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Investigation of the Formability of AA6010 in an Integrated Forming and Hardening Process Aiming to Reduce the Energy Consumption in High Volume Production of Automotive Components

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Abstract: Hot deformation and in-die quenching of aluminum components for the automotive industry is a cost and energy efficient technique that has been developed and thoroughly evaluated in recent years. The performance of this process is considered higher when compared to traditional cold metal forming due to shorter process times, low-cost machinery, and a high level of structural integrity in fabricated parts. The work presented in this paper provides several approaches for the formability of age hardenable 6xxx alloy sheets when forming at different temperatures. Warm tensile testing and formability cup testing were carried out to investigate the alloy formability at different temperatures. The results indicate that the formability of candidate alloys is not significantly affected by deformation temperatures or conditions, which provides great freedom when designing an automated production process with high productivity and minimal environmental impact. The candidate alloy can be deep drawn without severe thinning at the whole temperature range, from room temperature (RT) to solutionizing temperature.

Keywords: age hardenable aluminum alloys; hot forming; in-die quenching; formability; automotive components; sheet forming

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1. Introduction

Applications of age hardenable high strength aluminum alloys within the 6xxx series have many advantages compared to other groups of alloys in fatigue-loaded automotive parts, especially if the processing chain of manufacturing components can be more cost effective. Sheets and extrusions from alloys within the 6xxx series are candidates when a combination of strength and ductility is required. Hot forming has advantages when compared with cold forming when dealing with spring-back, formability, and microstructural control. The innovation is to integrate forming technology with hardening heat treatment processing steps which are suitable for fully automated production. The process involves a first step of solid solution heat treatment, directly followed by sufficient cooling to suppress the precipitation of hardening particles in combination with deformation. Technically, the hot blank is moved to a position in a temperature-controlled die system and pressed to a shape within a timeframe, keeping the full hardening potential to achieve the expected mechanical strength for the given alloy. Considering the reduced weight of the vehicle and end-of-life recyclability, the overall environmental impact and costs are believed to be reduced using this methodcompared to traditional methods [1,2].

Control arms are safety critical components in the automotive chassis and are subjected to high fatigue loads. Forming is typically conducted in soft annealed temper (O-temper) which provides good tolerances but has limited formability. The process is time- and energy-consuming as it requires new heat treatment to achieve T6 condition. Annealing commonly requires 4 h at 380–420 °C. Designing and producing suspension components from sheets by hot forming and in-die quenching processes provide improved possibilities regarding geometric tolerances. This enables the production of parts with sufficient fatigue and strength properties and reduced weight. Forming in as-quenched temper (W-temper) provides good formability and reduced process times. Zhang et al. tested the hot form and quench process in O-temper at room temperature before solution heat treatment and ageing and found that ductility/formability and strength potential were both significantly reduced compared with the original hot form and quench process [3]. Zheng et al. found that the deformation characteristics and post-form strength of heat-treatable aluminum alloys were significantly dependent on temper and forming processes [4].

The hot forming and in-die quenching technique has been demonstrated and described previously [5–12], and shows adequate responses regarding mechanical properties, spring-back, and geometrical tolerances compared to cold forming. Forming directly after solution heat treatment provides the advantages of hot forming as well as utilizing heating in this process step. From an industrial point of view, this will save the production for a process step and the cost of purchasing and operating the furnace. However, few lubrications can withstand such high temperatures, thus causing thinning and galling during forming [13].

Previous work in this project included deformation tests conducted on AA6010 sheets in W-temper at different deformation temperatures to investigate the effects on mechanical properties. This work was presented by Myrold et al. [6]. The hot deformation in-die quenching method with warm forming instead of hot forming was proposed where the blank was quenched to an intermediate temperature of 200–300 °C before deformation and die quenching, and artificial ageing. This proved to be an appropriate process in terms of lubrication and hardening response [6]. Zheng et al. found that intermediate temperature forming was sensitive to the transfer operation time and may have reduced post-treatment mechanical properties [14]. Shang et al. also found that the transferring and forming process should be completed quickly to avoid coarse precipitates [15]. Hence, transfer- and quenching-times are critical for this process. Figure 1 shows the different process routes tested in previous research [5,6]. All process routes involved deformation of the material in solid solution (W-temper). The presented processes are further investigated in this work.

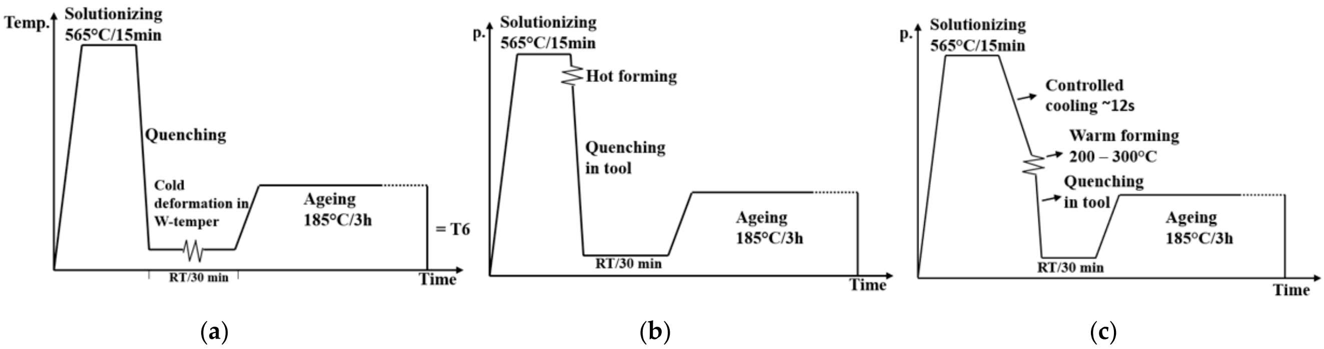


Figure 1. Illustrations of the thermomechanical process routes tested in previous research [5,6] where routes represent (**a**) cold forming, (**b**) hot forming, and (**c**) warm forming.

