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Investigation of material properties of tailored press hardening parts using numerical and physical simulation

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Abstract

In order to assure good resistance performances, automobile manufacturers are looking for high strength steel, especially for structural parts of body in white, which are formed by hot stamping process. With the aim of guaranteeing specific crash behavior, various technologies have been developed to provide tailored properties.

Typical tailored component is the B-pillar, which is studied in this work. In general, the pillar must be with greater resistance in some areas, while in others it must have greater toughness to absorb the energy of a possible impact. The tailored technology investigated in this work is the tailored tempering, in which different areas of the component experience different cooling histories leading to requested final mechanical properties.

The methodology used to investigate custom properties involves a first designing phase implemented with Finite Element (FE) commercial programs; FE simulations were performed to investigate the Press Hardening process of a 22MnB5 boron steel blank and in particular the thermo-mechanical cycles related with both the high-resistance and high-toughness regions of the pillar.

In the second phase of the proposed approach, the obtained thermo-mechanical cycles have been physically simulated, by using Gleeble 3185 system. The following consecutive steps was reproduced on home-designed specimens: (i) Blank heating for the complete austenitization (at a temperature of 930° C for 4 min). (ii) The heat loss due to the transport phase of the blank from the oven to the press. iii) The mechanical deformation of the blank due to the stamping phase. iv) The quenching phase of the part. (v) The cooling on air of the B-Pillar.

Finally, micro-hardness tests have been performed on the specimens subjected to physical simulation. FE model predictions and micro-hardness tests are in good agreement, showing that tailored tempering effectively leads to differentiation of the mechanical properties.

Keywords: Press Hardening; Tailored Tempering; Boron Steel; Finite Element Simulation; Physical Simulation

1. Introduction

In the automotive sector, the demand for new processes to produce high-strength parts with adequate costs and productivity is growing together with weight reduction and safety improvements. The high-strength advanced boron steel responds to these requests but to increase the formability of this alloy, the Press Hardening process is carried out. The direct Press Hardening process involves heating the blank in a furnace and subsequent forming and quenching in closed tool. The quenching phase allows to obtain a completely martensitic microstructure; however, this process could also extend to some components that require greater toughness in some regions. The possibility of realizing differentiated properties in the same part (high resistance in some regions and high-toughness in others) is becoming increasingly interesting because it avoids reaching these objectives by welding several parts or blanks. Typical examples of tailored parts are B-pillars and similar structural components. The automotive industry require that the B-pillar has an area (in general the upper one) with tensile strength up to 1500MPa which is associated with a low deformability (about 5%) obtained with the completely martensitic

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transformation during hot stamping, and a region with more toughness (the lower one), characterized by greater deformability for higher energy absorption and therefore better impact performance [1]. The engineering solutions for the realization of tailored parts that have been proposed over the years have been intrinsic tailored blank (partial austenitization, tailored tempering, partial quenching after process and partial annealing after process), tailored-welded and tailored-rolled blanks [2]. In this work, attention is focused on the tailored tempering methodology. This solution allows to obtain differentiated properties by controlling the time-temperature profile of the blank during the forming and quenching phases in the hot stamping process by adjusting the cooling conditions and the heat transfer between the die and the blank. In fact, a smaller temperature difference between the tool and the blank leads to less heat transfer, lower cooling rate and to a different microstructure. This is possible by creating tools with heating cartridges in one area and with cooling channels in another area; therefore, in the area where the cooling law during the process is more drastic, greater mechanical resistance is obtained. Commercial software such as Pam-Stamp and AutoForm allow an accurate process design and an adequate definition of the Press Hardening process parameters through a thermo-mechanical-metallurgical Finite Element analysis. These commercial software are a powerful tool for the definition of most influent parameters, for the optimization of the process, so for solve different technological problems. Comparisons between the simulation software for sheet metal forming used in the automotive industry have shown that both AutoForm and Pam-Stamp delivery very similar numerical results which are in general in good agreement with the real results. However AutoForm is two times faster than Pam-Stamp and it presents a better virtual productivity due to its pre/post processing environment and features [3]. In this work Pam-Stamp and AutoForm were adopted to simulate a tailored tempering hot stamping process on a B-pillar obtained from a 1.8mm thick sheet of boron steel 22MnB5. In particular AutoForm-Sigma, which is a AutoForm module, was used to analyze and improve the robustness of sheet metal products and processes.

