatment to reach T6 properties with challenges to keep tolerances and microstructure within expectations. Jensrud et al. developed a new profile shaping technique for manufacturing of automotive components in as quenched condition (W-temper). This gives a good formability and a reduction in processing time due to in-line heat treatment integrated with the mechanical operation [3]. This method is a measure of efficiency.

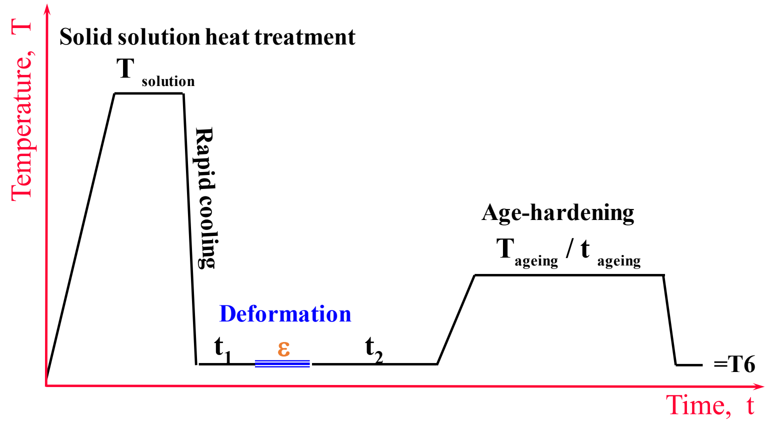

Fig. 1. The process route of forming in W-temper [5].

Forming prior to age hardening may also advantageously be carried out at elevated temperatures. Hot forming of aluminium has been widely explored and gives a further improved formability and productivity. A process with integrated forming and hardening has been proposed where the blank is simultaneously formed and quenched from solution heat treatment before artificial ageing [1,4]. This proved to be an effective process in terms of formability, efficiency, spring-back and properties. However, challenges with lubrication are encountered that results in sticking and thinning.

This research has been conducted in the framework of the above-mentioned work, except that hot forming is replaced by warm forming. Hot forming is defined as deformation at elevated temperatures below the recrystallization temperature [5]. This new proposal includes the integrated forming and quenching step with the alteration that the forming and final quenching happens as the material has reached an intermediate temperature of 200-300°C. Warm forming will provide a more controllable friction regime compared to hot forming and still obtains a low flow restriction and sufficient ductility. The deformation hardening mechanism combined with precipitation hardening is not well understood. The key mechanisms in age hardening of alloys deformed in W-temper are the interactions between dislocations, vacancies and formation of Guinier Preston (GP) zones, i.e. the first stage of precipitation hardening [6,7]. The contribution of each mechanism in age hardening after warm forming should be considered. As self-diffusion of dislocations increases with increasing temperatures, it would be reasonable to believe that the dislocations are annihilated during warm forming and therefore does not provide any strength contribution. However, whether the exposure time to high temperatures after forming are long enough for the dislocations to annihilate is not known.

In this paper, the quench sensitivity of relevant alloys has been carefully considered to obtain the required mechanical properties of load bearing automotive components. The limitations and latitude of the quenching step has been identified.

The sheet material evaluated is within AA6010 with a thickness of 5.3 mm. In this work it has been developed a process by a press quench tooling set-up integrated with heat treatment capability. The formability of the sheets is investigated by forming experiments performed in flat tool with subsequent testing of mechanical properties [8]. In this thermo-mechanical process, the solution heat treatment sequence of the material is a pre-process of the blank before the forming step with direct ageing from the press operation as the last step.

Materials Research Proceedings 28 (2023) 771-778 https://doi.org/10.21741/9781644902479-84

Method Development

The experimental setup requires proper control of time and temperature. During this method development, the cooling rate was measured with a thermo-logger that collected data with 0.1s intervals before the data was used for time control of the cooling. To select parameters for the forming trials, several experiments were designed and conducted at a laboratory scale. The experiments were intended to map cooling rate, quench sensitivity and resulting properties of the selected material. The cooling rates are so fast that it is difficult to manually stop the cooling or form at the correct temperatures during cooling. A manageable cooling rate had to be found that would not compromise the hardening of the material. Small sheet samples were cooled with different media; water, steel, compressed air, still air and insulated material. It was found that cooling the sheet between two steel plates gives a suitable cooling rate for the lab simulation of the process. The measured cooling rates for the different cooling media are listed in Table 1.

