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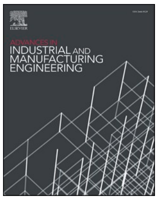

Repurposing steel press production lines for hot formed high-strength aluminium automotive body components

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ABSTRACT

Climate change and normative requirements are forcing car manufacturers to make their products ever lighter despite the highest safety requirements. For this case study a high-strength EN AW-7075 alloy is used as an example of how hot formed aluminium components for vehicle bodies can be produced on existing steel hot forming lines. Reusing production plants not only shortens the start-up time for mass production of hot formed and high-strength aluminium components, but also makes a significant contribution to the sustainable use of existing plant technologies and thus to improving the carbon footprint of manufacturing companies.

In addition to the presentation of the process control and the necessary conversion measures for the modification of a hot forming process from steel to aluminium, the most significant technological properties and the production costs of hot formed components made from both materials are compared. To be able to show the economic viability of a reallocation of existing and depreciated manufacturing plants, investigations of possible manufacturing parameters are carried out and presented.

The case study shows that by converting the furnace technology to Jet-Heating, significantly higher heating rates can be realised when compared with using radiation furnaces. As the furnace holding time was found to have no influence on the final strength in T4 and T6 state of EN AW-7075 specimens, the overall furnace cycle time is significantly lower than for press-hardened steels. Although the modifications necessary for the forming of aluminium alloys result in changed requirements for existing production plants, the additional costs per component for the plant conversion are marginal in relation to the assumed delivery volumes. It is demonstrated that for components with low material input, the use of 7000 series aluminium alloy components can become economically viable on a larger scale for OEMs.

1. Introduction

In the future lightweight construction will play an even greater role in increasing product efficiency and the reduction of emissions in the automotive industry. Current forecasts assume that fossil fuel resources such as oil, coal, and natural gas will be largely depleted within the next 50–130 years if reserves are kept being used at the current rate (British Petroleum Company, 2019). This fact and the associated CO_2 production is considered by EU Regulation No. 2019/631, which limited CO_2 emissions for new car fleets to 95 g/km from 2020 onwards (European Parliament and of the Council, 2009). However, 2021, the European Commission proposed an amendment to this EU regulation in order to strengthen CO_2 emission standards in line with the increased climate ambition. As a part of the general fossil fuel phase-out process, a 100% reduction in emissions for new passenger car sales is proposed from 2035 onwards (European Parliament and of the Council, 14.7.2021; IEA, 2021; Burch and Gilchrist, 02/2018). Furthermore, the European Green Deal of 2019 aims to transform the whole of the European economy with the goal of achieving climate neutrality by 2050 and decoupling economic growth from resource use. Currently, EU's industrial sector

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accounts for 20% of greenhouse gas (GHG) emissions. The European Green Deal therefore includes measures to strengthen decarbonisation efforts such as circular product design with a focus on reducing and reusing materials before recycling them (European Commission, 11.12.2019). Even though the next generation of vehicles will be largely electrified, using a mix of powertrain technologies such as battery electric vehicles (BEVs), hydrogen fuel cell vehicles (FCEVs), hydrogen internal combustion engines (H2-ICEs) and bio/synth fuelled internal combustion engines (ICEs), there is and in future will be a requirement for ever lighter and hence more energy efficient automotive bodies. In terms of the energy required to propel the vehicle as well as the embodied energy due to production, plant, materials etc. lightweight is critical to an efficient design. With increasing electrification of the automotive industry, the use of lightweight strategies can reduce carbon emissions and increase vehicle range as well as battery lifetime (Mruzek et al., 2016; Schiavo and Robinson, 2020; IEA, 2020). Whether fuel is burned in an IC engine or electrical energy is used from a battery that has been generated in a power station, the effective greenhouse gas emissions can be calculated and represented as g/km CO_2 equivalent (European Environment Agency, 26.10.2021). A more complete picture of the environmental impact of a vehicle would consider a cradle-to-cradle product cycle which can also be expressed using the metric of global warming potential (GWP). An example of this is produced by Volvo for the C40/XC40 range (Egeskog et al., 2020).

The weight of individual components and thus of the vehicle as a whole can be reduced by various lightweight measures such as concept, production, and material lightweight design; the latter two strategies being based on the substitution of materials by those with application-specific properties such as an increased specific strength. In this context, aluminium and its alloys are cost-effective and their lightweight potential is high. Previous studies have shown that weight savings of between 20 and 30% per component can be achieved if aluminium alloys are used instead of steel. This even applies to crash-relevant components such as side-impact beams (Schlosser et al., 2017). On a larger scale, the use of components based on high-strength aluminium alloys such as the 7000 series has so far frequently failed because of the significant increase in the component price, which is mainly due to the high material costs compared with steel. However, the process and the plant technology required for aluminium hot forming differ only slightly from that of those used to produce press-hardened steel components. Although continued plant operation after the depreciation phase is often desired, it may not always be economically viable due to the high process temperatures, which exceed 900 °C in press hardening plants, along with the associated wear of furnace equipment, component carriers and forming tools. As a consequence of the high maintenance costs, production plants often have to be partially removed or scrapped.

The continuation of production with existing plants, which would otherwise no longer be operated, may still be technically possible for aluminium hot forming and, compared with scrapping, not only be reasonable from an overall economic point of view but also when considering the overall CO_2 balance. This results in an additional advantage and significant potential regarding a sustainable and responsible environmental strategy of producing industrial companies. In industry circles, it is assumed that there are currently around 450–600 production lines in use worldwide for the hot forming of steel. Many of the lines have been built up in the last ten years in response to major technology developments by original equipment manufacturers (OEMs) which give rise to a greater proportion of press-hardened components in vehicle bodies, a significant number of which are likely to be available for repurposing in the coming years.

In this paper a particular focus of the case study is placed on the furnace system, since the furnace time has the greatest influence on the time period between the start of heat treatment and the removal of the formed component. Previous investigations of a representative component, namely a B-pillar made out of press hardening steel alloy, indicated a furnace time of 6 min, while the transfer time was 6 s and the forming and hardening process in the cooled tool was 30 s (Meza-García et al., 2019). In terms of throughput time and energy consumption, the results indicate that the focus should be directed towards modifying the furnace system.

Beyond this introduction, the paper is structured in four main parts. The first part gives an overview of the application of high-strength aluminium alloys in the automotive industry and discusses the materials' main characteristics with emphasis on the manufacturing process. The second part provides a review of a typical production plant for manufacturing press-hardened steel components and discusses the expected work packages required when moving over to high-strength aluminium alloys. The third part presents experiments on furnace technology with a special focus on the furnace parameters and their influence on the material properties. In the fourth part, a cost comparison is made between press-hardened steel and high-strength aluminium in the hot forming process using the example of a small and a large component.