These simulations were carried out in order to define the optimal process parameters that guarantee to obtain the upper part of the component with a completely martensitic structure (500HV) and the lower part with a completely bainitic structure (300HV). The main goal is to simulate the thermo-mechanical cycle on the Gleeble 3185 system and then make a comparison between numerical and experimental results by performing micro-hardness test.

The adopted procedure allows the development of a numerical-experimental methodology capable of accurately designing the hot stamping process.

Nomenclature

t-q	quenching time
t-t	transport time
T-b	temperature tools bottom

2. Method

The Press Hardening process of the B-Pillar PamStamp case of study proposed in [4] has been studied with a numerical-experimental methodology. Both Pam-Stamp and AutoForm-sigma programs were used to define process parameters that allow customized properties of the part with a tailored tempering approach. FE simulation were performed on 22MnB5 boron steel blank of 1.8mm thick.

Numerically simulated thermo-mechanical cycles were imported into the Gleeble system. These cycles were evaluated in some points of most resistant and ductile regions of the P-Pillar.

Subsequently, microhardness tests were performed to experimentally verify the results obtained from the numerical model.

2.1. FE Simulation of Press Hardening process

FEM model was developed to simulate heating, transport, stamping, quenching and cooling on air phases of Press Hardening process. Process parameters were optimized to perform high-resistance and high-toughness respectively in the upper and lower regions of the B-Pillar; these conditions avoid intrusion and absorb energy during a possible impact. Tools, in particular die and punch, have been both modeled in two parts, as highlighted in the Figure1 with the aim of implementing tool tempering approach. Furthermore, the contact between tools and blank has been modeled as “tool clearance after forming”. This means that the contact depends on the thinning of the sheet. There will be less heat transfer where thinning is greater and in areas where contact pressure is lower.

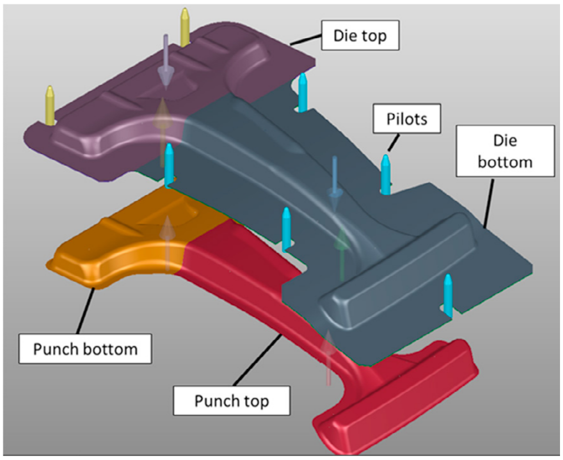

Fig. 1. Tools.

It was decided to keep the tools in contact with the upper part of the blank at a temperature of 80°C useful for obtaining a martensitic structure, while the tools in contact with the lower part at a temperature between 400°C and 450°C.

In order to identify optimal process parameters for obtaining a component with the desired properties, the influence of the bottom tool temperature, the transport time and the quenching time was studied using AutoForm-Sigma environment.

The time quenching was varied between 10s-20s and the time transport was varied between 5s-10s.

In industrial applications, the transport time is generally close to 5s in order to reduce the cycle time and to avoid high temperature drop due to the convection of the sheet with the air; in fact the components are stamped when the sheet has austenitic structure. However, longer transport times were investigated to evaluate the possibility of obtaining a bainitic structure in the ductile region of the B-Pillar.

By varying these process parameters it was possible to estimate, thanks to a specific algorithm for the Phase Change Plug-in implemented in FE software, the hardness values and the phase percentages of the stamped component. This internal algorithm takes into account the CCT and isothermal TTT diagrams, considering also the effects of dynamic recrystallization.