Table 1. Measured cooling rates for samples cooled from SHT in different cooling media.

Cooling medium	Cooling rate (°C/s)
Water	310
Closed steel	37
Open steel	18
Compressed air	10
Insulation	1.7

The selected cooling method still gives a high cooling rate so that manual handling of the sample during the experiments is difficult. To enable forming at elevated temperatures the cooling rate had to be slightly reduced to maintain temperature control when approaching the forming temperatures of 200-300°C, this can be achieved by cooling the samples in heated steel plates. A cooling tool was built as two steel plates with hinges and a handle that is heated in the oven to 100°C. After solution heat treatment, the samples are placed between the heated steel plates and cooled to the selected intermediate temperatures before being transported to the press for deformation and subsequent ageing. This process was validated by comparing the mechanical properties with a traditional process route shown in Table 2. The mechanical properties are not severely affected with the new proposed process route. Illustrations of the hot forming process route and the warm forming process route are shown in Fig. 2 and Fig. 3, respectively.

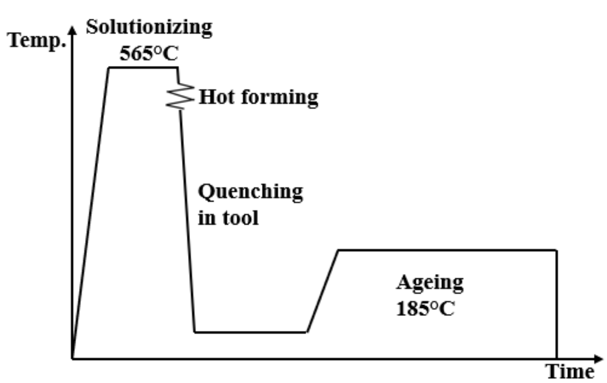

Fig. 2. Process route for hot forming.

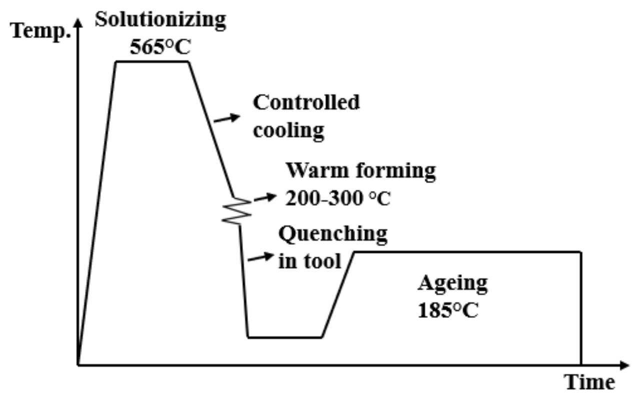

Fig. 3. Process route for warm forming.

Table 2. Comparison of mechanical properties after hot forming, warm forming and T6 condition with no deformation as reference.

	Yield strength (MPa)	Tensile strength (MPa)	Ag (%)	A (%)	Hardness HV10
Warm forming route	360	382	7.1	11.5	132
Hot forming route	354	373	7.9	13.9	130
Reference	364	382	7.5	12.6	135

At this point most process parameters have been selected and verified. The parameters for solution heat treatment, natural ageing and artificial ageing were selected based on the current industrial processes. Furthermore, the optimal forming temperature had to be found by investigation of all aspects of the material response to the process of forming at intermediate temperatures. The following experiments were conducted to find the influence on strength, ductility, anisotropy, and formability. After solution heat treatment, samples were cooled in a suitable manner and formed at 25°C (water quench), 100°C (between dies in the press), 200°C (cooling tool), 300°C (cooling tool) and 400°C (dies in the press). The samples were formed in a flat pressing tool by compression of 15% with a forming speed of 59 mm/s.