2. High-strength aluminium alloys in car body manufacturing

2.1. Application of aluminium in the automotive industry

In the automotive industry, various technologies are being pursued to ensure the required crash safety while reducing body weight in order to meet current and upcoming zero-emission regulations (European Parliament and of the Council, 14.7.2021). Here, aluminium plays an essential role as a substitute material for the steels otherwise used in lightweight construction. With a density of only 2.7 g/cm^3, aluminium is around three times lighter than steel. It has been calculated that primary weight reduction of over 40% can be achieved through the consistent use of aluminium alloys in car body structures (Eckstein and Goebbels, 04.04.2011). In terms of specific strength, high-strength aluminium alloys of the 7000 series even offer advantages over press-hardened steels such as the boron alloyed 22MnB5. The aluminium-copper alloy EN AW-7075, for example, indicates tensile strength values of around 600 MPa in the fully hardened condition (T6) which generally exceeds the specific strength of high-strength steels (Fig. 1). The specific strength value is a parameter for evaluating lightweight construction potentials and is calculated from the ratio of tensile strength to the density of the respective material.

On one hand, it is known that the production of primary aluminium using the fused-salt electrolysis process requires more than 200 MJ per kilogram, which is about ten times the amount of energy needed for steel production (Rankin, 2012). On the other hand, due to the lower density of aluminium, the overall weight of a car body may be reduced when compared with a conventional steel body (Tisza and Czinege, 2018). Consequently, the energy required during operation is reduced; which for fossil fuel powered cars reduces exhaust pipe GHG emissions, and for

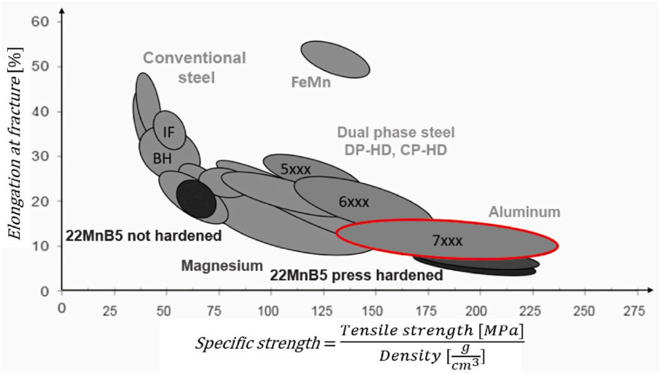

Fig. 1. Lightweight construction potential of various car body materials according to Schlosser et al. (Schlosser et al., 2017).

electric vehicles allows for a reduction in battery capacity for a given range, thereby reducing weight or alternatively allowing for a longer range. Due to the high use-phase efficiency, studies have shown that aluminium car bodies have lower life-cycle energy consumption and GHG emissions compared with steel, despite the higher emissions and higher primary energy required for production (Das, 2014; Raugei et al., 2015; Hottle et al., 2017). Mayyas et al. (2012) determined for a mileage of 150,000 km that the total life cycle CO_2 emissions of an aluminium-intensive vehicle body in white (BIW) are lower than those of a baseline BIW. Müller (2001) calculated a break-even mileage of 100,000 km in order to overcome the additional CO_2 consumption of aluminium car body production. Considering energy consumption and GHG emissions, the production impact on the life cycle can be significantly reduced if recycled secondary aluminium is used. As a result of the lower electricity requirement, secondary aluminium production saves about 90% of the process and energy-related emissions compared with primary aluminium production (Blomberg and Söderholm, 2009).

In the past, a substantial disadvantage of using high-strength aluminium alloys was considered to be their moderate formability. In comparison with the hot forming of steel, an adapted forming process is necessary to achieve the required degree of deformation. Nevertheless, previous projects (AMAG Austria Metall AG, 2014; Gao et al., 2017; Imperial College of Science Technology and Medicine, 25.05.2020; Imperial College of Science Technology and Medicine, 12.07.2017) have shown that with modifications to the tribology and the thermal process route, high-strength aluminium sheet grades can also be reliably formed in series production. The tribological behaviour of the sheet metal and tool material is a decisive process variable in tempered aluminium forming since, at high temperatures, the aluminium tends to adhere to the tool surface. To counteract this, well-functioning tool coating systems and lubricants are available on the market, which can be considered for these thermally demanding forming processes. The challenges regarding an increased corrosion tendency and the joining properties can be considered as manageable (AMAG Austria Metall AG, 2013).

2.2. *Manufacturing process of high strength aluminium alloys*

Compared with steel, which currently dominates the market due to its good price-performance ratio, the forming behaviour of high-strength and ultra-high-strength aluminium alloys is limited at room temperature. To redress this situation several thermoforming processes such as hot forming (also HFQ®) or the W-Temper process have been developed. Due to its high economic efficiency and the ability to produce complex geometries, the present consideration focuses on the hot forming process, the process route of which is shown in Fig. 2.

Hot forming of metallic materials is a mature and well-established technology to produce safety-relevant components and is used, for example, in press hardening of steel. Transferring this principle to aluminium alloys, an EN AW-7xxx blank is heated in a furnace or a heated plate tool to the alloy-dependent solution heat treatment temperature T_{SHT}, which for EN AW-7075 lies between 450 and 550 °C. If necessary, the temperature is then maintained for a certain period to homogenise the microstructure or to dissolve precipitates. Liu et al. (2020) have shown that the hardness and strength of components made of EN AW 7075 alloys increase with increasing furnace time and reach their maximum after 420–600 s, as the solution heat treatment temperature is reached and all phases are in solution. If the samples are "blackened" with graphite beforehand, the heating rate increases significantly, and a furnace time of 150–300 s is sufficient. As the holding time at T_{SHT} increases, the material hardness remains constant.

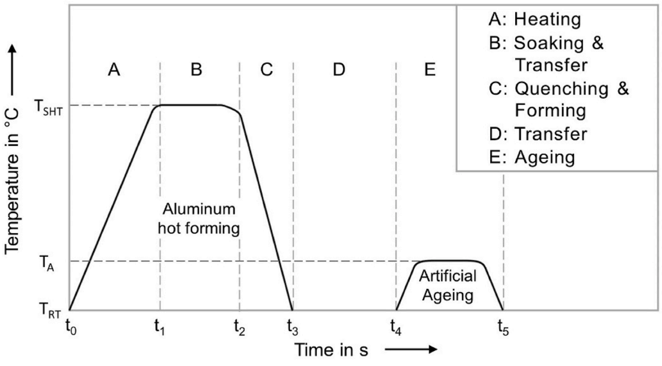

Fig. 2. Temperature profile of the hot forming process.