The AutoForm-Sigma analysis in regions A and B (Figure 2) has proved that to obtain a bainitic microstructure it would be necessary increase tools temperature until 425°C at least and increase quenching time. The increase in transport time, in the investigated range, doesn't influence the hardness in bottom part but lead to undesirable hardness value in high resistant zone for a partially martensitic structure. These comments are clarified through metamodels obtained with the kriging method using FE results. Hardness values resulting from FE simulation were used to calculate the hardness corresponding to different regions of the B-Pillar, by averaging the hardness of some nodes included in the region (Figure 2). Regions A and B are representative respectively of the high-toughness and high-resistance parts of the B-pillar. Regions C and D are near the side walls of the component and they have been considered to evaluate the hardness uniformity between regions with the same mechanical properties.

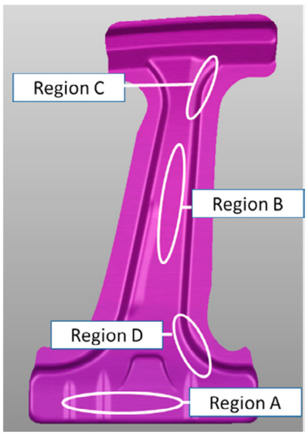

Fig. 2. Regions of the B-Pillar on which the numerical study was conducted.

Figure 3 shows the influence of the bottom tools temperature and the quenching time on the hardness of the lower side of the B-Pillar.

In Figure 4, on the other hand, the influence of the transport time and the quenching time on the hardness of the upper part of the B-Pillar is shown.

In Figure 3 it is possible to observe that the hardness of the lower part is more influenced by the tools temperature (punch and die bottom). An increase of tool bottom temperature parameter leads to a reduction in hardness, i.e. an increase in the percentage of the bainitic phase and therefore greater ductility. For the upper part, rather, an increase of transport time carries to a reduction of hardness. However for this part, a martensitic structure is desirable to ensure high resistive capacities; therefore a lower transport time is preferred.

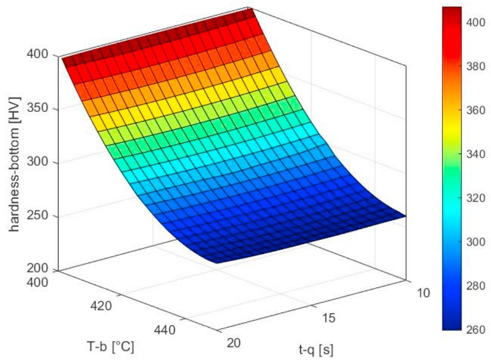

Fig. 3. Metamodel of hardness=f(T-b, t-q) for the bottom side of B-Pillar.

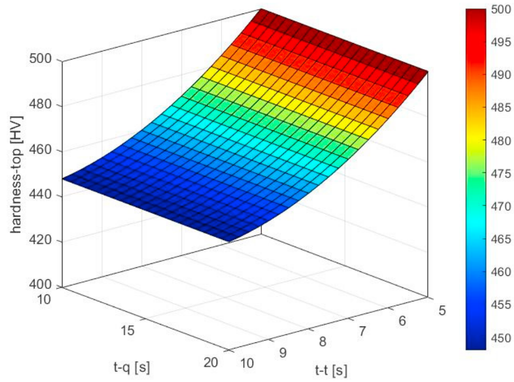

Fig. 4. Metamodel of hardness=f(t-t, t-q) for the top side of B-Pillar.

The choice of process parameters that allowed to have a tailored component with bainitic and martensitic zone was carried out by minimizing the hardness in the lower part and maximizing the hardness in the upper one.

The results show that to obtain a hardness between 450HV ÷ 500HV in the upper part of the component (completely martensitic structure) it is necessary to impose the least transport time (5s). On the other hand, to have a hardness between 250HV ÷ 300HV in the lower part (completely bainitic structure) a maximum tool temperature of 450°C is desirable. However, for energy saving reasons, a temperature of 425 °C was chosen which guarantees the desired properties.

