Hot deformation and die-quenching of 6000-seres alloys – the effect of quench-interruption temperature

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Abstract

The automotive industry face demands to produce lightweight vehicles and substituting steel with aluminium is a straightforward solution. Age hardenable aluminium alloys are attractive candidates when the aim is a combination of high strength and good ductility. To obtain a solution that is suitable for high-volume production, an integrated hot forming and in-die quenching process has been developed. The method involves less operations and less handling than the conventional production process. However, the developed method changes the temperature exposure of the part and hence alters the precipitation and clustering sequence during hardening. In the present work, the effect of the modified temperature sequence has been investigated and, in particular, the effect of direct artificial ageing (DAA) has been studied. The potential benefits of DAA are less time needed for production and less space needed for storage. A lab-scale set-up, with the ability to simulate the industrial scale integrated forming and quenching method, has been built. By application of a water-cooled compression tool combined with subsequent age-hardening we have explored the effect of the in-die quenching on three different age hardenable alloys. The temperature experienced by the blank has been measured throughout the process, and the effect of variations in the quench-interruption temperature has been investigated. For AA6082, the results indicate that for selected temperatures, the effect of changing the closed-die time is minimal, and that the effect of room temperature storage (RTS) is negligible.

Introduction

Material substitution represents one of the main ways to save vehicle weight. However, to retain the same properties as the corresponding steel part, the aluminium solution will potentially be somewhat bulky and take up more of the total volume of the car. This can represent a drawback, particularly in cases where extra space is needed for energy solutions, such as batteries in electrical cars. Hence, obtaining the desired design, properties and weight savings often requires utilising formed sheets or profiles. Using traditional production methods, this involves several processing steps and consequently results in high processing costs. A new method for forming of high-strength, age-hardenable aluminium sheets and profiles have been developed [1 - 6] where the forming operation is combined with in-die quenching. The method is associated with fewer process steps, lower required die pressure, reduced energy consumption, increased cost effectiveness, good ductility and eliminated spring-back.

To explore the potential of the new production line, a lab-scale experimental set-up with integrated heat treatment, forming and quenching has been built. This set-up has been used to investigate different ways of artificial age hardening of the press-formed material. In conventional production, the material is stored at room temperature before artificial ageing (AA). In a car-part production line, the room temperature storage means longer time from start of production to finished product, and the space needed for storage could also represent a bottle neck in the production flow. Also, for denser alloys (solute level higher than 1) natural ageing/room temperature storage has a negative effect, decreasing hardness after artificial ageing [7, 9]. Hence, being able to avoid room temperature storage of the material between forming and hardening could potentially lead to both increased strength and reduction of the total production time. In the experimental set-up we have the possibility to interrupt the quenching after forming at a predetermined temperature, the quench interruption temperature. In the present work we have studied the effect of direct artificial ageing (DAA) on hardness and tensile stress, starting from different quench interruption temperatures. These results have been compared to corresponding results from experiments with room temperature storage. A sketch of the combined hot forming and in-die quenching forming operation is shown in Figure 1.

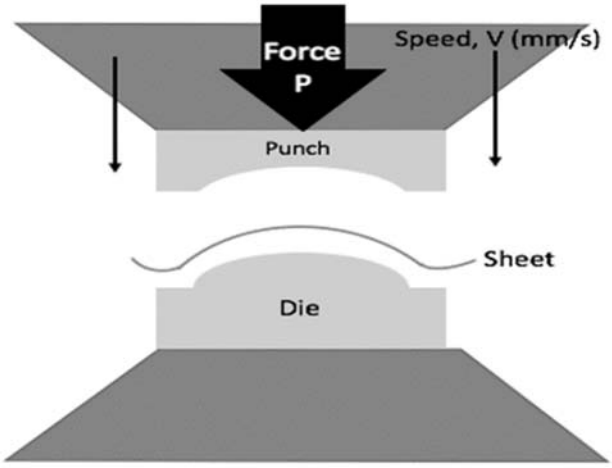

Figure 1: Sketch of the combined hot forming and in-die quenching forming operation.

Experimental setup and procedure

The experiments were carried out on two AA6082-alloys with slightly different Cr content and one AA6010 alloy. The chemical composition of the investigated alloys is shown in Table 1. The 6082.25 was industrially homogenized (575 ˚C for 2 h 15 min) and extruded to a thickness of 4.8 mm. The 6082.50 was homogenized at 535 ˚C for 5 h 20 minutes including heating time, and then extruded to a thickness of 3.9 mm. While 6010 was industrially homogenized and then rolled to a thickness of 4.0 mm.

Table 1: Chemical composition of samples used for deformation experiments in wt% 6082.25 and 6082.50 are extruded while 6010 has been rolled.

