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Warm forming of an AA5754 component for railway vehicle applications

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Abstract

In the present work, the design of the warm forming of a component in AA5754-O for railway vehicle applications is proposed: the increase of the working temperature overcomes the big limitation of aluminium alloys in terms of poor formability. The design of the process started from the characterization of both the mechanical and the strain behaviour of the alloy under investigation: tensile tests and formability tests, carried out in warm conditions (up to 250°C) provided the necessary data to be implemented within the numerical model created with the commercial Finite Element (FE) code Abaqus. The numerical activity was arranged according to an uncoupled thermo-mechanical approach: a preliminary mechanical simulation of the forming process at room temperature was run in order to evaluate the critical regions. Subsequently, thermal simulations of the heating up of both the tools and the blank were conducted to design the heating system in order to achieve a temperature distribution as uniform and close to the target (according to the results of the material characterization) in the blank deformation zone. Nodal temperature distribution coming from the thermal simulation was imported as a boundary condition into the subsequent mechanical step: strain severity was locally evaluated implementing the forming limit curves at different temperatures within the Abaqus FE model. Simulations results were subsequently validated performing experimental trials, confirming the beneficial effect of adopting warm conditions to avoid the risk of rupture: thus a sound component was successfully manufactured.

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Keywords: Aluminum alloys, formability, warm forming, finite element, local heating

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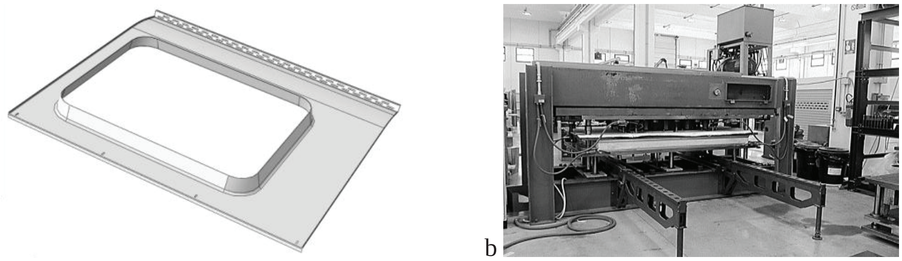
1. Introduction

Harmful emissions from road and railway vehicles are becoming a big source of concern for manufacturer; in addition, the stricter environmental standard framework is imposing to reduce the threshold values for the next future [1]. Such a situation leads to limit the vehicles' weight. One of the most effective way to lightweight vehicles is the massive adoption of light alloys: for example, using aluminium (Al) alloys a strong reduction of both CO_2 and NO_x emissions can be obtained without dramatically decreasing the vehicle performance [2]. Despite lights alloys provide high level of the strength-to-weight ratio, one of their most limiting drawback is the poor formability at room temperature: complex components can be only manufactured through several production steps or, alternatively, joining several sub-parts produced independently. On the other hand, it has widely reported in literature how beneficial for the formability is the increase of the working temperature [3]: in fact, in such a way the material forming limit strains are noticeably improved, so that the manufacturing of complex components becomes possible even in one-step processing. When a differential heating is applied in the peripheral region of the blank, the lower yield level in the flange promotes the material drawing-in [4]. Also in the case of a uniform temperature increase, components with higher shape complexity (like for example the bipolar plate for a fuel cell) can be obtained [5]. In this work, the design of the warm stamping of a AA5754 component for railway vehicle applications is proposed. A preliminary characterization, based on tensile and formability tests, was carried out in warm conditions: experimental data, collected in terms of flow stress and Forming Limit Curves, were implemented within the Finite Element model. The adoption of the numerical approach was an unavoidable step due to (i) the complexity of the process involving a wide number of parameters (both for the heating and the subsequent forming step) and (ii) the necessity of dramatically reducing the no more bearable trial-and-error costs. Numerical simulations were run according to an uncoupled thermo-mechanical approach: the thermal simulations were aimed to understand the most suitable heating layout (number, length and position of the electric cartridges) to obtain a favorable temperature distribution, as uniform as possible, in the deformation zone of a properly designed blank sheet. The resulting nodal temperature distribution was transferred to the subsequent mechanical analyses. The strain severity in the most critical zone was monitored comparing the current value of an output variable (directly available in the post-processing analyses) with the correspondent FLC implemented within the numerical model at different temperature levels. Numerical results were finally validated with the experimental stampings of the real component.