By choosing a transport time of 5s, a lower tools temperature of 425 °C and a maximum quenching time of 20s, the FEM results showed that the hardness values are almost similar in regions C and B. Instead, there is a substantial difference for regions A and D (in region D there are about 15HV less than in region A). The microstructure is uniform and completely martensitic in regions B and C, while it is not uniform in regions A and D. In fact, in region D the final structure is partially bainitic (79% bainite, 21% martensite) compared to region A completely bainitic (100%).

The numerical simulations also show that in the bottom side of the B-pillar, the bainitic transformation is completed during cooling in the air. In fact, at the end of the quenching phase, the structure is austenitic-bainitic (89% austenite, 12% bainite in region A and 50% austenite, 50% bainite in region D).

Figures 5a and 5b respectively show the microstructural phase percentages at the end of the quenching phase and at the end of the process.

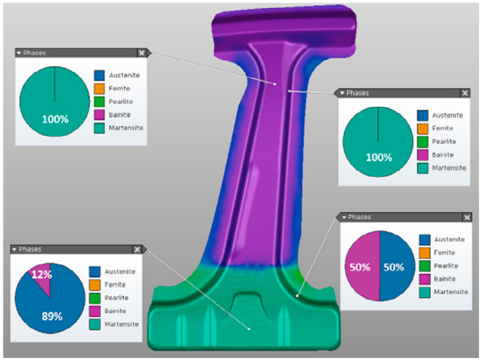

Fig. 5a. Pie chart of microstructure percentages at the end of the quenching phase.

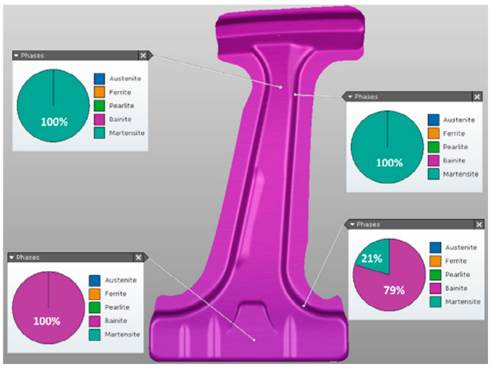

Fig. 5b. Pie chart of microstructure percentages at the end of stamping process.

To better understand the observed results, the thermo-mechanical cycles of the region B and C (Figure 6) and those of the two regions A and D (Figure 7) were examined.

Maximum plastic strain of A and B regions as well as of C and B regions are similar.

Thermal cycles of the four investigated regions are comparable until the end of the drawing phase, that ends when there is the maximum plastic strain. No appreciable difference there are between thermal cycles of B and C regions also in quenching and air-cooling phases, except for less drastic cooling near the walls.

On the contrary, Figure 7 shows that during the quenching, due to the loss of contact between blank and tools, the temperature near the wall D starts to drop below 400 °C (starting point of the martensitic transformation).

The decrease of heat exchange due to a reduction of pressure on the walls perpendicular to the working direction is not evident for the upper part of the B-Pillar. This happens because immediately after drawing phase, the temperature drops below

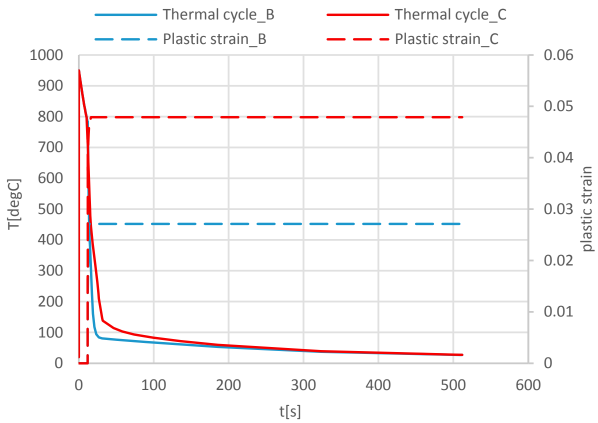

Fig. 6. T(t), ε(t) for the top side of B-Pillar (regions B, C).