After solution heat treatment the different conditions were analysed by tensile testing, shear testing and tear testing. The presented results are the averages from 3 parallel samples with standard deviations represented by error bars.

Results and Discussion

The tensile test results from samples being formed at different temperatures are shown in Fig. 4 and Fig. 5. The results show stable tensile strength and significant variations in yield strength. The elongation does not seem to have been severely affected by the different cases. This indicates that there is no significant reduction in tensile strength due to an altered cooling sequence. The contributions of hardening mechanisms are complex, and it would require TEM investigations to identify the strengthening precipitates for each deformation temperature. As the forming temperatures are varying, the cooling sequences are also different. The precipitation mechanisms might differ for the different conditions. It is reasonable to assume that the distributions of precipitation and dislocations vary with temperature, which may explain the reduction in yield strength for the case of deformation at 200°C. However, for this alloy and the tested conditions the varying contribution of mechanisms do not seem to have diminished the final properties of the material.

Another possible explanation to the small variations in the final properties of the material after deformation at elevated temperatures might be the high cooling rate during forming. The temperatures of the material at the end of deformation are not known. The cooling rate between cold dies and with applied force is high, and there is a possibility the samples have reached room temperature before the deformation is finished. In that case, the same hardening mechanisms would apply for all cases. However, with a die speed of 59mm/s and a deformation of 15%, the deformation is finished after 0.01s. This is not enough time for the samples to reach room temperature before the deformation is complete. Although, if the material temperature would be low at the end of deformation, the same would apply in a forming operation of larger scale as the sheet thickness would be the equal and have the same temperature gradient as in these experiments.

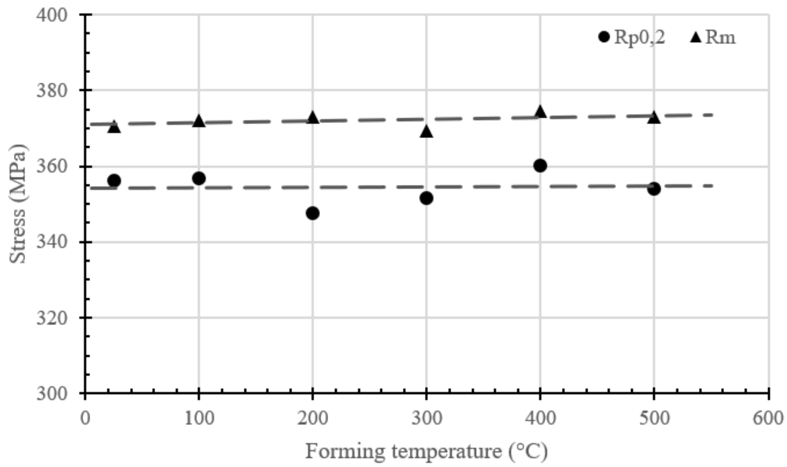

Fig. 4. Results from tensile tests of different forming conditions. Yield strength ($R_{p0,2}$) and tensile strength (R_m).

The elongation shown in Fig. 5 is not significantly affected by deformation temperature compared to cold forming. Ideally, the ductility should be improved at elevated forming temperatures, but it seems that hot forming is required for a slight increase in elongation. However, it is beneficial that severe reduction in elongation is not observed.

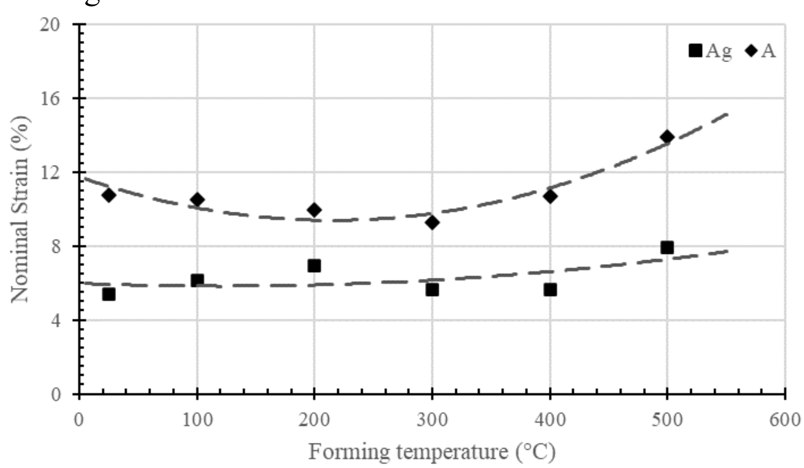

Fig. 5. Results from tensile tests of different forming conditions. Fracture elongation (A) and elongation at maximum force (Ag).