The formability of a material is the extent to which it can be deformed in a particular process before the onset of failure. Aluminum alloy sheets usually fail during forming either by localized necking or ductile fracture [16]. Wang et al. [17] studied the formability and failure mechanisms in AA2024 under hot forming conditions and found that ductility was improved by increasing temperatures up to 450 °C and was sharply decreased by further increasing the temperature. Bariani et al. [18] studied the effect of solubility on the high temperature formability of AA6016 and found that improved formability was generated at elevated temperatures. Fan et al. observed increased formability at 200 and 500 °C when testing formability in solution-treated Al-Mg-Si alloys under hot forming conditions [19]. Depending on the deformation mode, formability may also be strongly dependent on friction conditions in contacts between the work piece and tool. Yang et al. investigated friction evolution and lubricant breakdown behaviors in warm forming processes on AA7075 and found that increased temperature, contact load, and sliding speed caused an earlier breakdown of the lubricant and increased tool wearing [20]. Jiang et al. studied the effects of hot forming quenching conditions on friction and wear behaviors of AA7075 and found that the friction coefficient increased with increased die temperature, increased stamping speed and high load [21].

Forming temperature, stress state, and strain rate strongly influence the formability of a material. Generally, during forming at increased temperatures, the strength decreases and the ductility increases. However, deformation behaviors are more complex as precipitation, strain hardening, and recrystallization may occur. Strain hardening decreases with increasing temperature, while flow stress is not strongly temperature dependent which results in the stress-strain curve flattening out with increasing temperature. The flow during hot deformation is inhomogeneous and causes localized deformation, but if the recovery process keeps up with the deformation, large strains can be obtained before fracture [8,16,18,22].

A good indicator of a change in deformation condition is strain rate sensitivity that increases with temperature. The dislocation motion depends on stress, which is related to the strain rate. Strain rate sensitivity determines the extent to which the flow stress of a material changes with strain rate. During tensile deformation, strain is localized at weaker regions with a local reduction in area. If this reduction is accompanied by sufficient hardening, the strain proceeds elsewhere. When the strain is so high that work hardening becomes too low, necking is initiated, i.e., due to increased strain rate in the necking region, the flow stress increases in the developing neck, and prevents further development. Consequently, instability in a material that increases when the amount of work hardening decreases may be eliminated due to increased strain rate sensitivity, and thereof allows a more uniform strain after the onset of diffuse necking [8,10,16,22,23].

Final properties and strength potential depend on thermomechanical processes where contributing mechanisms may be a combination of dislocations and hardening precipitates. Fan et al. performed an experimental investigation of the strengthening behavior of the Al-Mg-Si-alloy in hot stamping and found that age hardening was the main strengthening mechanism, and that it was crucial to obtain super-saturated solid solution (SSSS) to achieve maximum strength [24]. Hidalgo–Manrique et al. investigated the microstructure and mechanical properties of AA6082 formed by the hot form quench process and observed that despite differences in local cooling conditions and microstructure, mechanical properties were consistent across different conditions [25].

The formability of a material with the press form hardening process has been mapped for different forming temperatures to identify the process window and opportunities connected to the method. Another perspective on the formability is the force required to deform the material. This is relevant from an energy consumption point of view.

The aim of the present work is to add to the overview of the concept, identifying all phenomena and responses that must be accounted for when implementing this production technique. The presented work represents a supplement to the previous work with the aim of providing a proof-of-concept of press form hardening from an industrial perspective.

2. Materials and Methods

Rolled sheets of AA6010 with a thickness of 5 mm were selected as candidate alloy materials for formability experiments. The alloy was chosen over AA6082 as it was promoted by the supplier. The measured mechanical properties in T6 condition are shown in Table 1 together with the mechanical properties measured after warm and hot deformation. For formability cup testing, rolled sheets of AA6082 were tested in addition to AA6010. AA6082 is widely used for automotive applications and is thus relevant for comparison. The alloy chemistry is similar except for the Cu-content, which is 0.25 wt% for 6010 and 0.01 wt% for 6082, whereas the Zn-content is 0.2 wt% for 6010 and 0.005 wt% for 6082. The 6082 alloy has a lower strength (yield and tensile) potential of approximately 30 MPa compared to the 6010 alloy in T6 condition. The expected mechanical properties in T6 have been measured and are shown in Table 2. All tensile tests presented in this paper were conducted on flat specimens in a Zwick Roell Z100 tensile test machine with an extensometer. Specimens had an original area of 66 mm^2, thickness of 5 mm, and length of 50 mm.

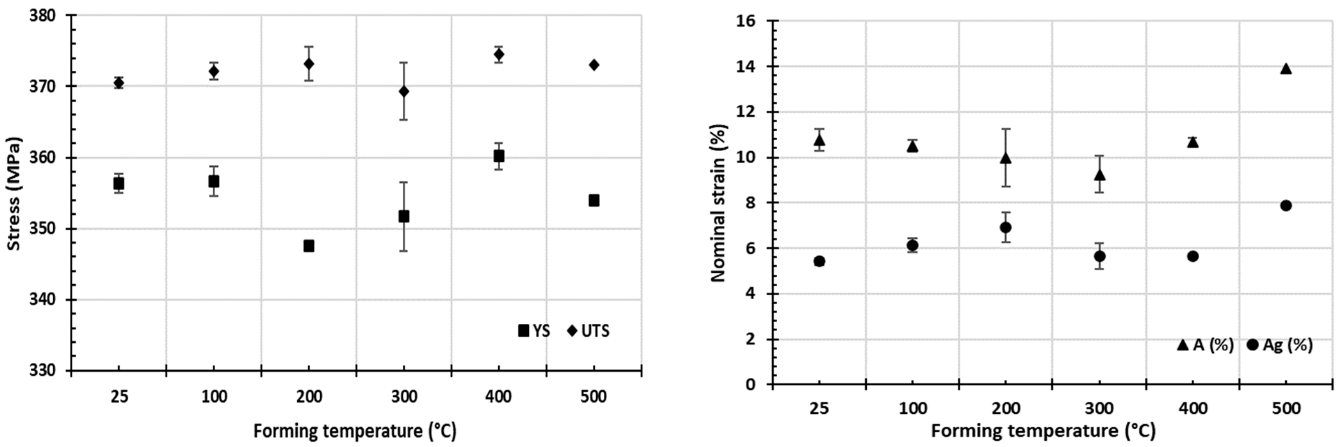
Table 1. Expected mechanical properties of AA6010 measured after warm forming (250 °C), hot forming (520 °C), and in T6 condition without deformation.

	YS (MPa)	UTS (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, T6	364	382	7.5	12.6	135

Table 2. Expected mechanical properties of AA6082 measured in T6 condition.