In direct comparison with press hardening, the furnace process window for EN AW-7075 sheet material is significantly larger since the formation of anti-corrosion coatings is not necessary, and grain coarsening can be expected much later than, for example, with 22MnB5 steel, where it starts after a few minutes. Consequently, as the aluminium alloy is less susceptible to furnace malfunctions and process disturbances, the scrap rate is reduced and economic efficiency is further increased. Afterwards the blank is transferred to a cooled tool, where it is formed and simultaneously quenched (Foster et al., 2009). The cooling rate can be adjusted by tempering the tools, but must be fast enough to achieve a supersaturated solid solution state and to prevent the formation of coarse secondary phases at grain boundaries. When using an EN AW-7075 alloy, the temperature of the blanks must not fall below 425 °C during the transfer from the furnace to the quenching unit. The critical cooling rate for quenching in the tool is approximately 100 K/s, for EN AW-7075, and should be kept below 200 °C to avoid a possible loss of the hardening potential (Milkereit et al., 2018). Due to the high formability of the material after solution heat treatment, the hot forming process route also allows the production of complex-shaped components such as interior door panels or B-pillars. The final aging step, which leads to the target strength of the component through precipitation hardening, requires additional organisational precautions. It can be combined with downstream processes such as cathodic dip coating (CDC) so that no extra process step is required.

3. Adaptation of existing production plants

A typical production line for the manufacture of press hardened steel components essentially consists of five operations (Fig. 3):

1. automation for handling blanks or finished components,
2. furnace for blank heating,
3. press (with tool) for forming and quenching,
4. cooling unit for cooling the tool, and
5. laser cutting machine for final trimming (not shown).

The most common combination of furnace and press technology on the market, considering the sales figures of large equipment suppliers, is the combination of roller hearth furnaces and hydraulic presses (Bachman, 26.07.2018; schwartz GmbH; Zeichner, 19.12.2013). The plant adaptations described in this paper, therefore, refer to this case; although the retrofitting of other technologies in use is also conceivable in a similar way. A thorough and realistic review of the plant condition must always be the first step in such considerations. The following assessments should be made as to:

- the mechanical wear condition of moving components;
- the integrity of hydraulic or pneumatic systems;
- the wear condition of components or assemblies due to the high thermal stress and a possible replacement for long-term operation;
- the state of sensors and control technology, and whether system support is guaranteed for another five to ten years.

The same issues occur, however, if a further use for press hardening is to be examined. Particularly regarding thermal wear, the significantly higher process temperatures place even higher demands on the

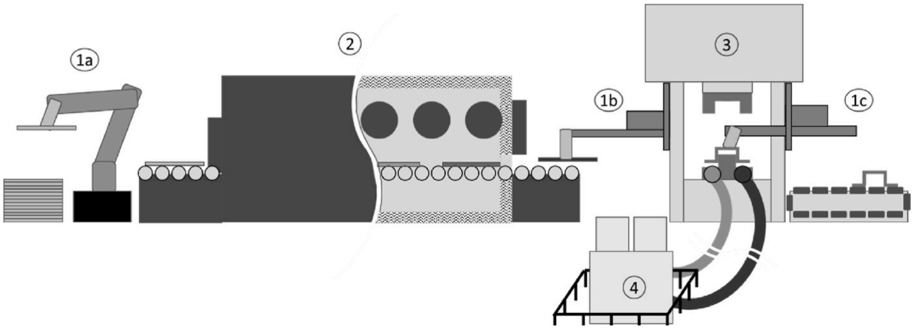

Fig. 3. Principle representation of the plant operations for hot forming production of steel components.

condition of the production plant. The following sections describe the expected work packages for the individual technology areas.

3.1. Automation

Fig. 3 shows an example of the two usual automation solutions, handling by a robot (1a) or through a linear feeder system (1b + c), which are used individually or in combination. Robots are generally characterised by higher variability, whereas spring systems can often achieve faster transfer speeds and, therefore, shorter transfer times (Schuler Pressen GmbH). Both technologies are equally suitable for the manipulation of steel and aluminium blanks or components. The high process temperatures during press hardening make particular demands on the handling systems, which must be protected from the considerable heat input, and sometimes they must be actively cooled. The lower process temperatures in aluminium hot forming allow unrestricted further operation if necessary; even cooling or heat protection devices can be omitted, thus increasing the load capacity and speed of the systems. Additionally, the variable mass to be moved is reduced by about 20–30% for aluminium blanks with similar component dimensions, provided that a comparable component stiffness is assumed. This also has a positive effect on the load capacity, speed, mechanical wear, and deflection. In view of the maximum blank temperature of almost 500 °C after heating and the critical quenching temperature of about 400 °C (Luckey et al., 2013), an uncontrolled free cooling time between leaving the heated furnace area and the start of forming and quenching in the die in less than 15 s should be achievable in hot forming of EN AW-7075. This assumes a sheet thickness of 2.0 mm, but this period will be affected by the thickness dimension. Such values should be relatively easy to achieve with most plant layouts, especially considering the potential for improved transfer unit dynamics described above.

A relevant difference is the fixation of the blanks or components, especially if magnetic manipulators are initially used. In the furnace loading and press unloading areas, these can be replaced by vacuum suction cups. A corresponding retrofit requires a compressed air supply, which in most cases is available at the production line, as well as the routing of air hoses. Vacuum suction cups are particularly suitable for separating blanks during furnace loading; mechanical grippers are more common in other places. In the furnace unloading or press loading zone, magnetic grippers would not be used due to the high temperatures and the associated paramagnetic properties of the steel blanks. In cases that magnetic sensors are used, for example to check the position of blanks or components, they must be replaced by optical, inductive, or tactile sensors in the production of aluminium materials. For this purpose, market off-the-shelf solutions are available which, if necessary, require the modification of the sensor technology (Mahayotsanun et al., 2009; Vacca, 03.12.2020).