2. The case study

In the present work, the stamping of an inner window panel (2000 mm x 1300 mm, thickness 2 mm) is proposed. A 3D drawing of the component is proposed in Fig. 1a, while in Fig. 1b the stamping machine is depicted.



a b

Fig. 1. Case study: (a) 3D drawing of the investigated component, (b) press machine used for the experimental trials

In the present work, both the heating system of the tools (length and number of the heaters) and the process parameters to perform the warm stamping operation, have been designed.

2.1. Material characterization in warm condition

The alloy under investigation (AA5754) belongs to the group of the strain hardenable Al alloys. Sheets having the thickness of 2 mm and purchased in the annealed condition (O) were used for experiments. The mechanical behaviour in warm conditions was evaluated by means of tensile tests carried out using the Gleeble system 3180 (Fig. 2a). Different temperatures (150, 200 and 250°C) and strain rates (0.001, 0.01 and 0.1 s^{-1}) were investigated (3 replications for each test condition). Specimens, designed according to the International Standard [6], were cut by laser from different orientations (0°, 45° and 90°) in order to evaluate the anisotropic behaviour.

Formability tests were carried out at the same temperature levels of the tensile tests. According to the International Standard [7], 6 different specimen geometries (fig. 2b) were tested adopting an experimental equipment specifically designed and able to deform the specimen through a heated hemispherical punch and to continuously acquire the strain field by means of a Digital Image Correlation (DIC) system.

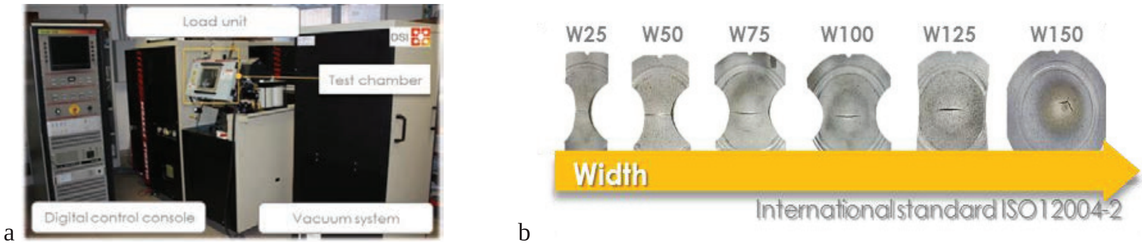


Fig. 2. a) Gleeble system adopted for tensile tests; b) geometries of the specimen adopted for formability tests.

Stress-strain curves coming from the tensile tests were fitted using the Hollomon's exponential law ($\sigma = K\varepsilon^n$) and are shown in Fig.3a. As concerns the anisotropic behaviour, the effect of the temperature resulted to be negligible and it has not taken into account in the numerical simulations. On the contrary, as highlighted in Fig.3b, the effect of the temperature is beneficial on the material formability: FLD_0 (i.e. the critical major strain value in plane strain condition) is shifted upward when increasing the test temperature. In a similar way, the graph in Fig. 3b confirms that increasing the strain rate lead to a decreasing of the material formability [4,8].

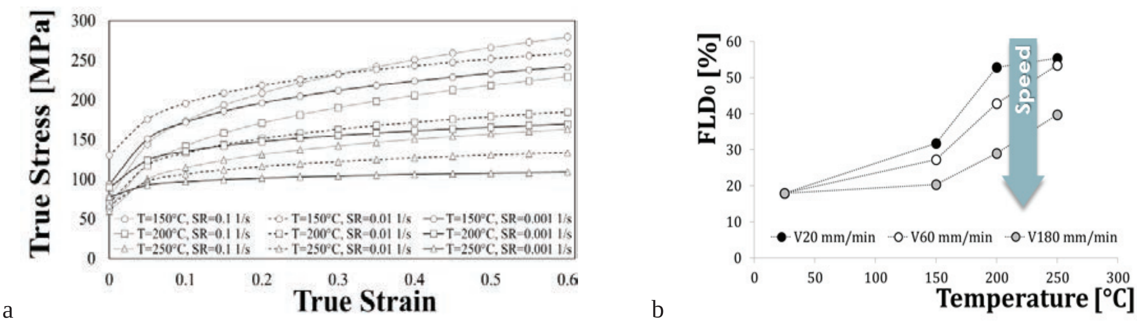


Fig. 3. Effect of the temperature and the strain rate on: a) flow stress curves; b) major strain value in plane strain condition (FLD_0)