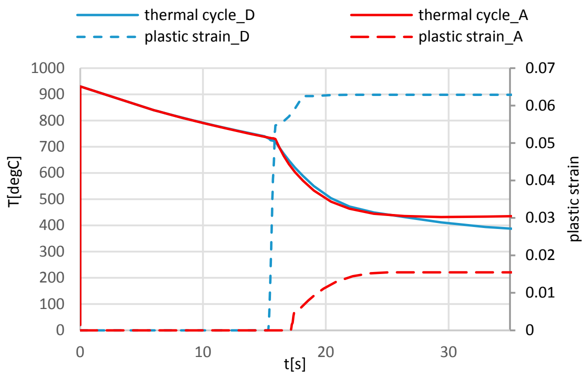

Fig. 7. T(t), ε(t) for the bottom side of B-Pillar (regions A,D).

400 °C, by obtaining martensitic transformation.

The thermal cycles shown in Figure 6 and Figure 7 were then imposed on the Gleeble system to verify the numerical results with the experimental ones.

2.2. Experimental test

To physically simulate the Press Hardening process, the Gleeble 3180 system was adopted (an overview of the experimental set-up is proposed in Figure 8. Experimental tests were performed by using machined shaped 22MnB5 sheet specimens of 1.8mm thick. The Figure 9 shows a specimen used in the experiments. For the preparation of the test, thermocouples were welded on the surface of the specimen in the central point (control point) and at different distance from

the same (5mm, 10mm, 18.5mm) along longitudinal specimen direction. These thermocouples have allowed to measure thermal gradient during the tests.
In order to have uniform temperature in the center of the specimen, a proper specimen geometry was designed (Figure 9) and an appropriate gripping system in stainless steel was adopted (Figure 10). The less conductivity of the grip material, in addition to the grip geometry which have grooves designed to reduce the heat exchange surface with the specimen, ensured a more uniform thermal gradient with respect to that obtained using the classical grip system without grooves and in copper material.

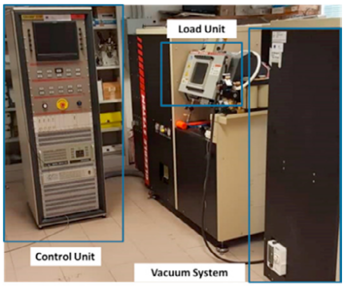

Fig. 8. Experimental set-up for Gleeble system.

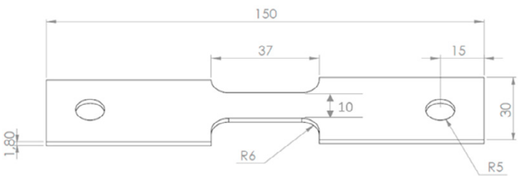

Fig. 9. Geometry of Gleeble specimen.

Fig. 10. Grip Gleeble.

During each Gleeble test, the sample was heated by exploiting the Joule effect induced on the sample by a modulated current flow based on the temperature acquired from a k-type thermocouple directly welded in the control point.

The imposed thermal cycle includes:

- Heating up to 705 °C with a heating rate of 10K/s, followed by heating up to the full austenitizing temperature (930 °C) with a heating rate of 5K/s;
- keep at 930 °C for 4 minutes to homogenize the austenitic structure;
- Thermo-mechanical cycle obtained from the numerical model which simulates the transport, drawing, quenching and cooling on air phases.

Air forced system was used to reproduce the quenching phase characterized by high cooling rate.
With the aim of experimentally verifying the FE results, Qness microhardness tester was then adopted, performing Vickers tests on the specimen surface after its grinding and polishing. Microhardness tests were performed by adopting a load equal to 1kg with a dwell time of 5 seconds. For each sample, microhardness tests were performed along the longitudinal path and along a path parallel to the previous one at 2mm distance. The two paths were realized with a pitch of 1mm.

3. Results

Three Gleeble tests were realized for each thermo-mechanical cycle corresponding to the investigated regions and hardness results were mediated in order to obtain for each region a single hardness profile along the longitudinal direction of the Gleeble specimen. The Figure 11 highlights the two hardness profiles corresponding to the Gleeble tests obtained imposing in the control point the thermo-mechanical cycles of A and B regions.