3.2. Press

New plants for aluminium hot forming are usually designed with drawing cushions, as the forming of aluminium materials can result in additional requirements for the process control of forming speeds and pressures (Anyasodor and Koroschetz, 2018; Gauhar et al., 2017). In the case of particularly demanding geometries and sensitive phases in the cooling process, accelerating the press table in the direction of the punch movement reduces the risk of cracks in thinned-out areas of the component. Conventional production systems for press hardening steels usually do not have a drawing cushion technology and, apart from the financial outlay, retrofitting is often out of the question for technical reasons such as the lack of installation space. The extent to which support of the punch movement or control of the pressure distribution is required for deep drawn components must be considered on a case-by-case basis. In principle, the production of aluminium components in the hot forming process does not require a drawing cushion, so that presses without this technology can also be considered for repurposing. As an alternative to a drawing cushion on the press side, gas pressure springs in the die can also be considered as they are often used for press hardening of steel. Although in a typical implementation only local and linearly increasing back pressures can be set, they are a suitable and comparatively simple means of controlling the material flow. For more complex applications, the use of controlled nitrogen spring systems is also conceivable, with the aid of a discontinuous hold-down force curve that can be set over the drawing path (Doege and Behrens, 2010).

Concerning the tool functions and dimensions, it can be assumed that these do not differ significantly from those used in press hardening. Due to the lower material strength of the aluminium alloys, it is not necessary to apply the full force of a press designed for steel hot forming during the forming process. As with press hardening, however, the maximum pressures do not have to be applied for the forming, but in the pressure or holding phase to ensure the best possible heat transfer between the component and the cooled tool. In this phase, the requirements of both material groups for press technology differ only slightly. The lubricant to be applied during aluminium forming can promote the heat flow from the component to the tool and thus possibly contribute to a reduction of the required pressures in the holding phase.

The use of additional lubrication is not necessary when processing coated steel blanks. The aluminium-silicon or zinc blank coatings usually used in press hardening serve on the one hand to protect against oxidation during heating, but also to reduce friction during forming. Since blanks made of EN AW-7075 do not need to be coated for oxidation protection, the lubricating effect does not apply in this case. It is therefore advisable to apply a sufficient lubricant to the blanks and/or the tool prior to forming. This can take place immediately before the blanks are placed in the press, which can be achieved by spraying, for example, during the transfer phase from the furnace to the press. Due to the short transfer time, a lubricant with comparatively low viscosity is required here to achieve uniform wetting of the blank. Due to the blank temperature of around 450 °C at this point, a considerable amount of the lubricant can be assumed to evaporate, so that a suction device would have to be provided in the area between the furnace and the press in order to remove the vaporised lubricant.

Another solution, less demanding in terms of plant and process technology, is the use of heat-resistant lubricants, which are applied to the aluminium blanks before they are heated. A suitable time for this could be whilst shaped blanks are being trimmed, as suggested by Luckey et al. (2013). In this case, organisational measures must be taken to protect the blanks from external factors such as humidity, temperature fluctuations, and contamination. Modern lubrication systems with a permissible temperature range up to about 900 °C are commercially available and have been successfully tested in preliminary investigations during the forming of EN AW-7075. Since these lubricants have a high evaporation point, and consequently no steam or smoke development is to be expected, the installation of an additional suction device would not be necessary.

In order to extract heat from a hot blank quickly and effectively, and to achieve the required cooling gradient, hot forming tools are water-cooled. Since considerable amounts of heat energy have to be extracted from the tools, especially for production with short cycle times, they are connected to cooling units. These units cool a cooling medium to constant flow temperature, typically 25 ± 5 °C, using an open or closed water circuit (Erens, 2010; Lin et al., 2014).

As previously mentioned, the required cooling gradient for EN AW-7075 is about 100 K/s, which is significantly higher than the critical value for boron-manganese steels; but should also be achievable with the most common plant technologies. Here, the temperature of the cooling medium is not as important as the volume flow rate required to quickly extract the process heat from the tool system. An assessment of the performance of existing cooling circuits and units is required to ascertain the suitability of current plants and must be verified in each case. From a process engineering point of view, it is also possible to increase the cooling gradient by measures such as reducing the number of strokes, increasing the pressing forces, or extending the holding times. Thus, production can be carried out with a slightly lower output if necessary in order to avoid complex and expensive modifications to the cooling system.

3.3. *Laser cutting system*

When converting to aluminium processing, the continued use of an existing laser cutting system depends on which laser source is used. In modern systems for cutting press-hardened steel components, solid-state lasers are usually installed. Due to their longer maintenance intervals, simpler beam guidance, and higher efficiency, they are more economical and user-friendly than CO_2 lasers (Arteaga, 01/2021; Isgro, 2016). Solid-state lasers such as fibre or disk lasers are also suitable for cutting aluminium since they are also less sensitive to reflections on reflective surfaces, which can damage the laser (Keller, 2017). CO_2 lasers are, therefore, usually only used for steel sheets with greater sheet thicknesses. Laser powers of 3 kW or more, which are usually used for laser processing systems, are sufficient for cutting aluminium so would present an economically viable solution. In contrast to the processing of steel sheets increased explosion protection requirements must be observed for aluminium due to the cutting dust. Depending on the plant design, it is necessary to retrofit additional extraction and dust disposal devices. Independent of the cutting system, the use of component-specific part holders is essential. The costs for this should not differ significantly from those for a new steel component and are therefore not considered separately. When designing the laser holders, the weakly pronounced paramagnetism of aluminium materials, described in Section 3.1, must be considered. Compared with press hardened steel components, magnetic clamping devices cannot be used, and position or quality checks must be carried out using mechanical or optical sensors.

An alternative to laser cutting is, as with steel in general, trimming in the tool. Here, for example, holes can be shear cut before or during the forming process or final contours can be cut directly before the bottom dead centre of the press is reached by appropriate designs in the tool. Whether such a process can be used depends primarily on the component geometry and the permissible dimensional deviations of the contour line, as well as the requirements for the cutting edge. The forces to be expected for components made of EN AW-7075 are lower than those for press hardening steels due to the lower initial material strength and the material condition that prevails during or after cooling. There are no particular demands on the design of the press regarding sufficient cutting impact damping. Aluminium hot forming, therefore, offers far more potential applications for tool trimming, and at least, the new investment in a laser cutting system can be omitted.

3.4. *Furnace*

As described in the introduction, roller hearth furnaces are classically used for heating press-hardened components; estimates suggest that they account for up to 90% of all furnace technologies in use. The essential design features of these continuous furnace systems are a) the operation mode of the transport system and b) the heating method of the blanks. The requirements of the transport system for the transfer of aluminium blanks are very similar to those used for steel blanks. The characteristic features are:

- a narrow roller pitch for the passage of blanks in various sizes and formats;
- a subdivision of the roller hearth into several individual drives to be able to set the required, sometimes very different speeds, for the entry and passage of blanks especially for the fast material exit; and
- a high level of maintenance-friendliness of the blank modules, as well as their exchangeability during production in order to achieve the highest possible plant availability.