	YS (MPa)	UTS (MPa)	Ag (%)	A (%)	Hardness HV10
T6	328	348	6	11	117

Figure 2 was obtained from [6] and shows the mechanical properties of an AA6010 5 mm sheet deformed at different temperatures and artificially aged to T6. Samples were solution heat-treated at 565 °C/15 min before cooling to different temperatures for deformation, followed by quenching to RT and ageing. Forming was performed on sheet blanks in a flat pressing tool by compression of 15%. The material holds an ultimate tensile strength of above 350 MPa in all cases, which is above the common requirements for age hardenable aluminum alloys. The results proved great flexibility in the temperature range for forming in W-temper.



(**a**) (**b**)

Figure 2. The resulting mechanical properties of AA6010 sheets after trials with different forming temperatures [6] are presented in (**a**) yield strength (YS) and ultimate tensile strength (UTS) as a function of deformation and (**b**) total elongation (A) and elongation at maximum strength (Ag).

Several methods were developed to investigate different aspects of formability of the alloy during forming at different temperatures: warm tensile testing at two different conditions and cup forming in a tool designed and built for sheet forming trials. A commonly used technique to investigate warm formability is in a heating chamber using tensile test equipment. The specimen is solution heat-treated and quenched before it is mounted to the tensile tester inside a heating chamber, then heated to the test temperature and tested. The available equipment had a maximum heating capacity of 240 °C, therefore, for these trials, only forming temperatures up to 240 °C were tested. It should be noted that the condition of the material in these tests was assumably not in super-saturated solid solution condition (W-temper) as precipitation initiates immediately after quenching, and the time before the specimen has reached the test temperature will generate a certain degree of precipitation. This method is hereby called "Route 1". To achieve a state as close as possible to W-temper, a new test setup was needed for warm tensile testing during cooling from solution heat treatment.

To test warm formability of the material by tensile testing in W-temper/as-quenched condition (route 2), a test line was extended from tensile test equipment. The line was equipped with an air circulation furnace for solution heat treatment, a cooling tool, and a tensile test machine with a heating chamber. As testing at intermediate temperatures must occur mid-quench, time is important. Cooling to 250 °C must be sufficiently fast to avoid precipitation, and at the same time be sufficiently slow to stop at the preselected temperature. A tool was designed and built for this purpose, with two steel plates with hinges and a handle, heated to 100 °C, where the specimen was placed between the plates to achieve a manageable cooling rate. The test route is illustrated in Figure 3.

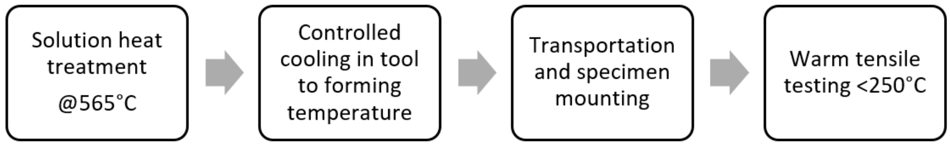


Figure 3. The test route developed for tensile tests in W-condition.

Formability cup tests were also conducted to further investigate the formability of AA6010 in comparison to AA6082 at different temperatures. The alloys were tested in two separate campaigns in different presses, with some alterations to process parameters, such as friction and forming speed. Thus, alloys and campaigns could not be directly compared, but the relative results from each case could be discussed in terms of formability. Thence, formability effects were compared for both tests. The test is a modified Erichsen cupping test with modifications to specimen and tool dimensions. A deep drawing cup forming tool attached to a 300-ton press was used to form cups from blanks with diameters of 10 cm. Blanks and the tool are shown in Figure 4. The cup forming tool consisted of a springed lower die with a fixed half-dome punch and the upper die had a die ring. Groves were pre-formed on the blanks for easy positioning and fixing of the blank in a clamping ring during drawing. For forming at >500 °C, the blank was solution heat-treated before being placed directly on the cup tool for forming. For forming of 6082 at 350 °C, the blank was air-cooled to the forming temperature. For forming at 250 °C, the blank was solution heat-treated, cooled in a cooling tool to the target temperature before being placed on the cup tool for forming. For cold forming, blanks were quenched in water after solutionizing prior to forming.

It should be noted that lubrication was not equal for the two campaigns. The forming trials on 6010 were performed with Copper paste as a lubrication, which had a very low friction coefficient, but friction issues can be ignored. As for the 6082 forming campaign, Fuchs F25Al was used as a lubrication and provided a higher friction coefficient. Cups were formed in 6082 with both lubricants to compare formability at different friction conditions.

The test matrix, with test conditions and measured properties in formability experiments, are summarized in Table 3.

(**a**) (**b**) (**c**)

Figure 4. Formability cup tests, equipment, and samples. (**a**) The cup tool attached to a 300-ton press (**b**) the lower die with clamping ring to fix the blank during deep drawing, and (**c**) the blank with pre-formed grooves with a depth of 1.5–2 mm to fit the clamping ring.

Table 3. Test conditions for warm tensile testing and formability cup tests.