Shear testing were performed according to ASTM B831-05. A notched, rectangular specimen is subjected to a single shear force to failure in a fixture using a tensile test machine. The shear strength is the maximum force required to fracture the sample. Three parallels were tested for each condition. The results from shear testing are shown in Fig. 6, i.e. the average shear strength with standard deviation for the different quenching and forming conditions. The shear test shows the fracture shear strength. Insignificant differences are observed for the shear strength of the different conditions. There is a large variation for the undeformed condition which was water quenched.

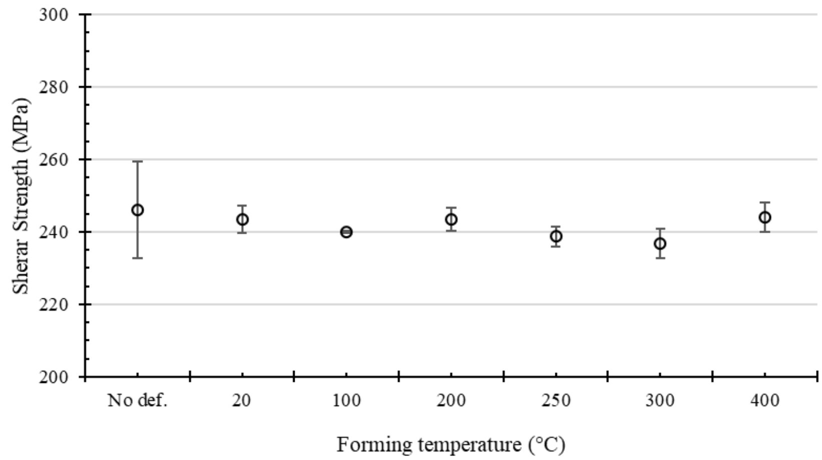

Fig. 6. Shear test results from samples deformed at different temperatures. Average shear strength with standard deviation.

Table 3. Results from shear tests.

Shear tests		
Forming temperature	**Cooling medium**	**Shear Strength (MPa)**
No def.	Water	246
20°C	Water	243
100°C	Cold dies	240
200°C	Cooling tool	243
250°C	Cooling tool	239
300°C	Cooling tool	237
400°C	Cold dies	244

Tear tests were performed according to ASTM B871-1 and involves a single edge notched specimen that is statically loaded through pin loading holes. The test is an indicator of toughness and provides a comparative measure of resistance to unstable fracture. The tear test shows the ability of a material to absorb plastic deformation and can reveal significant reduction in toughness. The tear strength shown in Fig. 7 is reduced for intermediate forming temperatures. The samples being water quenched and quenched in a cold tool have a higher tear strength than the samples being pre-cooled in the cooling tool. This indicates that the cooling rate affects the toughness of the material as the cooling rate is slower for the samples cooled in the cooling tool.