3. Finite Element Model

A numerical approach was adopted to define the optimal values of the wide number of involved parameters.

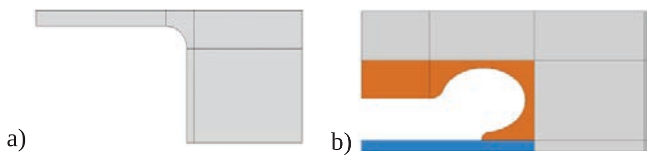


Fig. 4. Simulated blank geometry: a) starting and b) modified blank.

According to results from preliminary simulations, also confirmed by experimental trials, the regions close to the window corners revealed to be the most critical ones. Starting from the blank shape in Fig. 4a, the geometry of the initial blank was modified considering an additional portion (highlighted in orange in Fig. 4b) aimed to avoid fractures by promoting the material flow-in (due to the large portion of the blank under the blank holder, no material flow can occur from the upper part). In addition, a central stripe (blue region in Fig. 4b) was added to improve the contact with the heated punch during the stamping process.

3.1. Uncoupled thermo-mechanical approach

The experimental equipment depicted in Fig. 1b was modelled for the thermal simulations; as shown in Fig. 5a, the symmetry condition was exploited to reduce the computational costs. The heat conduction and the convection with the surrounding environment were taken into account for the steady-state thermal simulations (Fig. 5b).

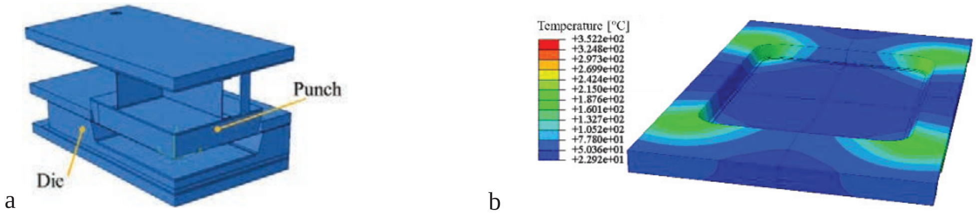


Fig. 5. Preliminary thermal simulations: (a) modelled assembly and (b) temperature distribution in the die

Cartridges were used for heating both the punch and the die; in particular, rod heating elements characterized by a specific power of 0.24 W/mm^2 were adopted for the punch, while elements with a specific power of 0.22 W/mm^2 for the die. Thermal simulations were run changing the number of active heating cartridges both in the punch and in the die: for example, in Fig. 6, different configurations have been compared, each characterized by a different number of heating elements in the die (D) and in the punch (P).

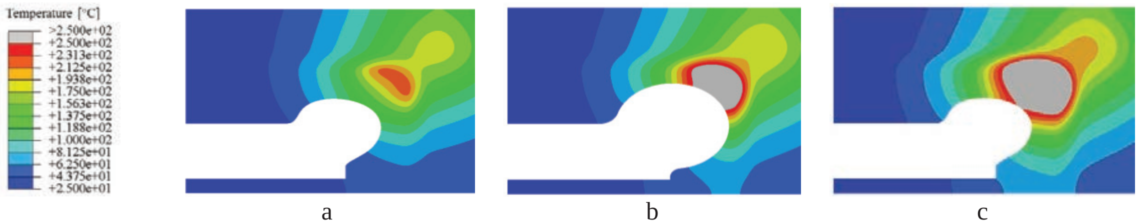


Fig. 6. Temperature distribution when using different heating elements in the die (D) and in the punch (P): (a) 2D-2P, (b) 2D-3P and (c) 2D-4P.