	Si	Fe	Cu	Mn	Cr	Mg	Zn
6082.25	0.92	0.17	0.01	0.55	0.15	0.64	0.02
6082.50	1.02	0.19	0.01	0.52	0.01	0.66	0.005
6010	1.00	0.29	0.24	0.51	0.05	0.73	0.20

The setup for the forming experiments included an air-circulating furnace for heating of the blanks before forming, a pressing tool attached to an MTS 311 – 1000 kN hydraulic driven press and an oil bath for artificial ageing after deformation. The pressing tool was designed and built by AP&T [6,12]. The force required to deform the samples was maximum 600 kN, giving a degree of deformation of

15% for the 6082.25 and 20% for 6082.50 and 6010. Channels for cooling water perforated both the upper and the lower part of the die, and a constant flow of water through the die during the experiments allowed for fast and reproducible cooling rate. To avoid heat transfer/cooling of the sample before deformation, four spikes attached to the lower part of the die, standing on springs, ensured that the sample was held a certain distance above the lower die before compression. During the deformation experiments, the upper die moved downward until the sample came into contact with the lower die and forming of the sample started. When the forming was over, the upper die was raised, the sample was lifted by the spikes and separated from the die. The centre distance between the spikes were 60 and 46 mm, and the samples were placed freely on top of the spikes.

Samples for testing were machined from the extruded/rolled material. The sample geometry is shown in Figure 2, and it was designed so that the sample was big enough to rest on the spikes and so that the area of deformation was suitable for the capacity of the press. The thickness of the wings was 1 mm, the length of the sample (a) was 70 mm and the width (b) was 65 mm for all the samples. The width of the tested area (c) was 35 mm for the 6082.25-samples and 20 mm for 6082.50 and 6010-samples. The temperature during deformation was measured by placing a thermocouple in a drilled hole in the sample, in a distance of 20 mm from the edge of the sample (as shown in Figure 2).
Lubrication (Molykote G-Rapid Plus) was used to reduce friction and ensure even heat transfer during testing.

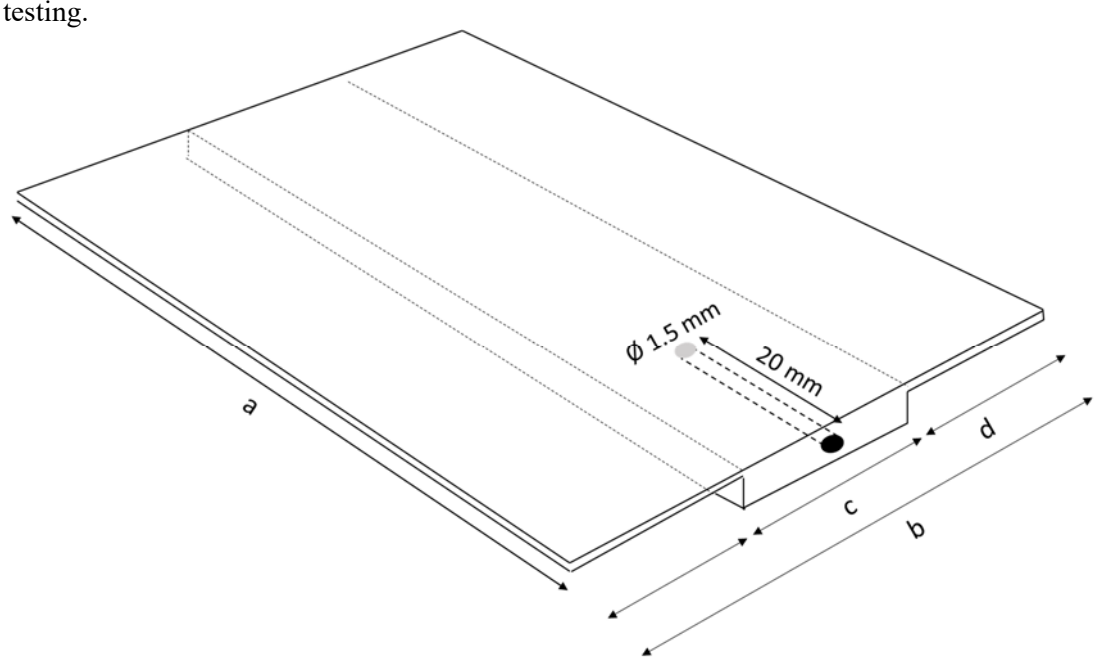

Figure 2: Sample geometry. The length of the sample (a) was 70 mm and the width (b) was 65 mm for all the samples. The width of the tested area (c) was 35 mm for the 6082.25-samples and 20 mm for 6082.50 and 6010-samples.