A conversion of the roll transport system for the heating of aluminium blanks is therefore not necessary. As a result of differences in the blank surface, aluminium sheet material may behave differently during transport through a roller hearth furnace, since press-hardened steels are typically coated with an aluminium-silicon or zinc layer. Since aluminium blanks are lacking these coatings and their lubricating properties, slight and superficial damage in the form of scratches or soiling is to be expected with a repurposed plant. Therefore, it may be necessary to refrain from producing outer body components that will be visible with their requirement for high surface quality. Typically, however, the high-strength EN AW-7075 alloys described here are likely to be used for structural components, for which the general high surface finish requirements are low.

In contrast to the roller transport system, the radiation heating used for steel blanks is not suitable for rapid heating of aluminium blanks. Applying the Stefan-Boltzmann law, the power density of thermal radiation is calculated in the 4th power of the absolute temperatures of the furnace chamber and the material to be heated. The significantly lower heating temperature for aluminium blanks and additionally the low radiation value or emissivity of reflecting aluminium surfaces (which is about 20%) would therefore lead to unacceptably long heating times. For blanks with a thickness of 2.0 mm, processing times would equate to approximately 12 min. The Jet-Heating process is better suited for heating aluminium blanks since it provides a very intensive, convective heating using an impingement flow, as shown in Fig. 4.

Jet-Heating technology offers highly uniform and rapid heating of components, in particular for those with simple geometries such as sheets, blanks, or bars. The temperature can be adjusted very precisely without the danger of overheating, which results in high repeatability. Furthermore, as the Jet-Heating system can be easily integrated into existing roller hearth furnaces, it offers a potential solution for retrofitting in existing production lines. The associated lower operating temperatures will also significantly benefit the thermal and mechanical wear and afford a considerably extended operating time.

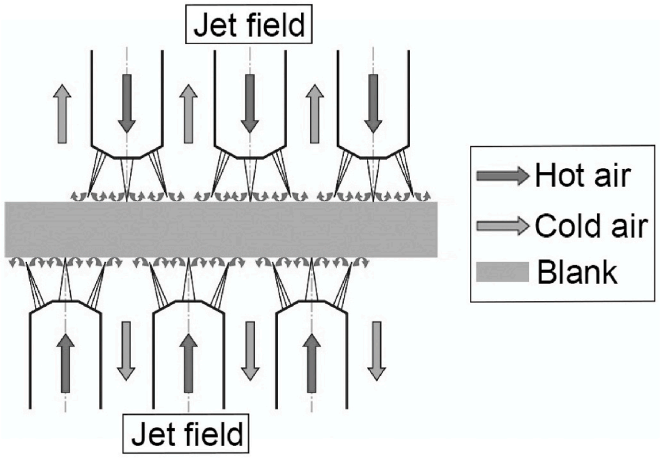

Fig. 4. Functional principle of the Jet-Heating technology for the efficient heating of aluminium blanks.

Especially when high throughput rates are required for heating of aluminium components or blanks, the combination of roller hearth furnaces and Jet-Heating is probably the most efficient solution available at present. Based on the experience of more than 300 furnace systems delivered by the company BSN for comparable applications, the evidence suggests that a successful retrofitting of a roller hearth furnace with this sophisticated heating technology should present few problems.

Fig. 5 shows the equipment of such an adapted roller hearth furnace with 4 nozzle boxes. Although the nozzle fields suspended in the upper furnace area only pressurise the blanks from above (i.e. from one side), short heating times of less than 2 min can be achieved with optimised design. All nozzle arrays are equipped with a circulation unit and a specially controlled heating system. Existing gas burners can be installed in the nozzle boxes and thus, just like the furnace body and the roller transport system, can also be reused. The use of gas emits less CO_2 per kWh compared with electrically derived heat (European energy mix) and thus further increases the environmental efficiency of such reuse (European Environment Agency, 26.10.2021; Quaschning, 2019).

4. Parameter determination for process design

Previous studies identified the heating rate and holding time at solution heat treatment temperature as important factors affecting the strength of EN AW-7xxx sheet material. A higher heating rate results in the material taking less time to reach solution temperature and thus in shorter cycle times. Furthermore, rapid heating results in more precipitates with smaller size and uniform distribution during aging (Liu et al., 2020). Hebbar et al. (2020) demonstrated for EN AW-7020 that a holding time of 5 s at solution temperature is sufficient to reduce hardness to less than half compared with the initial state. Further increasing the holding time did not bring any significant changes. In the context of the associated temperature management, furnace technology plays a crucial role. Radiation or convection heating in a furnace leads to long cycle times and low productivity, even if the sheets are coated. Nevertheless, these heating methods are widely used in the automotive industry due to their availability, suitability for mass production and the uniform temperature distribution (Shao et al., 2018).

Fig. 6 shows the heating curves of EN AW-7075 tensile specimens according to DIN 50125 form H with a parallel length of 75 mm and a thickness of 2 mm. In order to determine the heating profile, the specimens were equipped with thermocouples that monitor temperature values with a frequency of 1 Hz. The measurements were carried out in a convection or radiation furnace, with coated and uncoated specimens. Tensile specimens were chosen for temperature measurement due to the limited dimensions of the furnace chambers. The coating was a (black) heat-resistant liquid lubricant and the furnace temperature was set to 480 °C. Each heating curve shown in Fig. 6 is based on the mean value of three measurements. It can be seen that when using a radiation furnace, the coating has a major impact on the heating time required for reaching the solution heat treatment temperature. Coated specimens reach the target temperature 300 s faster, which corresponds to a time saving of approximately 55%. However, when using a convection furnace, this influence is insignificant (15 s difference for reaching target temperature), which is why bare sheets can be used here.

To increase the heating rate, induction heating and resistance heating methods are commonly used. With regard to aluminium alloys, the latter requires a relatively high power input due to the low electrical resistance of such material (Zheng et al., 2018). Induction heating is also less efficient due to the low magnetic permeability of aluminium alloys and non-uniform temperature distribution issues (Shao et al., 2018). For these reasons, Jet-Heating technology shows a great potential for retrofitting existing furnaces and thus will be investigated in this case study. The Jet-Heating process seems to be more suitable for aluminium blanks, since heating takes place via an intensive, convective impingement flow (see Section 3.4). In order to carry out a realistic and

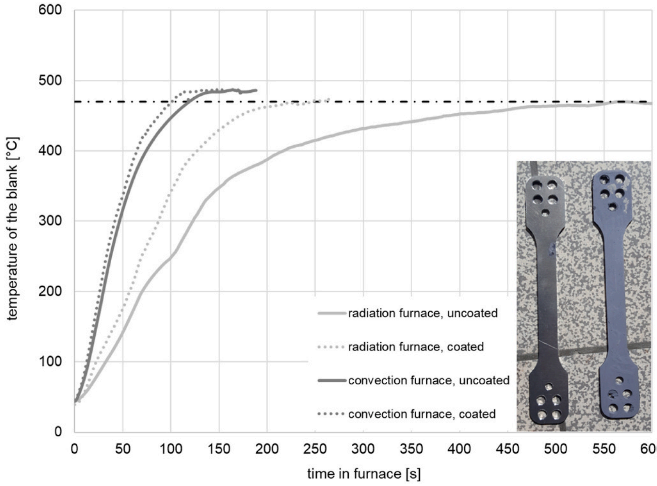

Fig. 6. Heating curves of coated and uncoated EN AW-7075 samples using different furnace types.