Temperature distributions shown in Fig. 6 allowed to choose the most suitable configuration according to the following considerations: (i) the portion of the blank that had to undergo the highest strain should reach a temperature as close as possible to 250°C (which revealed to be the optimal temperature level according to the alloy characterization); (ii) as specified by the cartridge provider, the maximum temperature of the region where the cartridge is inserted should be strictly lower than 650°C. According to above considerations, the configuration labelled as 2D-2P (2 active cartridges in the die and 2 in the punch) was chosen as the best one, since in the other two investigated conditions the tools temperature (in particular on the punch side) was too close to the limit value. Temperature distribution shown in Fig. 6a was subsequently imported into the forming step as a predefined field for the mechanical analysis (the explicit solver was used, checking that the system kinetic energy was always negligible with respect to the internal energy). Tools were modelled as rigid bodies (element size 30 mm) while blank as a deformable one (element size 4 mm, 5 through-thickness integration points). Material yielding was modelled according to the Hill48 yield function and implementing the anisotropic behavior from the material characterization.

In Fig. 7 the simulation conducted setting the punch speed at the intermediate value of 60 mm/min and superimposing the optimal temperature distribution in Fig. 6a (Fig. 7a) has been compared with the one at room temperature (Fig. 7b). Contour plots show FLDCRT values [9], the Abaqus output variable measuring the distance between the nodal strain condition to the correspondent FLC. It can be noted that stamping in warm conditions allows to successful manufacture the component (the gray region overcoming the FLC is out of the final desired shape, thus not affecting the final quality of the component).

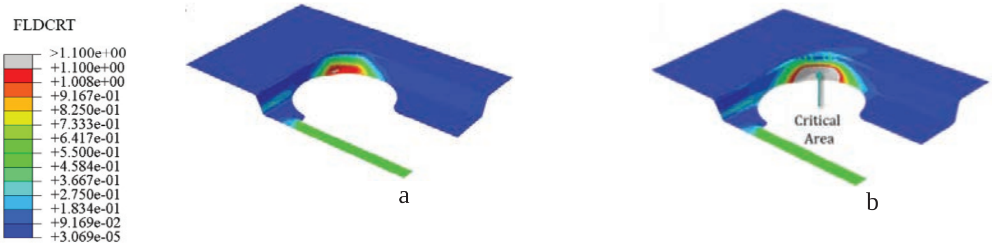


Fig. 7. Effect of the temperature on the FLDCRT map: a) using the heating configuration “2D-2P”; (b) using no heating (room temperature).

The strain rate effect was also simulated: FE simulations were conducted setting the punch to the maximum and minimum punch speed investigated in the formability tests (20 and 180 mm/min, respectively). Contour plots in Fig. 8 show the distribution of the FLDCRT output variable when setting the punch speed to 180 mm/min (Fig. 8a) and 20 mm/min (Fig. 8a), while keeping the temperature distribution unchanged (heating configuration “2D-2P”). It can be noted that the severity of strain in the deformation zone much increased when moving from 20 to 180mm/min.

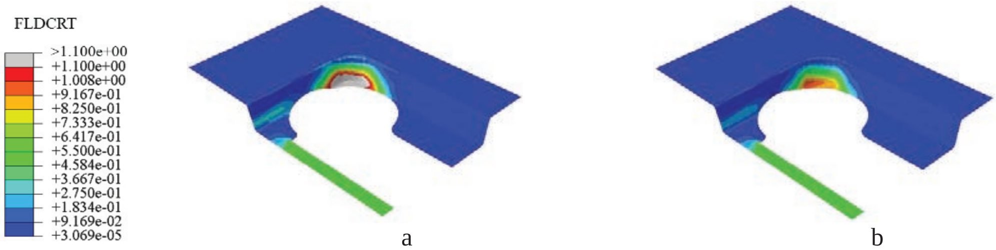


Fig. 8. Effect of the strain rate on the FLDCRT map: a) setting the punch speed to 180mm/min ; (b) setting the punch speed to 20 mm/min.