Directly before deformation, the sample was solution heat treated for 30 minutes in an air circulating furnace. The solution heat treatment temperature was (1) 540 ˚C for the 6082.25-samples; (2) 545 ˚C for 6082.50-samples and (3) 565 ˚C for the 6010 samples.

A timer was started at the moment when the sample was taken out of the furnace to be placed on the spikes. 6 seconds after the sample had been removed from the furnace, the forming operation started simultaneously with the quenching of the sample. For the samples being brought directly to artificial ageing (as illustrated in Figure 3), the press was opened when the sample reached the predetermined temperature and the samples were immediately lowered into an oil bath set at temperature (1) 190˚C for the 6082.25-samples and (2) 185 ˚C for the 6082.50 and 6010-samples. The artificial ageing time

was 3 hours. For samples stored at room temperature before artificial ageing (as illustrated in Figure 4), the press was opened when the sample had the predefined temperature and then air-cooled to room temperature. It was then left sitting on the spikes for air cooling for 30 minutes. After 30 minutes, the thermocouple was removed, and the sample was lowered into an oil-bath for artificial ageing for 3 hours at (1) 190˚C for the 6082.25-samples and (2) 185 ˚C for the 6082.50 and 6010-samples. After artificial ageing, the samples were quenched in water. Three parallels were done for each experimental condition. After heat treatment, the samples were polished, and hardness was measured using an Innovatest Nova 360 micro-macro Vickers & Brinell hardness tester. The hardness was measured normal to the ED-ND plane (where ED is the extrusion/rolling direction and ND is the normal direction). For the 6082.25-samples, 30 measurements were done per condition (10 per sample). For the other samples 15 measurements were done per condition (5 per sample).

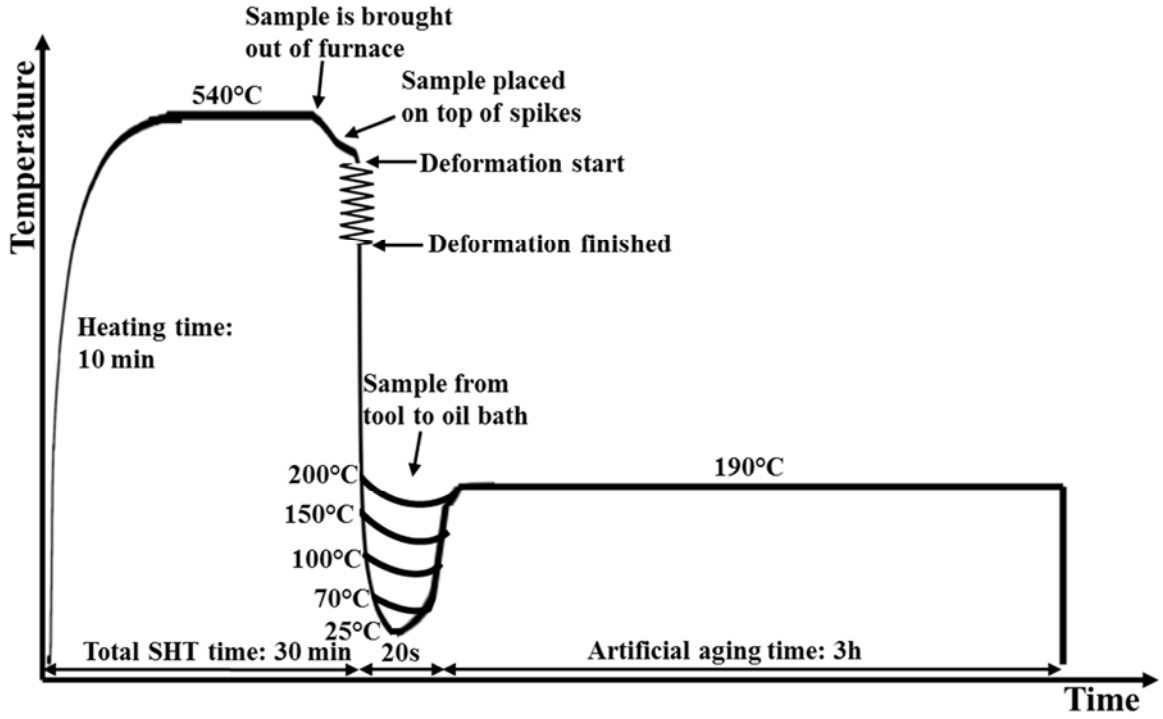

Figure 3: Sketch of temperature vs. time during the experiments where the samples were subjected to direct artificial ageing after integrated forming and in-die quenching.