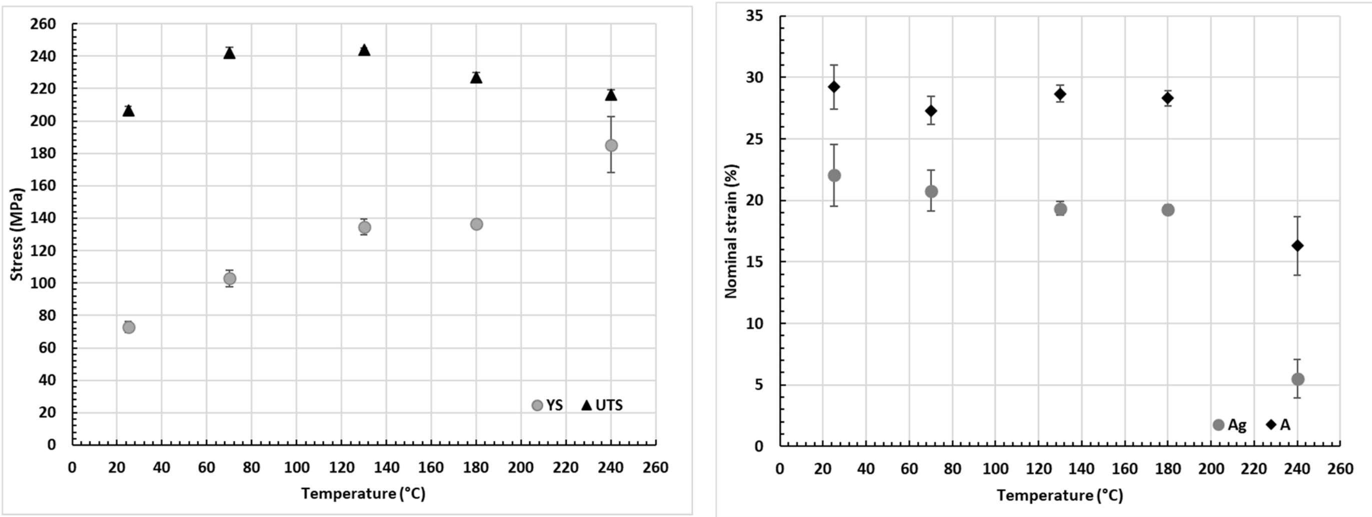
Formability Testing				
Test	Tensile testing heated from W-temper	Tensile testing in W-temper (SSSS)	Formability cup testing	Formability cup testing
Material	6010R (5 mm)	6010R (5 mm)	6010R (5 mm)	6082R (4.8 mm)
Target forming temperature [°C]	150, 180, 220, 240	240, 210, 180, 150, 25	SHT-temp., 250, 25	530, 350, 25
Measured parameters	Stress, strain	Stress, strain	Force, displacement, thinning, defects	Force, displacement, thinning, defects

3. Results

3.1. Tensile Testing in Route 1: Heated from W-Condition

The results from tensile testing in route 1 are shown in Figure 5. Ultimate tensile strengths and yield strengths are presented in Figure 5a, with standard deviations from six parallels. The ultimate tensile strength slightly increases at forming temperatures of 70 and 130 °C and is reduced with increasing temperature. The scatter is small for all temperatures except 240 °C. The yield strength increases with increasing temperature. The unchanged ultimate tensile strength during warm tensile testing indicates no reduction in force is required for warm forming at temperatures up to 240 °C. The decreased yield strength shows that less work hardening occurs. Figure 5b presents the elongation at warm tensile testing, where A is the fracture elongation and Ag the elongation at maximum force. Both A and Ag are reduced with increasing forming temperature. There is a relatively large scatter for 25 and 240 °C.

Unchanged ultimate tensile strength and reduced elongation suggest that formability is reduced at the intermediate forming temperature in this state.

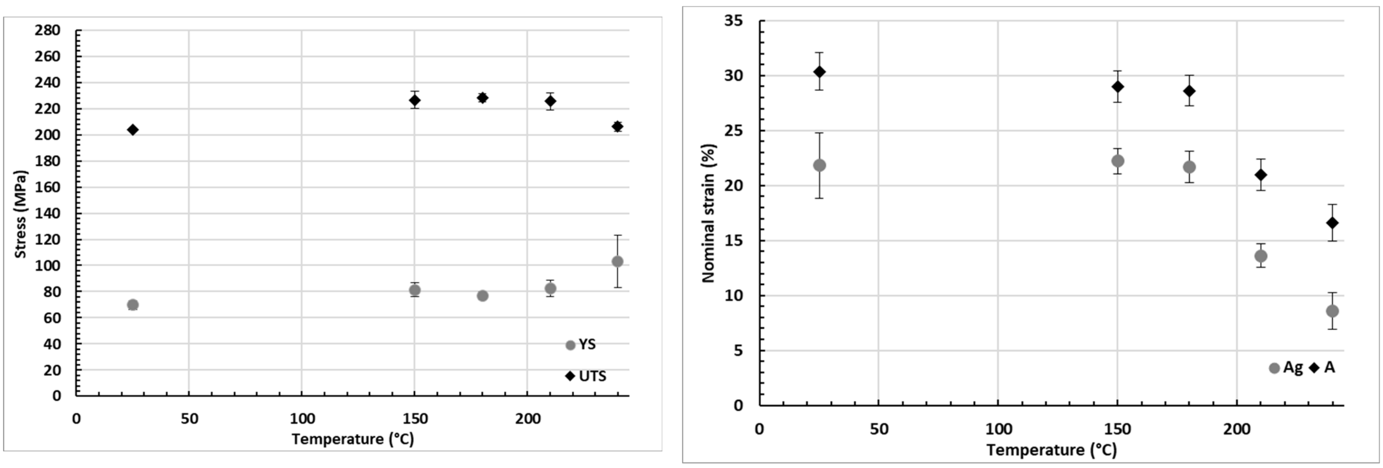


(**a**) (**b**)

Figure 5. Resulting mechanical properties during warm tensile testing on specimens heated to different temperatures from W-temper are presented in (**a**) yield strength (YS) and ultimate tensile strength (UTS) as a function of deformation temperature and (**b**) total elongation (A) and elongation at maximum strength (Ag).

3.2. Tensile Testing in Route 2: W-Temper

The results from tensile testing in W-temper are shown in Figure 6. The ultimate tensile strength does not change significantly with increasing forming temperature. A slight increase is observed at 150 and 180 °C compared with room temperature and 240 °C. As for yield strength, the same tendency as for route 1 is not observed. The yield strength remains relatively low, which indicates that the amount of work hardening is the same at tested forming temperatures and that precipitation does not occur during or prior to forming. The reduction in elongation is similar to the conditions presented in Figure 5. The instability mode seems to appear at a lower strain at higher temperatures than at room temperature.



(**a**) (**b**)

Figure 6. Resulting mechanical properties during warm tensile testing on specimens in W-temper, i.e., after cooling from SHT to target deformation temperature are presented by (**a**) yield strength (YS) and tensile strength (UTS) as a function of deformation temperature and (**b**) total elongation (A) and elongation at maximum strength (Ag).