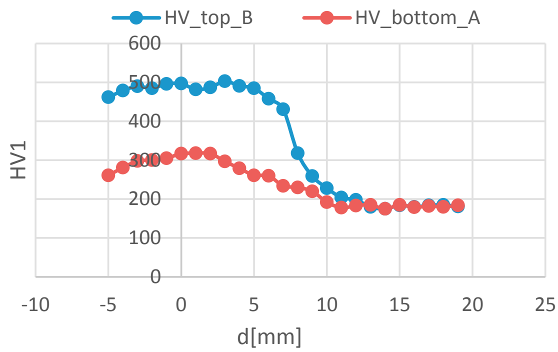

Fig. 11. Comparison hardness results between thermo-mechanical cycle region B and region A.

Both hardness profiles are presented with the origin in the point where the control thermocouple was welded, so that it is possible to rapidly compare the effects of the two different thermo-mechanical cycles imposed in the control point. Hardness differences in this point are because at the end of Press Hardening process the A region is fully bainitic (about 300HV), while the B region is fully martensitic (about 485HV). These hardness values are very close to those numerically estimated that differ of about 3% for the B region and 1% for the A region. Moreover hardness profiles show a low hardness variation around the control point for an amplitude of about 5mm. This can be justified by the chosen gripping system which creates, as verified by temperatures recorded by the welded thermocouples, a low thermal gradient near the center of the specimen.

Figure 12 compares hardness profiles in the longitudinal direction of the specimens obtained imposing the thermo-mechanical cycles of the A and D region.

In the same figure the hardness numerically estimated in the two regions of the B-Pillar more-toughness zone are shown.

For the numerical results, the error bands indicating the variability of data with respect to the average value for regions A and D were highlighted.

Considering the hardness numerical values in correspondence of point in which the control thermocouple was welded, it is possible to observe that the hardness is lower of about 20HV for the specimen subjected at thermo-mechanical cycle of region D. This is justified by different thermal history of these two cycles. In fact, the numerical results envisage a completely bainitic structure in region A and a partially bainitic structure with 21% martensite in region D.

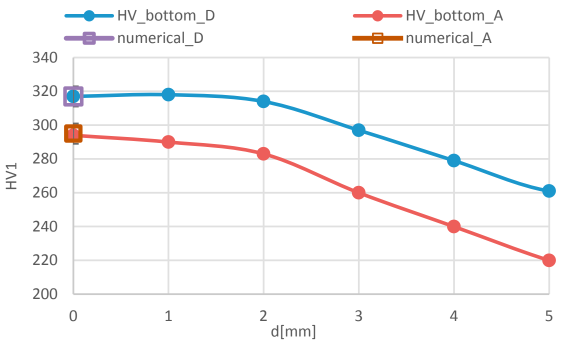

Fig. 12. Comparison hardness values obtained by imposing thermo-mechanical cycles in region A and D.

This result agrees with what highlighted in the Figure 7. In fact, in region D during quenching, given the hypothesis of "tool clearance after forming", there is less heat transfer in areas that are perpendicular to the stamping direction. This leads to a temperature drop below 400 ° C after the quenching phase which causes the transformation of the residual austenite into martensite. The presence of martensite at the end of cooling on air phase is linked to the incomplete bainitic transformation in the quenching phase.

This result shows that in the tool tempering approach, it is very important have a sufficient quenching time in order to obtain a complete bainitic structure. For example respect to the optimized solution, a complete bainitic structures in A and D regions is observed increasing the quenching time from 20s to 200s.

Tailored tool tempering approach would lead to longer cycle times than those typical of the classic Press-Hardening process.

4. Conclusions

This work leads to following conclusions:

- Numerical simulation showed that the tool tempering approach allows to obtain a component with tailored properties. The analysis with AutoForm-Sigma allowed to observe that the hardness of the lower part of the B-Pillar is mainly influenced by the quenching time and the temperature of the lower tool. The hardness of the upper part of the B-Pillar, however, is influenced by the quenching time and the transport time.
- The physical simulation has proved to be a valid tool for the experimental verification of the results estimated with the numerical simulation.
- The microstructure of the part region with greater toughness is sensitive to the contact loss among this part region and tools, and the contact loss increase by greater sheet thinning and lower contact pressure. In these part regions homogeneous microstructures are obtained by increasing quenching time.

Acknowledgements

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