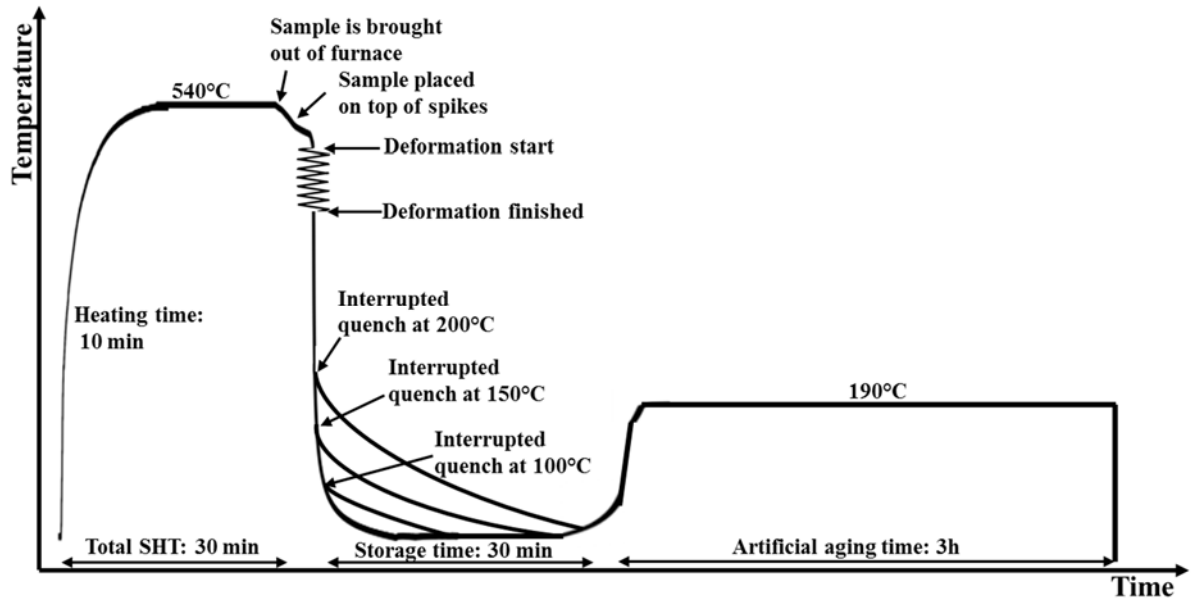

Figure 4: Sketch of temperature vs. time during the experiments where the samples were subjected to room temperature storage and artificial ageing.

The formed and heat-treated samples were subjected to tensile testing using a Zwick Roell Z2.5 micro tensile testing machine. Three samples were obtained from the longitudinal plane in the extrusion/rolling direction as illustrated in Figure 4. The dimensions of the samples for tensile testing are also shown in Figure 4. Three samples for tensile testing were machined from each formed sample (*i.e.* a total of 9 parallel tensile tests for each forming/heat treatment condition). The results from the tensile tests will be discussed by terms and definitions obtained from [8].

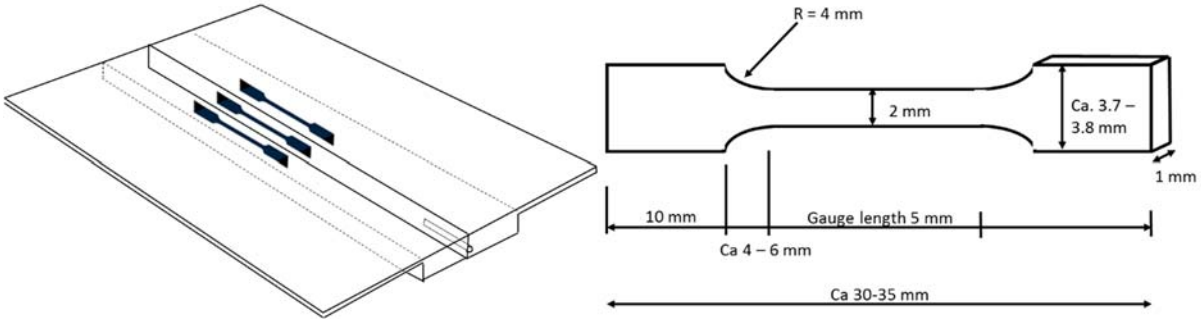

Figure 4: Tensile specimen dimensions and the position in the sample from which the tensile specimens were obtained.

The grain structure in the as-extruded profiles/rolled sheets were investigated using light optical microscopy. Sample preparation included grinding to 2.4 µm with SiC grinding paper and polishing with polycrystalline diamond suspension to 1 µm. The samples were anodised in 5% HBF4 aqueous solution at 20 Volts for 120 seconds.