3.3. Formability Cup Testing

Results from formability cup testing are presented as the force required to form cups, maximum displacement before instability occurs, and thinning of the material as a function of the forming temperature. Figure 7 shows the force-displacement curve for AA 6010 at different forming temperatures. For all forming temperatures, blanks were solution heat-treated at 565 °C for 15 min before direct transportation to the press (565 °C), tool cooling to deformation temperature (250 °C), or water quenching (25 °C) before forming. The force required to form cups is relatively low at a forming temperature of 565 °C, while the intermediate forming temperature requires approximately the same force as for cold forming. This confirms the observation from warm tensile testing where the tensile strength is not reduced when testing at temperatures up to 240 °C. The displacement at which cups are completely formed is approximately 66 mm, and the increase in force observed after approximately 55 mm is due to grooves detaching from the clamping ring in the lower die.

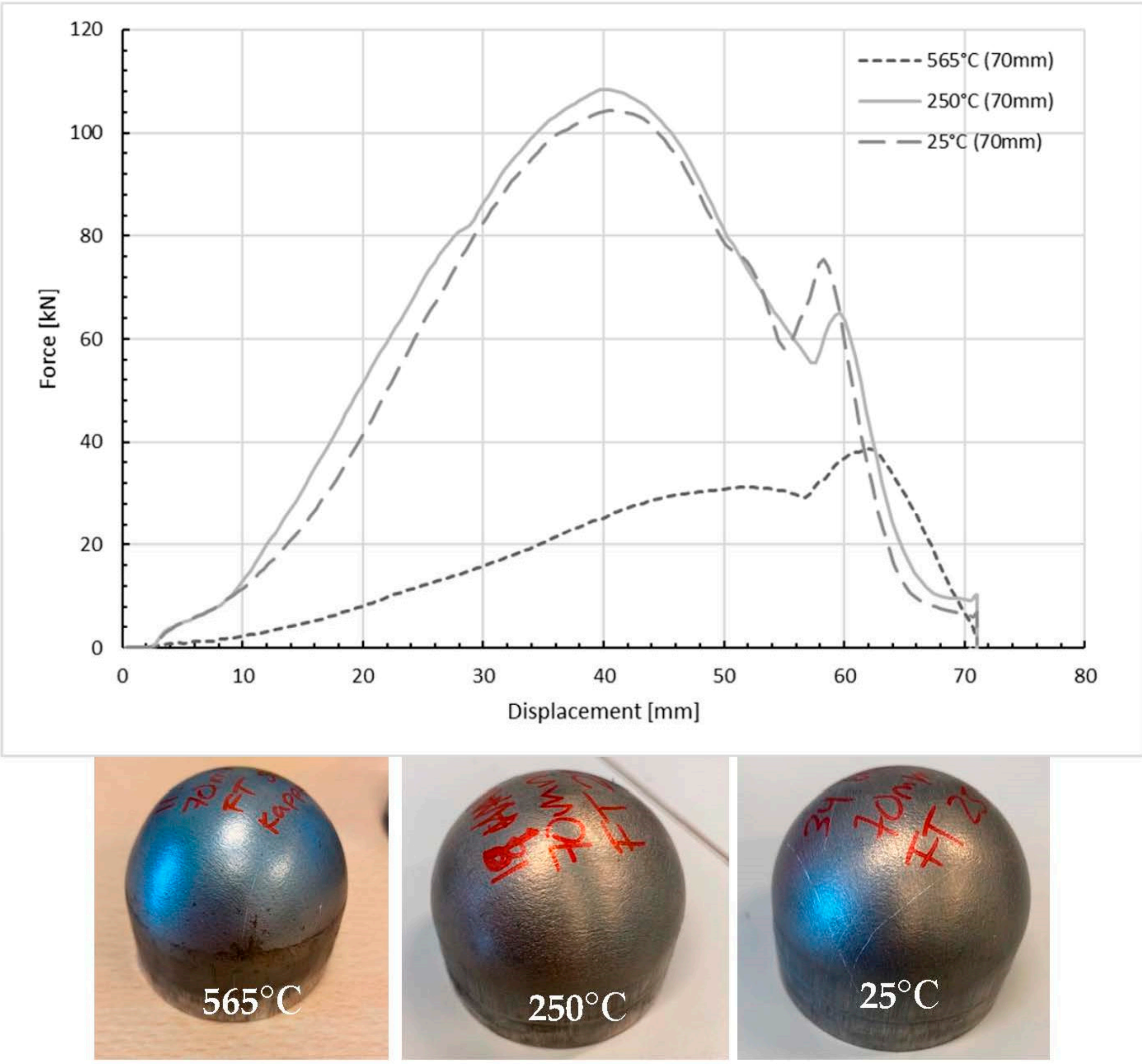


Figure 7. Force-displacement curve of samples formed at 565 °C, 250 °C, and 25 °C.

Figure 8 shows the force-displacement curve for AA6082 at different forming temperatures. For all forming temperatures, blanks were solution heat-treated at 540 °C for 30 min before direct transportation to the press (530 °C), air cooling to deformation temperature (350 °C), or water quenching (25 °C) before forming. The force required to form cups is highest at room temperature and reduced by approximately 45 kN for 350 °C and approximately 65 kN for 530 °C. This did not align with results from the 6010 alloy. For 6082, it appears that formability is altered even at intermediate temperatures. At the same time, it should be noted that the forming temperature is 100 °C higher in this case—therefore, we may have captured a temperature range where the formability curve shifts rapidly with increasing temperature. When the curve drops after the peak, instability occurs for all conditions. It should be noted that the displacement is equal in all cases.