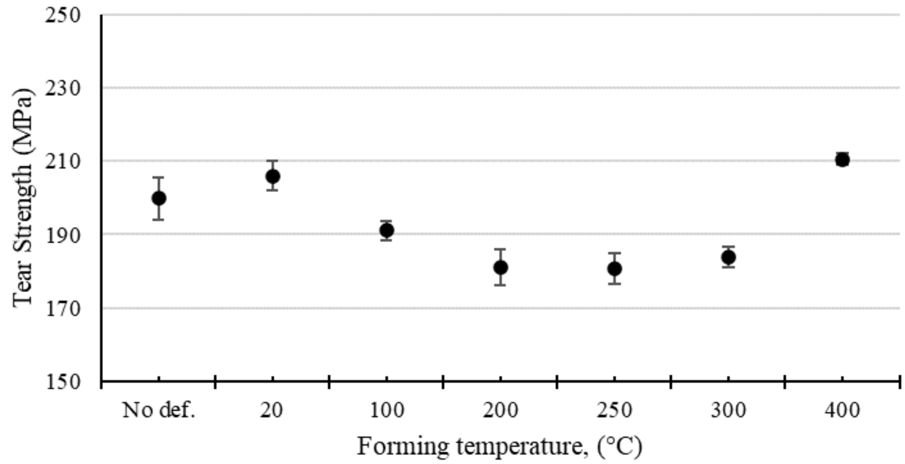

Fig. 7. Tear test results from samples formed at different temperatures. Average tear strength with standard deviation.

Table 4. Tear test results, average tear strength.

Tear tests		
Forming temperature	**Cooling medium**	**Tear Strength (MPa)**
No def.	Water	200
20°C	Water	206
100°C	Cold dies	191
200°C	Cooling tool	181
250°C	Cooling tool	181
300°C	Cooling tool	184
400°C	Cold dies	210

When comparing the tear test results with the tensile test results, the reduction in tear strength applies to the same conditions that show increased work hardening. Hence, the total performance of the material at all forming temperatures argue for a capable method and material. There are no test results that suggest that the proposed method inflict detrimental effects on the alloy properties. However, further testing of the method will be conducted, including hot tensile testing, microstructure investigations and additional alloys.

Summary

A method for warm forming of an AA6010 sheet material at intermediate temperatures have been developed. The proposed process route results in acceptable material properties in terms of strength, ductility, and toughness. The high strength material holds a potential of above 350 MPa in tensile strength, which is well above the common requirement for age hardenable aluminium alloys. In addition to satisfying material properties, the method enables sheet forming with good formability and extended possibilities in terms of lubrication.

Acknowledgement

The research has been carried out as a part of the Norwegian Research Council funded BIA-IPN project SUFICCS (Superior Fatigue Stressed Chassis Components). The project involves the following partners: Raufoss Technology AS, Hydro Aluminium AS, AP&T, SINTEF Manufacturing AS and SINTEF Industry. The experiments were carried out at SINTEF Manufacturing AS.

References

[1] R.P. Garrett, J. Lin, T.A. Dean, Solution Heat treatment and Cold Die Quenching in Forming AA 6xxx Sheet Components: Feasibility Study, Adv. Mater. Res. 6-8 (2005) 673-680. http://doi.org/10.4028/www.scientific.net/AMR.6-8.673

[2] O. Jensrud, K.E. Snilsberg, A. Kolbu, Conceptual testing of Press Form Hardening of High-Strength Aluminium Alloys, Aluminium Extr. Finish. (2016) 16-20.

[3] O. Jensrud, T. Høiland, A new advanced profile shaping technique for design and manufacturing of automotive components, The ExtruForm®, ET08 Orlando 13-16. May 2008, Proceedings of the ET08, Vol. 2 2008.

[4] B. Myrold, O. Jensrud, K.E. Snilsberg, The Influence of Quench Interruption and Direct Artificial Ageing on the Hardening Response in AA 6082 during Hot Deformation and In-Die Quenching, Metals 10 (2020) 935. https://doi.org/10.3390/met10070935

[5] ASM International, Metals Handbook, Vol. 14: Forming and Forging, 1988.

[6] O. Jensrud, K. Pedersen, Warm forming as an energy efficient process in manufacturing of high strength aluminium parts, Metall. Sci. Technol. 31 (2013).

[7] A. Latkowski, J. Grytiecki, M. Bronicki, Arch. Metal. 32 (1989) 313-325.

[8] K.E. Snilsberg, T. Welo, K.E. Moen, B. Holmedal, O. Jensrud, C. Koroschetz, A New Tribological System Test for Integrated Hot Forming and Die Quenching of Aluminium Alloy Sheets, ESAFORM Dublin, 2017.