Results and discussion

Grain structure in the extruded and deformed samples

The grain structure in the 6082.25 material was investigated using optical microscopy, and sample images are included in Figure 5. As shown in the figure, the as-extruded profiles have a relatively thin

recrystallized surface layer (300 – 400 µm). This layer was seen to grow somewhat during the initial solution heat treatment (to 400 – 800 µm). The recrystallized area was avoided when preparing samples for hardness and tensile testing.

The effect of quench interruption and direct artificial ageing

The results from the hardness testing of all the deformed samples are shown in Figure 6. The figure displays the average hardness for each condition as well as the spread in the measurements. The number of measurements is higher for the 6082.25 material, and the spread in the measurements is also lowest for this alloy. As can be seen from the figure, the hardness after RTS + AA and DAA for 6082.25 is very similar, with a slightly higher hardness after RTS + AA for quench interruption at 70 ˚C and 100 ˚C. The tensile testing supports the hardness measurements done on the material quench interrupted at 70 ˚C. As can be seen from Figure 7, the material quench interrupted at 70 ˚C shows lower stress-values after direct artificial ageing as compared to room temperature storage. It can also be noted that for this quench interruption temperature, the fracture elongation (Figure 8) is lower after RTS + AA compared to DAA. For the material quench interrupted at 100 ˚C, tensile testing shows similar stress-values after RTS + AA and direct artificial ageing, *i.e.* not supporting the hardness measurements. Also, the fracture elongation is higher after RTS + AA as compared to direct artificial ageing for this temperature.

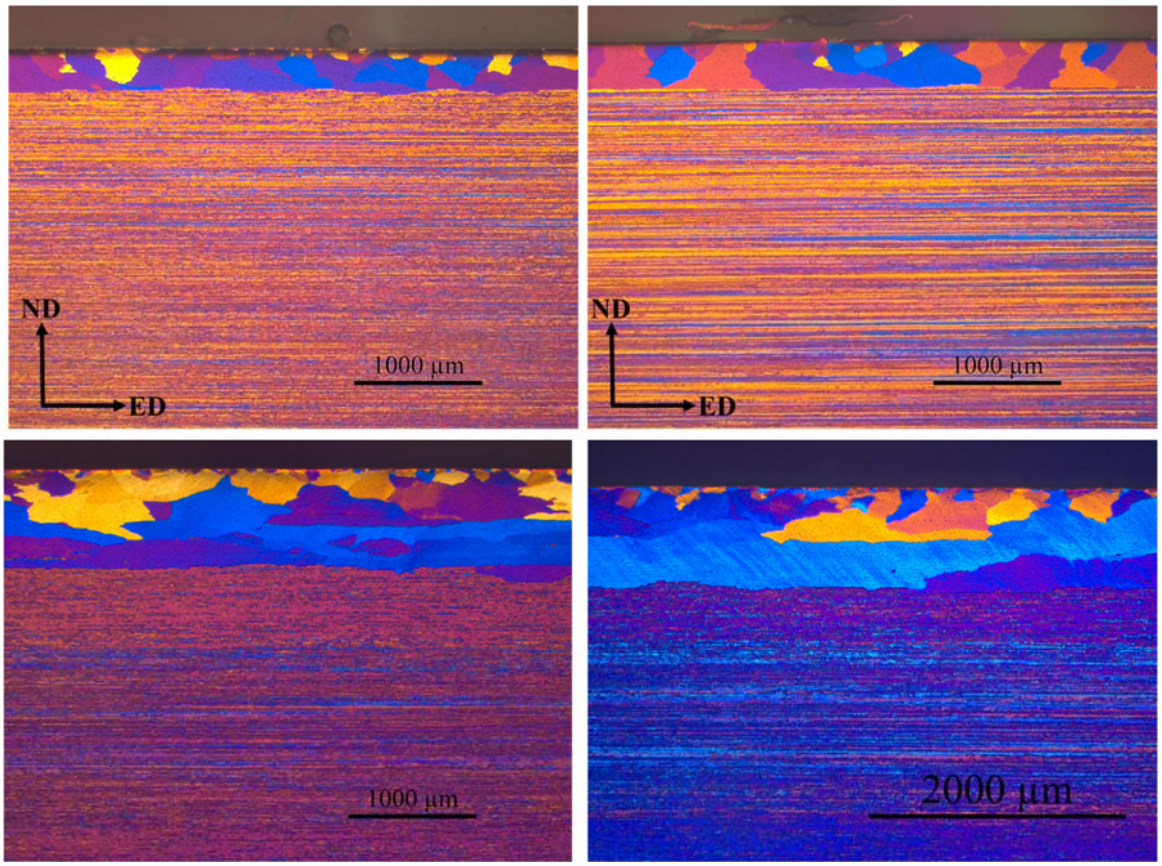

Figure 5: The images show light optical images obtained from the longitudinal plane.The two top images show the as-extruded profile (before solution heat treatment and forming). The two bottom images show the material after solution heat treatment and tool-quenching to room temperature.