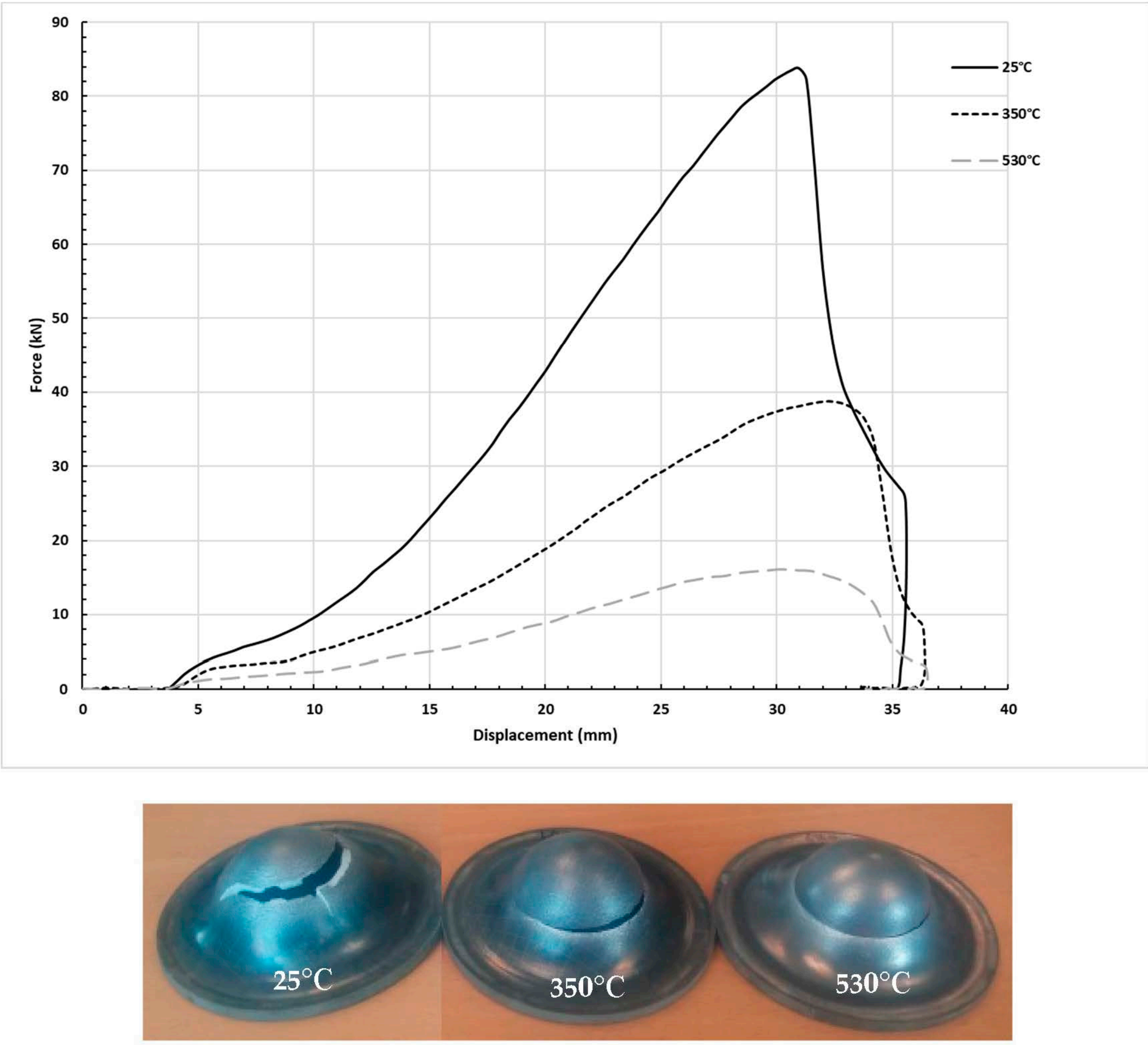


Figure 8. The force-displacement curve after formability cup testing of AA6082 at different conditions and temperatures with a displacement of 32 mm. Formed cups are shown in the lower image. From left to right: 25 °C, 350 °C, and 530 °C.

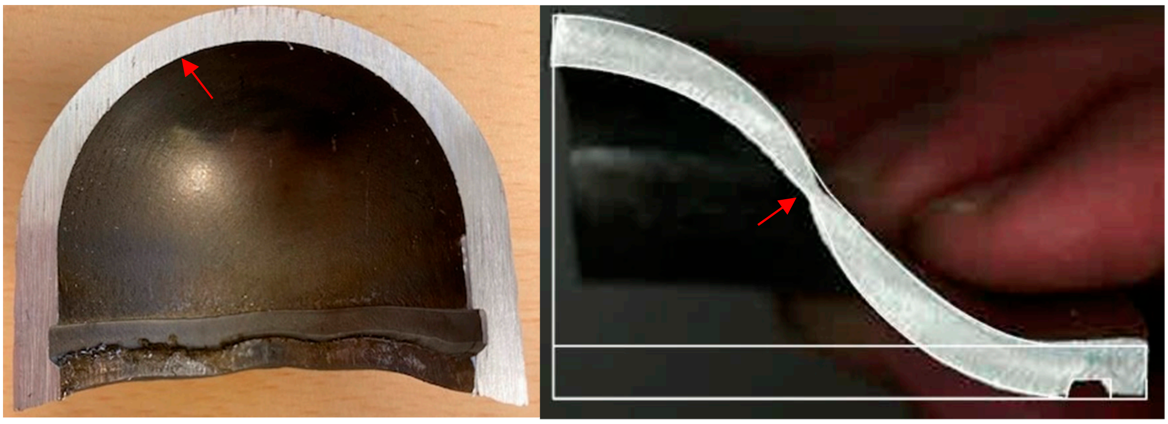
Tables 4 and 5 show measured thinning and maximum displacement values after forming. Additionally, required force and preset forming speed values are listed. We observe that 70 mm is the total displacement of the punch and above the distance necessary to form a complete cup. The amount of thinning indicates an initiation of instability/necking of the material during forming, where 100% thinning represents fracture. Maximum thinning is measured at the thinnest part of the cup cross section as shown in Figure 9. For 6082, failure occurs at the approximate same point in all cases. As for the 6010 alloy, slightly more thinning is observed in cups formed at 250 °C and 565 °C, but overall, the ability to form complete cups with no fracturing or necking indicates good formability of the tested alloy during hot forming, warm forming, and cold forming in W-condition. It should be emphasized that forming conditions are different for both alloys, with a higher friction coefficient and higher forming speed for 6082, which could greatly affect tensile properties during forming.

Table 4. Results and observations from formability cup testing of AA6010 at different deformation temperatures.

Alloy	Forming Temperature [°C]	Forming Speed [mm/s]	Max Force [kN]	Max Displacement [mm]	Max Thinning [%]
6010	565	41	36	70	37
	250	41	105	70	36
	25	41	104	70	20

Table 5. Results and observations from formability cup testing of AA6082 at different deformation temperatures.

Alloy	Forming Temperature [°C]	Forming Speed [mm/s]	Max Force [kN]	Max Displacement [mm]	Max Thinning [%]
6082	530	80	16	31.1	Fracture
	350	80	37	31.6	Fracture
	25	80	84	32.1	Fracture



(**a**) (**b**)

Figure 9. Cross section examples after deformation for (**a**) 6010 and (**b**) 6082. Thinning was measured at the thinnest position in the cup wall. Both were formed with copper paste as lubrication.

