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Process Window Definition to Predict Mechanical Properties of Press Hardened Parts of Boron Steel with Tailored Properties

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Abstract. Tailored Tool Tempering (TTT) is an innovative method able to calibrate the strength and ductility characteristics of the components manufacture by means of Press-Hardening process. The process parameters that most influence the final mechanical properties of the soft zone are quenching time and temperature of the heated tools.

In this work, with the aim of defining a process window to estimate the soft zone properties of an automotive B-pillar in Usibor®2000 steel using TTT Press-Hardening approach, the strength and ductility of the soft zone are studied varying the quenching time and the temperature of the heated tools. Using a numerical-experimental approach, a Finite Element (FE) model is firstly developed in AutoForm to simulate the TTT Press-Hardening process and to define thermo-mechanical cycles that are characteristics of the soft zone as a function of quenching parameters (quenching time and temperature of the heated tools). FE thermo-mechanical cycles are then physically simulated on Usibor®2000 specimens using Gleeble 3180 system. The treated specimens are subsequently subjected to micro-hardness and tensile tests. Experimental results are adopted to train an artificial neural network used to construct the process window.

Introduction

The Press-Hardening process is increasingly used in the automotive sector to manufacture structural components with high mechanical strength. Generally, high-strength steels are used, as such materials allow to reduce the components thickness, respecting the trend to lightweight constructs, guaranteeing at the same time a high safety [1 – 4]. The classic direct Press-Hardening process involves: (i) the heating of the blank in the oven to the temperature of complete austenitization, (ii) the transfer into the die, (iii) stamping, (iv) quenching and (v) cooling at room temperature. During quenching phase, transformation from austenite to martensite occurs when a cooling rate greater than 27 K/s is respected [1, 5]. In addition to the high mechanical strength provided to the components at the end of the process, this technology offers good formability, lower springback and it requires lower forming load [6,7]. However, a negative aspect of the classic Press-Hardening process is the low ductility of the component.

To improve crash performances, a new technology called Tailored Press-Hardening has been developed [8]. The key idea of this technology is to obtain components with optimized mechanical properties. The most used industrial approach is the Tailored Tool Tempering (TTT) one. This approach involves a partial quenching of the component, thanks to a differentiated heating of the tools. This is possible by realizing tools with heating cartridges in one area and with cooling channels in another area. Greater mechanical strength is obtained in the area subjected to a drastic cooling law, while greater ductility is reached in the area where the cooling law is less drastic [8].

Process parameters (e.g., blank heating temperature, transfer time in die, quenching time, tool temperature, blank thickness) are crucial for the Press-Hardening process. In fact, these process parameters affect the final microstructure and mechanical properties of the component. For this reason, it is necessary to design the process correctly so that the desired mechanical properties can be achieved. To support the design, several researchers have developed Finite Element (FE) models that allow to estimate the mechanical properties of the component at the end of the process. Abdollahpoor et al. [9] developed a thermal-mechanical-metallurgical model to investigate microstructure sensitivity and hardness for different input parameters such as tool temperature, punch speed, contact pressure, friction coefficient, tool conductivity. George et al. [10] developed a FE code in LS-DYNA to predict hardness on a B-Pillar component as a function of tool temperature. Moreover, Cui et al. [11] developed a numerical model for hot stamping process to study the effect of the number of process cycles and holding time on the microstructure. Akerstrom and Oldenburg [12] used a model based on Kirkaldy's equations to predict the austenite decomposition into perlite, ferrite, bainite and martensite. This model was implemented in the FE software LS-DYNA to evaluate hardness and microstructure at the end of the process. Later, Zhang et al. [13] established a theoretical model for phase transformation of USIBOR®1500 based on Kirkaldy-Venugopalan model. They exploited the theoretical model to estimate the martensite fraction on the formed part at the end of Press-Hardening process, which was numerically simulated in DYNAFORM. Kim et al. [14] used FE simulation coupled with quench factor analysis to determine the process window adopted to predict hardness for different quenching time and tool temperature. In general, current scientific research aims at improving the prediction of mechanical properties by combining numerical simulations with experimental investigations. For this purpose, research is studying the use of Gleeble system to physically simulate (at the laboratory scale) thermo-mechanical Press-Hardening cycles. Palmieri et al. [15-16] performed FE simulations of the hot stamping process of a B-Pillar component with tailored properties. Numerical thermo-mechanical cycles were then extrapolated from FE simulations and physically reproduced on USIBOR®1500 specimens by means of Gleeble system. Finally, Gleeble specimens were subjected to hardness tests to compare FE prediction of hardness with experimental data. Moreover, Hagenah [17] used Gleeble system to reproduce a hot stamping cycle with the aim of evaluating how the tensile strength varies with the cooling rate and the true plastic strain.