The reason for the increased hardness after RTS + AA of the samples quench interrupted at 70 ˚C is not easily seen from the present result. One possible explanation might be formation of Mg-Si clusters occurring during air-cooling to room temperature. The slow cooling rate from 70 ˚C to room temperature can possibly be compared to the study done by Yamada *et.al.* [9] where step quenching,

i.e. interrupted quenching and holding time at an elevated temperature, promoted the formation of Mg-Si-vacancy clusters that act as nucleation sites for β" precipitates. These experiments also included storage at room temperature before artificial ageing. To explore this speculation, further microstructure characterization is planned.

As can be seen in Figure 6, the effect of quench interruption followed by direct artificial ageing and room temperature storage was also tested for 6082.50. This alloy is, as seen in Table 1, very similar to 6082.25, with the main difference being that 6082.25 also contains Cr, increasing the dispersoid density (*e.g.* Lodgaard [10]). For 6082.50, the hardness after direct artificial ageing was higher than after RTS + AA for all quench interruption temperatures. This is in accordance with the suggestion by Kovaćs *et al.* [11], that omitting room temperature storage after quenching from solution heat treatment should result in increased strength and hardness of 6082-alloys. With the exception of quench interruption at 70 ˚C and 100 ˚C, the suggestion of Kovaćs *et al.* [11] is also in accordance with the results of the 6082.25 alloy. To explore the effect of Cr-addition on strength and hardness, further experiments are planned. Figure 6 finally also shows results from hardness measurements of AA6010-material, subjected to integrated deformation and in-die quenching. The hardness measured in samples subjected to direct artificial ageing is seen to be significantly lower than the samples stored at room temperature before ageing. The spread in the measurements for this alloy is also relatively high.