4. Experimental trials and comparison between numerical and experimental results

Experimental trials in warm conditions were successfully carried out and used to validate numerical results. At first, the results from the FE thermal simulations were validated.

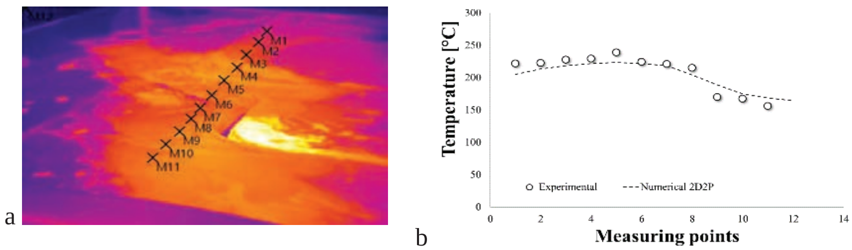


Fig. 9. (a) Image of the heated tools acquired by the thermal infrared camera; (b) numerical/experimental temperature distribution along the path

The heating configuration “2D-2P” was implemented and after 13 minutes heating (being the punch in contact with the undeformed blank), both the tools reached the target temperature of about 250°C in the regions in front of the critical area on the blank; before stamping, the tools were slightly opened to acquire the temperature distribution over the blank by means of a thermal infrared camera (Fig. 9a) and the comparison between numerical and experimental temperatures has been plotted in Fig. 9b. A good fitting between numerical and experimental results was found. Before stamping, both sides of the blank were brushed with a graphite paste to improve the material draw-in. The effect of the punch speed, i.e. the effect of the strain rate the material was subjected during the forming process, was investigated conducting the stamping process at two different punch speeds (60 and 180 mm/min), but keeping the temperature distribution unchanged. In figure 10 the formed parts have been shown.

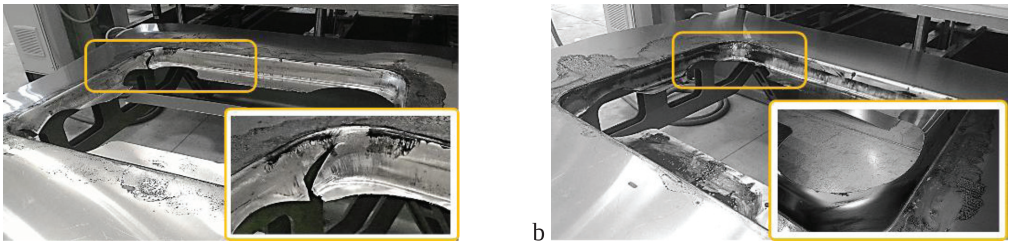


Fig. 10. Effect of punch speed: (a) sound part (punch speed = 60 mm/min); (b) fractured part (punch speed = 180 mm/min)

At the highest punch speed (180 mm/min), the wide critical region predicted by the numerical simulation (see the grey zone at FLDCRT>1.1 in Fig. 8a) is effectively produced on the real part and a visible crack is present; on the other hand, when decreasing the punch speed to 60 mm/min, the sound component shown in Fig 10b could be obtained, as predicted by the numerical model (no grey zone in Fig. 8b).

Conclusions

In the present work the warm stamping of a structural component for railway applications has been designed by means of a numerical/experimental approach. Preliminary thermal simulations were run to determine the best heating configuration to ensure a temperature as closest as possible to 250°C in the critical region. Temperature distributions were imported into a dynamic structural model and the severity of the stamping process was monitored through the FLDCRT output variable. Simulations setting the predicted temperature distribution and changing the punch speed revealed that the adoption of the warm conditions and of a punch speed equal to 20 mm/min led to completely avoid any critical values (i.e. higher than 1.1) of the FLDCRT parameter; when adopting the punch speed of 60 mm/min a small portion overcome the FLC, but it is located out of the final desired shape. Stamping trials, carried out setting the heating system according to the results from the thermal simulations, confirmed that: (i) the predicted numerical temperature distribution can be effectively obtained over the blank; (ii) if reducing the punch speed from 180 mm/min to 60 mm/min, ruptures in the critical region (the corners) can be avoided.

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