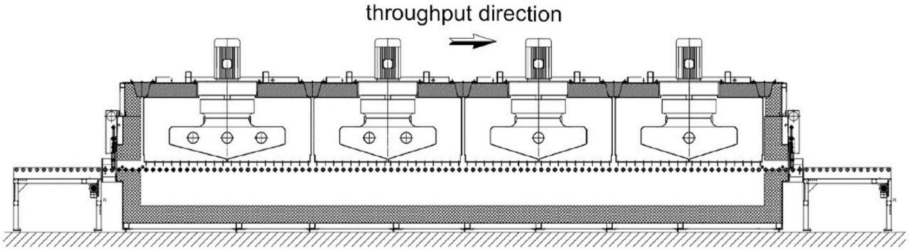

Fig. 5. Longitudinal section of a roller hearth furnace equipped with nozzle boxes.

industry-oriented evaluation of the process variables, rectangular blanks each made of EN AW-7075 with dimensions of 290 × 150 mm and a sheet thickness of 2.0 mm were used instead of tensile specimens. These blanks were heated to at least 460 °C in a test furnace using Jet-Heating technology, kept at temperature with seven different furnace holding times (0, 60, 120, 180, 240, 300 and 600 s) and then quenched in a water bath. To determine an average heating profile three blanks for each furnace holding time were employed; they were equipped with thermocouples that monitored the temperature values with a frequency of 1 Hz. Although the experimental furnace was not a retrofitted roller hearth furnace, but a new continuous strip furnace with one-sided Jet-Heating technology, the basic principle along with the mode of operation and the one-sided heating appropriately represented the setup described in this case study. It can even be assumed that in case of a targeted retrofit of an existing roller hearth furnace for heating of sheet metal even shorter heating times could be achieved, since the distances between the nozzles as well as the distance to the material to be heated were optimised for billets and not for blanks as in the existing test setup.

By way of example, Fig. 7 shows two heating curves of the tests carried out in the experimental Jet-Heating furnace and used to provide a realistic estimation of process cycle times. Measuring curve 1, which represents a short holding time, shows an experiment in which the sample sheet was held for 180 s after reaching 460 °C; measuring curve 2 shows an experiment with a long holding time of 300 s. The specimens passed through an unheated furnace neck of approximately 1 m at the furnace inlet and for this reason the temperature increase in the measuring curves for the first 75–90 s is not representative.

During the pass-through times at the furnace inlet, no active heating of the blanks using Jet-Heating took place. Considering a roller hearth furnace designed for blank operation, it can be assumed that heating gradients similar to those indicated in the theoretical measuring curves shown in Fig. 7 can be achieved. Taking into account the resulting theoretical starting times of 66 s for the short holding time (measuring curve 1) and 47 s for the long holding time (curve 2), the required solution temperature of 460 °C can be reached after 167 s for the short holding time and 174 s for the long holding time curve.

Since the furnace cycle time is not only determined by the heating rate, but also by the holding time at solution heat treatment temperature, the influence of different holding times on the material strength needs to be determined and compared with previous investigations (see Section 2). Therefore, the rectangular blanks heat treated in the Jet-Heating furnace were quenched and stored at room temperature for ten days, and thus reached a stable T4 condition (Gale and Totemeier, 2004). Subsequently, the blanks were cleaned with acetone and a Brinell measurement was carried out according to DIN EN ISO 6506-1 in order to determine the hardness and thus to investigate the influence of the furnace holding time on the material.

A tungsten carbide ball with a diameter of 2.5 mm, a testing force of 62.5 kgf (612,9 N) and a loading time of 15 s was used for the measurement. This test method is particularly suitable for non-ferrous metals such as wrought aluminium alloys. The hardness measuring points were taken in each corner and in the centre of the blank, thus giving a total of 5 hardness values per blank. This procedure was repeated for the 3 blanks per furnace holding time. Afterwards, the blanks were artificially aged at 180 °C for 20 min, which corresponds approximately to the conditions in a cathodic dip painting bath in a production process for vehicle bodies. This treatment was intended to give the sample blanks a T6x state and thus the desired mechanical properties. Finally, the previously described Brinell hardness test procedure was carried out again. Fig. 8 shows the average hardness values of EN AW-7075 sheet material as a function of the furnace holding time and the material state.

Hardness measurements in the T4 state indicate values between 135 and 139 HBW, which can be converted into tensile strengths of 459–472 MPa using a factor of 3.4 as indicated by Heine (2015). This corresponds well with the initial T4 delivery condition of the sheet material. However, it is noticeable that there is no significant difference in the

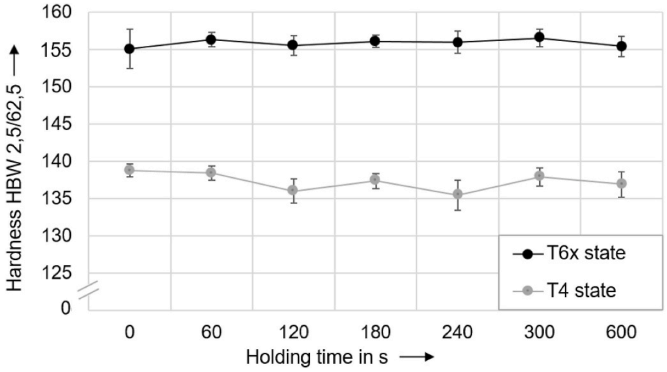

Fig. 8. Hardening results after tests with different holding times.