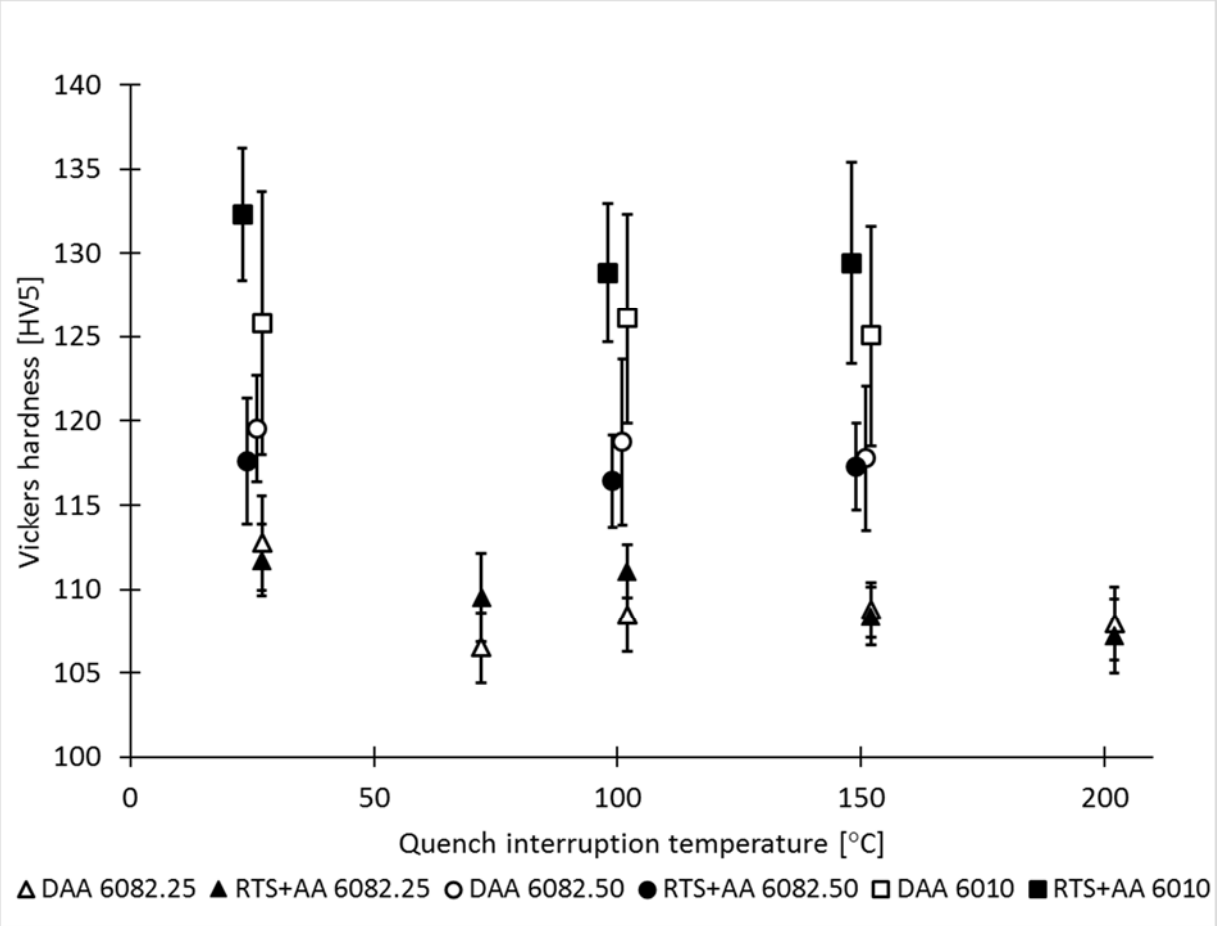

Figure 6: Vickers hardness as a function of quench interruption time for samples subjected to integrated forming and in-die quenching. The figure show both samples directly artificially aged (DAA) after in-die quenching and material stored at room temperature before ageing (RTS+AA)

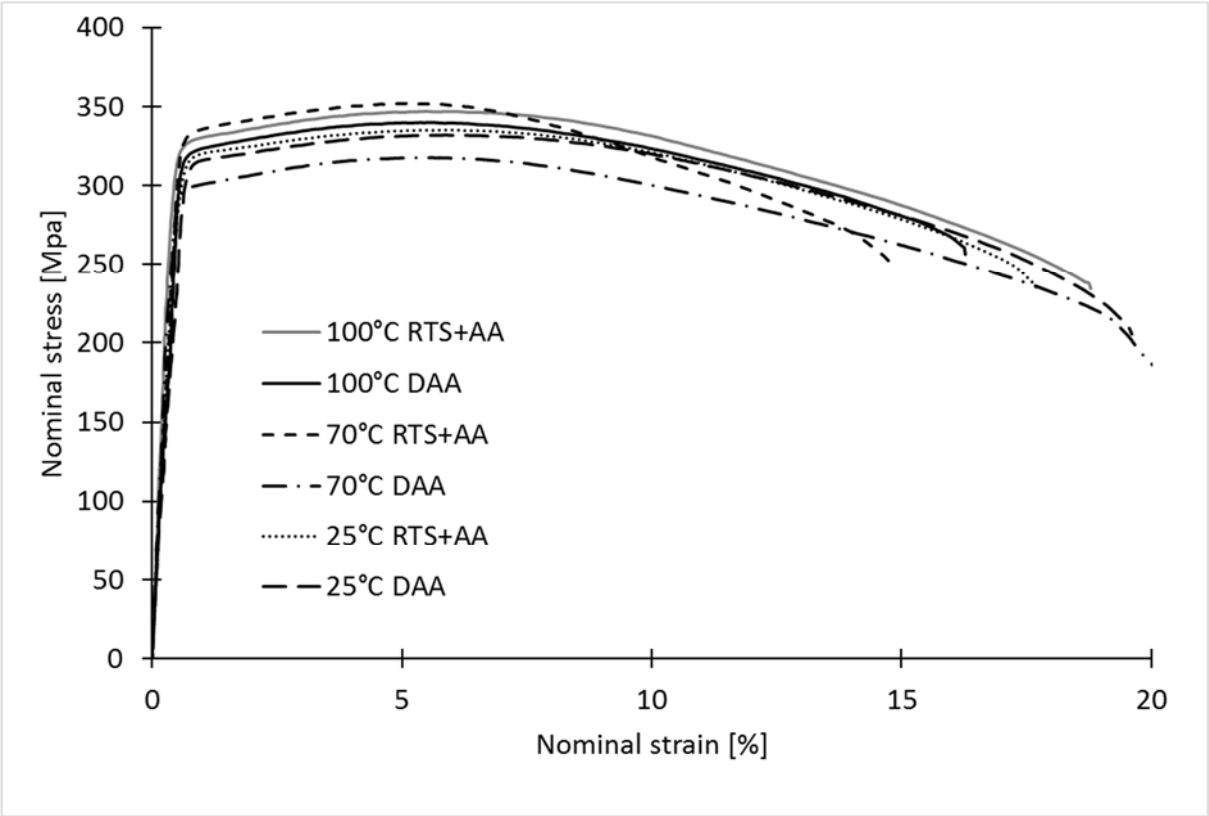

Figure 7: Normal stress-strain curves for samples subjected to integrated forming and in-die quenching. The figure shows results from 6082.25-material quenched to different temperatures in the die and then subjected to direct artificial ageing (DAA) or room temperature storage before ageing (RTS+AA.