In this work, numerical simulation is combined with physical simulation to obtain a process window for estimating the soft zone properties of an automotive B-pillar in Usibor®2000 steel using TTT Press-Hardening approach. With this goal, the strength and ductility of the soft zone are studied varying the quenching time and the temperature of the heated tools. Using a numerical-experimental approach, a FE model is firstly developed in AutoForm to simulate the TTT Press-Hardening process and to define thermo-mechanical cycles that are characteristics of the soft zone as a function of quenching parameters. Thermo-mechanical cycles are then physically simulated on Usibor®2000 specimens using 3185 Gleeble system. The treated specimens are subsequently subjected to micro-hardness and tensile tests.

Materials and Methods

In this study, the investigated material is Al-Si-coated boron steel, specifically USIBOR®2000, with a thickness of 2 mm. The chemical and mechanical properties are listed in Table 1 and Table 2, respectively [18].

Table 1. Chemistry max [%] for USIBOR®2000

Material	C	Mn	Si	B
USIBOR®2000	0.36	0.80	0.80	0.005

Table 2. Mechanical properties for USIBOR®2000

Material	Yield stress [MPa]	Tensile strength [MPa]	Elongation [%]
USIBOR®2000	≥ 1400	≥ 1800	5

The microstructure of as-delivered blanks consists of homogeneously distributed ferrite and pearlite, whose hardness is approximately equal to 175 HV2.

USIBOR®2000, has been recently added to the family of ultra-high strength steel, it is produced modifying some chemical characteristics of USIBOR®1500 steel. Compared with the firstgeneration, the new products increased by 30% in strength, reaching up to 2000 MPa; moreover, it could bring 10 to 15 percent weight savings compared to existing hot stamping solutions.

In this work, this new press hardened steel has been investigated to manufacture an automotive B-Pillar by means of Press-Hardening process with TTT approach. The adopted methodology is described in the following points:

(i) FE model to simulate the Press-Hardening process of a B-Pillar with the TTT approach has been developed with the commercial software AutoForm R10. Thermo-mechanical cycles as a function of process parameters have been obtained from FE model in the soft zone. The process parameter investigated are quenching time and temperature of heated tools since these parameters are that most influence the ductility of the part as demonstrated in the previous work [15-16].

(ii) Thermo-mechanical cycles obtained from FE model have been implemented in Gleeble 3180 physical simulator and experimentally simulated in the central zone of USIBOR®2000 specimens 2 mm thick. The geometry of a Gleeble specimen is illustrated in Figure 1.

(iii) For each thermo-mechanical cycle, six Gleeble tests have been performed. Three specimens tested by Gleeble have been used for micro-hardness tests. The other three specimens have been destined for tensile tests after a preliminary cross section reduction by machining of the specimen central zone, in order to allow strain localization in that zone during tensile test. The geometry of the specimen adopted for tensile tests (notched specimen) is shown in Figure 2.

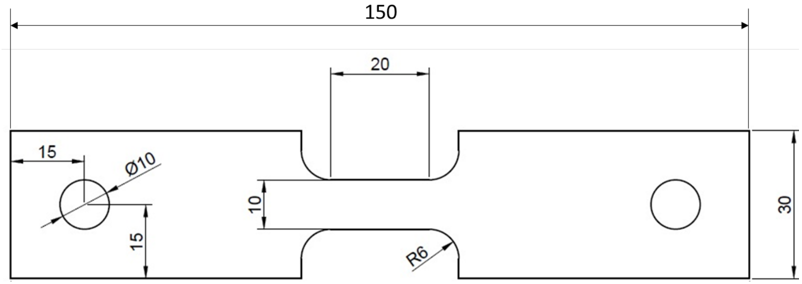

Fig. 1. Geometry of specimens adopted for Gleeble tests

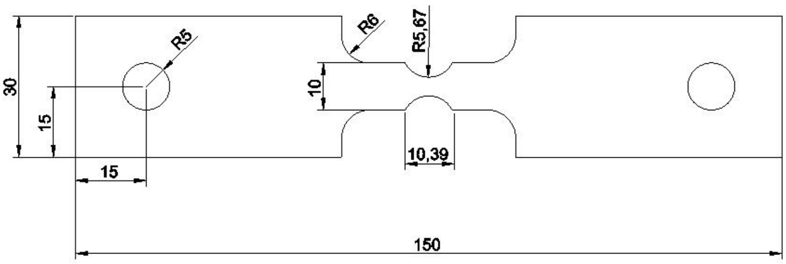

Fig. 2. Geometry of specimens (notched specimen) adopted for tensile tests

(iv) The results of the hardness and tensile tests on the specimens treated by physical simulation allow to obtain a process window that estimates the mechanical properties achievable in the soft region of the B-Pillar for each combination of the quenching parameters investigated. This process window has been derived by means of artificial neural network (ANN).