Figure 10 shows the force-displacement curve from hot forming with different friction coefficients. μ_{low} refers to lubrication with copper paste and μ_{high} refers to lubrication with Fuchs F25Al. Corresponding data and observations are shown in Table 6. The force required to form cups is slightly higher at low friction. Instability and fractures occur at an earlier point at high friction.

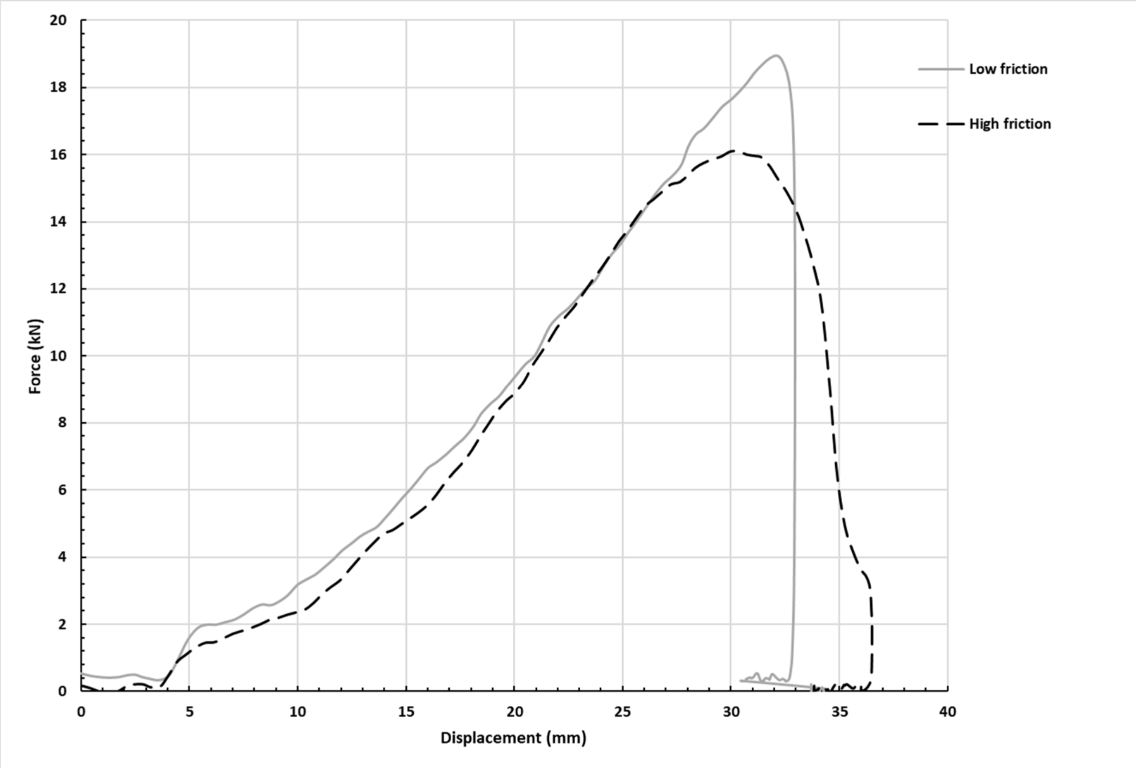


Figure 10. Force-displacement curves after forming cups with different friction conditions to 32 mm. Dashed lines are from testing with copper paste which generates low friction (**right** image) and the solid line is from testing with Fuchs which generates higher friction (**left** image).

Table 6. Cup testing results at two friction conditions.

Alloy	Forming Temperature [°C]	Friction Condition	Forming Speed [mm/s]	Max Force [kN]	Max Displacement [mm]	Max Thinning [%]
6082	530	μ (low)	80	18	31.1	1.8
	530	μ (high)	80	16	31.5	Fracture

4. Discussion

Tensile testing with two different temperature routes shows different results in terms of formability. This proves the importance of testing in the actual state to capture the true events of hardening and ductility during deformation.

Warm tensile testing by route 1 (Figure 5) showed a reduction in total strain at increasing temperatures up to 240 °C. The reduced elongation at intermediate forming temperatures is most probably caused by increased instability strain at increased temperatures, i.e., necking and fracture due to insufficient recovery processes at tested temperatures. Precipitation is enabled during the heating time from room temperature to forming temperature. Resulting from this is an increased yield strength with increased forming temperature, and decreased work hardening. Less work hardening leads to non-uniform strain during forming, hence this promotes thinning/necking and failure at an early stage.

Tensile testing with route 2 (W-condition) shows the same tendency as for route 1 regarding reduced elongation, but the fracture elongation remains relatively unchanged. Therefore, in this case, it can be argued that formability is reduced with increasing temperatures. The yield strength increases only slightly, which indicates that little precipitation occurs during increased temperature exposure. The relation between ultimate tensile strength and yield strength shows the same degree of work hardening at 240 °C as for room temperature. The combination of work hardening and early instability occurring at intermediate temperatures results in diminished formability. Future work should include tensile testing at higher temperatures to capture the forming temperature at which formability shifts, preferably in a Gleeble machine.

The fracture area was measured, and the area reduction calculated from A_f and A_0 and plotted in Figure 11. Contraction can be related to the thinning of the sheet and is a measure of the strain tolerances of the alloy. The level of contraction is fairly similar for the forming temperatures of 25 °C, 150 °C, and 240 °C, which imply that ductility is not significantly affected by tested temperatures. Calculations and simulations performed on relevant components in the project generated an acceptable thinning of approximately 20%. The test results show that alloy tolerances are not critical at this point. This provides a safety margin regarding local thinning in a product and ensures a reliable process.