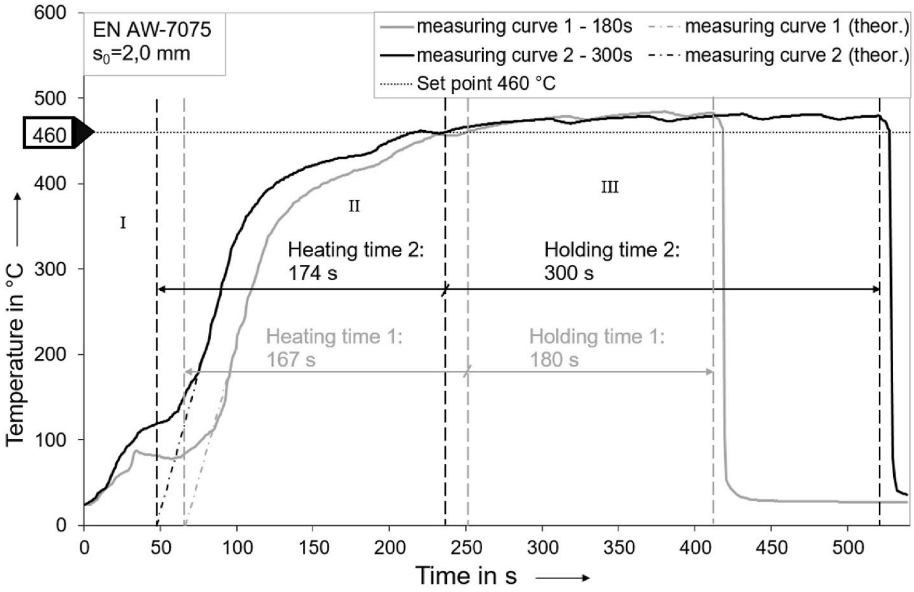

Fig. 7. Heating behaviour of aluminium samples in the Jet-Heating furnace.

hardness values and hence in the strength for an increase in furnace holding times. This corresponds well with the results from Hebbar et al. (2020), in which a holding time longer than 5 s did not cause any further changes in material strength. The same applies to the hardness values in the heat treated state after ageing at 180 °C. These vary between 155 and 157 HBW and can be converted into tensile strengths of 527–534 MPa. Although this does not quite correspond to the maximum hardness of the material (12% reduction compared with the initial T6 condition), the results can be considered as satisfactory due to the realistic ageing process. Further investigations regarding formability and mechanical properties of press-hardening steels (Behrens et al., 2020; Tungtrongpairoj et al., 2009) and high-strength aluminium alloys (Schmiedt et al., 2021; Du et al., 2021) can be found in previous studies.

Since the holding time in the furnace seems to have no influence, the overall furnace time will be determined by the heating time alone and is thus approximately 170 s (Fig. 7). For further considerations, a furnace run-through time of 3 min is assumed as a first approximation. Based on the measurement results, further reductions in throughput time can be achieved in the future, as the distances between the nozzles and the distance to the heated material were not optimised in the experimental Jet-Heating furnace.

5. Component costs in comparison

Using the example of a miniature side impact beam as a reference for small components and a B-pillar as a reference for a large components, a cost comparison between press-hardened steel and aluminium in the hot forming process is made. Based on previous investigations (Schlosser et al., 2017) results are available for the sheet thicknesses required for comparable crash performance, which are scaled accordingly and transferred to the two example components. All assumptions made, such as the lubrication costs or the overall equipment effectiveness, are based on standard automotive industry values. A variation of these values within a typical range was investigated and found to have a negligible impact on component costs due to the assumed delivery volume. All costings can be found in Tables 1–3. The table cells with a white background are based on measurement results (e.g. furnace cycle time) and industry standards (e.g. project framework), while the values marked with a grey background are derived from these figures.

It is assumed that for small components the cycle time is limited by the speed of the automation and the press, so that the difference between aluminium and steel production is mainly due to the lower temperature during aluminium hot forming, leading to an overall shorter cooling time (see Table 1). For the press hardening process of large components and with the assumed furnace throughput, the cycle time is limited by the furnace so that 22 s is estimated here. For the aluminium hot forming process, the faster heating and the significantly shorter furnace holding time result in shorter furnace cycle times; and therefore, as with the small components, an average cycle time of 15 s is assumed. Further differences in terms of availability and maintenance are considered in favour of the aluminium hot forming process due to the significantly lower process temperatures, so that a higher Overall Equipment Effectiveness (OEE) value of 0.75 and 25% lower maintenance costs are reasonably estimated here.

Table 1
Calculation bases for the cost comparison.

Reference part	Small component: Miniature side impact beam		Large component: B-pillar	
Material	22MnB5	EN-AW 7075	22MnB5	EN-AW 7075
Project framework	5 years vehicle lifetime, 400,000 components per year, 4 components per stroke			
Batch size in the furnace [mm]	400 × 1000		1700 × 2300	
Heated furnace chamber [mm]	11,700 × 2000		28,000 × 2500	
Furnace cycle time [s]	300	180	360	180
Heating temperature [°C]	920	480	920	480
Output				
Cycle time [s]	17	14	22	15
Overall Equipment Effectiveness [-]	0.7	0.75	0.7	0.75
Strokes per shift (gross, 7.5 h) [-]	1588	1929	1227	1800
Strokes per shift (net) [-]	1112	1446	859	1350
Components per shift (net) [-]	4447	5786	3436	5400
Components per hour (net) [-]	556	723	430	675

According to the offers of furnace manufacturers, the investment costs for the conversion of existing small furnace systems to the Jet-Heating technology amount to approximately €215,000 (see Table 2). As the size of the components or blanks increases, the conversion of several furnace zones becomes necessary, increasing the costs to €485,000 when a B-pillar is considered. Assuming that depreciated production equipment is continued to be used for the production of aluminium components, no fixed depreciation costs are considered. For the aluminium component, trimming takes place in the tool, while the steel component is trimmed in a 3D laser system, which is why tooling costs are estimated to be 15% higher for aluminium hot forming. In terms of variable costs, the heating costs for small aluminium components are higher despite lower target temperature. This is because only gas costs are taken into account when heating steel components, whereas both gas costs as well as electricity costs of the fans must be considered when Jet-Heating technology is used. In the case of B-pillars, the heating costs of aluminium and steel components are nearly equal, since radiant heating of larger components requires multiple furnace zones and thus a significantly higher gas consumption. Furthermore, the lubrication costs required for aluminium forming are assumed to be €0.02 for smaller components and €0.04 for larger components. In contrast no lubricant is required for 22MnB5 steel material, as the coating layer serves as lubrication.