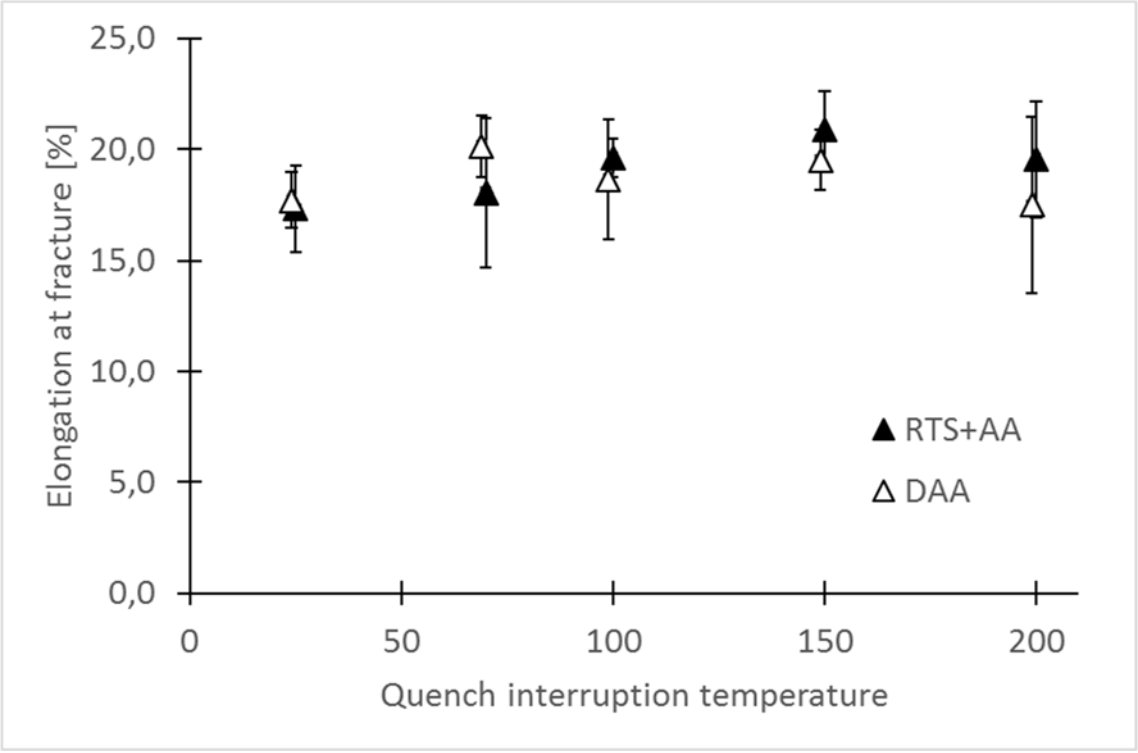

Figure 8: Fracture elongation for samples subjected to integrated forming and in-die quenching. The figure shows results from 6082.25-material quenched to different temperatures in the die and then subjected to direct artificial ageing or room temperature storage before ageing.

For all the above experiments, the introduction of dislocation motion in deformation may affect the resulting strength by altering the dislocation density or the vacancy concentration. These mechanisms may suppress the mechanisms causing the distinguished properties observed by artificial ageing compared to room temperature storage of non-deformed samples. Quench interruption at temperatures 150 ˚C and below has been found to be favourable for the final tensile strength of the 6082.25 material (Figure 7). The results above also support that the direct artificial ageing may be introduced to the process, as it would not be detrimental to the properties.

Conclusions

In this work, a lab-scale experimental set-up for integrated hot forming and in-die quenching has been used to deform aluminium sheets and profiles from three aluminium alloys. During and after deformation, the deformed blanks were cooled by the forming tool. When a pre-set temperature was reached, the samples were either subjected directly to artificial ageing (DAA) or they were stored at room temperature for 30 minutes before being aged (RTS+AA). Hardness and tensile testing were applied to study the effect of direct artificial ageing compared to room temperature storage before artificial ageing. For the extruded AA6082-alloys, there is no significant effect on hardness or stress-strain curve for quench interruption at 100˚C -150˚C. For the AA6010 alloy, the hardness after room temperature storage followed by artificial ageing was found to be higher than after direct artificial ageing for all quench interruption temperatures.

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