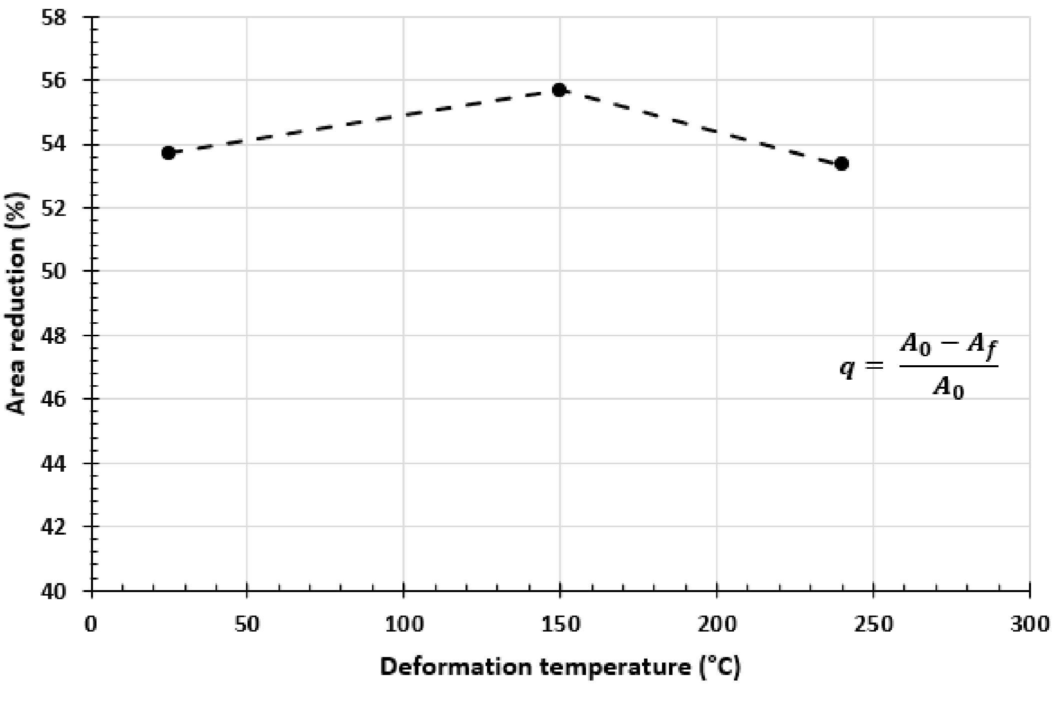


Figure 11. Contraction at fracture as measured and calculated from tensile specimens tested at 25, 150, and 240 °C.

Formability cup tests support observations from warm tensile testing where the force required to deform a material is equal for cold forming and forming at intermediate temperatures. This suggests that at certain temperatures above 250 °C, formability is significantly improved as the strain hardening rate annihilates instability effects. The cup testing of AA6082 at 350 °C suggests that the formability shift occurs at a temperature between 250 and 350 °C. However, this may also be alloy dependent. Regarding formability, i.e., the amount of plastic deformation without fracturing, the material shows a satisfying formability for tested forming temperatures. Though, a significant difference in the formability of both tested alloys was observed, even at equal friction conditions. The candidate alloy

AA6010 proved to have sufficient strength and ductility to be deep drawn. The deformation mode in cup testing is considered more representative of the process than tensile tests.

Regarding formability and lubrication, future work with formability cup testing should address lubrication issues and how they affect forming processes. In the present work, friction was nearly eliminated by using copper paste. It was demonstrated that at very low friction, the ability of the material to move on the stamp top promoted a mode of forming that was not sensitive to strain localization. A comparison of high and low friction coefficients indicates that instability occurs earlier with higher friction. Few options of decent lubrications are available for hot forming, which may argue for forming at intermediate temperatures where lubrication is not an issue.

So, why argue for hot and warm forming? It may rather be a question of why it is beneficial to form parts in W-temper. From an industrial point of view, we should aim to reduce the number of production steps, and even more important, energy consumption. Traditional forming in O-temper provides greater room for action as the condition is quite stable, therefore, the storage time before forming can be long. W-temper is a highly unstable condition, and precipitation will initiate immediately and affect the final properties. Therefore, the material cannot stay in this condition for too long and may introduce challenges with batch production.

Concerning energy consumption, O-temper is not an effective process route as it requires extra heating operation in addition to solutionizing and ageing. Forming in W-temper, warm or cold, reduces the number of process steps. Combining forming and quenching after solution heat treatment leaves the part in solid solution and with full hardening potential, as demonstrated in previous research [5,6]. As work hardening is decreased at increased forming temperatures and the recovery process is sufficiently fast, forming of complex geometries is enabled without introducing instability. Furthermore, an increased risk of buckling of a part produced from sheets with solution heat treatment after forming is eliminated.

From an environmental perspective, where energy efficiency and automation are relevant, hot/warm deformation and in-die quenching processes are completely feasible, enabling an automated production line to produce parts with high precision in terms of geometry and properties due to time and temperature controls. The cycle time can be remarkably reduced compared to the present production of relevant parts, hence the total energy consumption. The present work in combination with previous work [5,6] demonstrates large flexibility in the process route, enabling a tailored process for relevant products and product properties.

5. Conclusions

Formability in AA6010 has been tested by different approaches. Interpreting and comparing results from different formability tests leads to the perception that AA6010 has inherently good formability across the entire temperature range under tested conditions.

- The need for more results is identified in the present work as the project was unable to capture temperatures at which formability shifted. Tensile testing in W-temper should be conducted at several temperatures above 240 °C and up to solution heat treatment temperatures.
- The strain at UTS and fracture reduces with increasing forming temperatures, but a large area reduction of above 50% proves that the alloy has large thinning tolerances before fracture. Thus, formability in terms of ductility is acceptable.
- The force required to form cups is significantly reduced, approximately 65 kN (70%) for AA6010 at hot forming compared with warm and cold forming.
- Additional microstructure investigations are necessary to completely understand hardening contributions, i.e., dislocation and precipitate interactions, and how they affect the ageing potential.

Most likely, differences in formability between deformation temperatures are so small that they will not be crucial for the overall process. The results indicate that forming in

W-temper may be preferred in automated production processes and provide certain design freedom with respect to forming temperatures.

The motivation for this project is reduced energy consumption in future production processes. Based on the testing carried out so far, we observed that satisfactory properties and material responses are achieved both during forming and in the final product by W-temper forming. Considering traditional forming routes, this new technique will reduce the number of process steps. In other words, it will eliminate a heating step, which requires more machinery and more energy for heating. Additionally, the integration of deformation, quenching, and hardening increases the strengthening potential as contributions from both dislocations and precipitates may occur. As the proposed press form hardening process seems to be a feasible and relevant process in terms of time and energy consumption, formability, lubrication, geometry, and automation, a life cycle assessment can be conducted for new production lines to substantiate these claims.

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