The material costs for aluminium are based on the average London Metal Exchange (LME) trading price as well as the average currency exchange rate for 2021 (see Table 3). In addition, processing costs for aluminium need to be considered, which include all steps from slab to finished sheet such as rolling, hardening or alloying. Press-hardening steels are not traded on the LME, so an average market end price for 2021 is used here. The material costs per component comprise the material price, the logistic costs per blank and the scrap price resulting from the trimmed material. Component costs are calculated by adding fixed costs, variable costs and material costs per component. Assuming that depreciated production equipment is continued to be used, the resulting component costs in the case of the miniature side impact beam made of aluminium are only 17% higher than for a classic, press-hardened steel component, despite the considerable additional material price of 436%. This is offset by a weight saving of 31% per component. Put in proportion, this would correspond to an additional component price of €2.60 per kilogram saved. In particular, the higher material input for the B-pillar significantly increases variable costs. The higher investment costs for a conversion of a long roller-hearth furnace are reflected in the fixed costs, but are insignificant in terms of the component throughput considered. The almost fourfold component costs are also offset by a weight saving of 31% due to the same sheet thickness ratio, resulting in an additional saving in the component price of €9.54 per kilogram. Given the high material price, a large component with a comparable weight, but without the relevant blank trimming would result in an additional €6.98 per kilogram saved.

If the aluminium components were to be produced on a plant that could no longer be used for the press hardening process due to the significantly higher process temperatures, the costs for plant conversion would have to be compared with a completely new investment, which shifts the cost ratio much further in favour of aluminium hot forming production. As these are purely theoretical considerations, it should be emphasised that more detailed investigations for specific applications

Table 2
Comparison of fixed and variable costs.

Reference part	Small component: Miniature side impact beam		Large component: B-pillar	
Material	22MnB5	EN-AW 7075	22MnB5	EN-AW 7075
Fixed costs				
One-time furnace conversion [€]	0	215,000	0	485,000
Plant depreciation [€/a]	0	0	0	0
Maintenance [€/a]	160,000	120,000	160,000	120,000
Press tool [€]	130,000	150,000	130,000	150,000
Other material (e.g. container) [€]	10,000	10,000	10,000	10,000
Apportionment of fixed costs per component [€]	**0.47**	**0.49**	**0.47**	**0.62**
Variable costs				
Staff [€/h]	292.5	292.5	292.5	292.5
Electricity [€/h]	10	10	11	11
Heating costs per component [€]	0.0066	0.00843	0.0375	0.036
Cleaning [€]	0	0	0	0
Laser trimming per component [€]	1.0	0	1.5	0
Lubrication per component [€]	0	0.02	0	0.04
Apportionment of variable costs per component [€]	**1.55**	**0.45**	**2.24**	**0.53**

Table 3
Calculation of material and component costs.

Reference part	Small component: Miniature side impact beam		Large component: B-pillar	
Material	22MnB5	EN-AW 7075	22MnB5	EN-AW 7075
Material				
Density [kg/dm^3]	7.85	2.71	7.85	2.71
LME [USD/t]		2471		2471
LME [€/t]		2051		2051
Scrap value [€/t]	300	880	300	880
Processing costs [€/t]		2980		2980
Material costs [€/t]	1164	5031	1164	5031
Blank and component				
Length of the blank [mm]	350	350	1550	1550
Width of the blank [mm]	250	250	575	575
Thickness of the blank [mm]	1	2	1.5	3
Components per blank [-]	1	1	1	1
Volume of the blank [mm^3]	87,500	175,000	1,336,875	2,673,750
Weight of the blank [kg]	0.69	0.47	10.49	7.25
Logistics costs per blank [€]	0.05	0.05	0.05	0.05
Trimming share per component [%]	15	15	30	30
Volume of the component [mm^3]	74,375	148,750	935,813	1,871,625
Weight of the component [kg]	0.58	0.40	7.35	5.07
Material costs per component [€]	**0.82**	**2.37**	**11.33**	**34.59**
Total				
Costs per component [€]	2.84	3.31	14.04	35.74
Weight saving by using Al [kg]	0.18		2.27	
Costs per kg weight saving [€]	2.60		9.54	

must be carried out depending on the component requirements, the process, and the existing plant technology and may deviate from the theoretical considerations. Not included in the cost calculation are any additional license fees that may be incurred by the user depending on the selected process routes and materials or coatings.

Finally, the analysis was driven by an approach that examined the technical and financial feasibility of repurposing a plant that was designed to produce steel automotive parts into one that uses aluminium. One should not lose sight of the fundamental and overarching reason for proposing the plant conversion was to reduce the environmental impact of producing vehicle bodies, and to enable the production of lighter vehicles that use less energy throughout their operational life. That said, subsequent work should involve a Life Cycle Assessment (LCA) to examine all stages of the process from cradle to cradle, providing a true measure of the global warming potential. Such a study would provide a quantitative measure of the significance of this and similar repurposing measures relative to the total impact.

6. Conclusion

The European Union's Green Deal aim to be GHG neutral by 2050 provides an imperative that emissions are reduced. Repurposing existing steel hot forming lines can contribute to this objective by saving demolition as well as embodied energy costs of new plants and contribute towards the production of lower priced lightweight vehicles. Based on theoretical considerations, the case study has shown how a manufacturing technology for aluminium alloys, which has not yet finally established itself on the market due to its costs and technological challenges, can be brought into series production using sustainable approaches. For small components with low material input, component costs result that are economically justifiable even in comparison with press-hardened steels. Since the conversion measures are technically feasible and financially viable, future work should investigate further using LCA models to demonstrate benefits by comparing global warming potential with alternative solutions. In practical application, it can be assumed that further optimisations can be implemented and the performance as well as economic efficiency in the production of high-strength aluminium components can be further improved. For example, the use of a cooling stage immediately before forming is conceivable, which would simplify process control even further. Thus, the main points of this case study are as follows:

- When using a radiation furnace, the coating of aluminium specimens has a major impact on the heating time required for reaching the solution heat treatment temperature. However, when using a convection furnace, this influence is found to be insignificant, which permits the use of bare sheets.
- By converting the furnace technology to Jet-Heating, significantly higher heating rates can be realised compared to radiation furnaces. It is shown by means of EN AW-7075 samples that the holding time after reaching the solution temperature has no significant influence on the final strength in T4-as well as T6-states. Thus, the overall furnace cycle time is significantly lower than for press hardening steels.
- The modifications necessary for the forming of high-strength aluminium alloys results in changed requirements for existing production lines, such as in the area of automation. Repurposing those

lines is necessary, but in relation to assumed delivery volumes, the additional costs per component for the converted plant are marginal.
- The cost comparison for the production of components made of the boron steel 22MnB5 and aluminium alloy EN AW-7075 has shown that the additional costs per kg are €2.60 (small component) and €9.54 (large component) when aluminium hot forming is considered. If trimming is optimised, e.g. by using developed blanks, the additional costs per kg saved are reduced to €6.98 even for large components.

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Declaration of competing interest

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