FE – model of Press-Hardening process

With the aim of defining a process window for the estimation of the soft zone properties of an automotive B-pillar in Usibor®2000 steel using TTT Press-Hardening approach, in this work the strength and ductility of the soft zone are studied varying quenching time and the temperature of the heated tools. To evaluate the effect of these quenching parameters, the range of temperature for heated tools is from 430 °C to 500 °C and the quenching time from 20 s to 250 s.

A Finite Element (FE) model is developed in AutoForm R10 to simulate the TTT Press-Hardening process. Details on the FE model are given in reference [16]. Some tools have been modeled in heated and cooled parts, with the aim of implementing TTT approach. The contact between tools and blank are modelled as ideally adapted, this means that the temperature distribution is more homogenous. The conditions of FE simulation are summarized in Table 3.

Table 3. Conditions for FE simulations

Parameters	Values
HTC (Heat transfer coefficient) [mW/mm^2*K]	3.5 with a scaling factor as a function of pressure
Friction coefficient	0.45
Quenching force [kN]	$1.2*10^4$
Forming velocity [mm/s]	200
Temperature of cooled tools [°C]	80
Temperature of heated tools [°C]	430 °C – 465 °C – 500
Temperature of blank [°C]	930
Transport time [s]	7.5
Quenching time [s]	20 – 110 – 150 – 200 – 250

The described FE-model has been adopted to obtain the thermo-mechanical cycles characteristics of the soft zone as a function of quenching parameters.

Artificial Neural Network (ANN) modelling

The purpose of the developed ANN model is to create a process window to predict mechanical properties of low strength regions of B-Pillar component for different values of quenching parameters. A two-layer feed-forward neural network with sigmoid hidden neurons and linear output neurons have been considered. Figure 3 shows a schematic diagram of neural network. In particular, for this case study, the ANN model is characterized by two input parameters that are quenching time and temperature of heated tools, and three output parameters that are hardness (Hardness), ultimate tensile strength (Tensile strength) and elongation (Rupture deformability). The number of neurons in the input and output layer is equal to the number of input and output parameters, respectively. Finally, a single neuron is chosen for hidden layers. If too many neurons in the hidden layers are chosen, overfitting problem can occur.

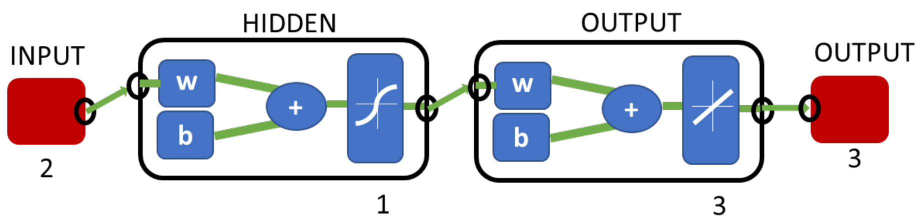

Fig. 3. Diagram of neural network

A random initial distribution of weights has been implemented. The available data set has been divided into three parts: training, validation and testing data. The ANN model has been trained using 80% of the total data randomly selected, while the remaining data 10% has been used for validation and the other 10% for testing. The training set is used to train the network. Training continues as long as the network continues improving on the validation set. The test set provides a completely independent measure of network accuracy.

After being trained, the ANN model can map the relationship between quenching parameters and mechanical properties of the B-Pillar soft zones. Then, it can be used as process window to predict mechanical properties for combinations of process parameters not yet investigated or to choose quenching parameters to achieve certain desired mechanical properties. To verify the reliability of neural network results, new combinations of process parameter has been used to realize FE simulations that allow to obtain new thermo-mechanical cycles to physically simulate by means of

Gleeble system. Finally, experimental results of hardness and tensile tests have been compared with neural network prediction.

Experimental Procedure

For the physical simulation of the numerical thermo-mechanical cycles extrapolated from FE-model of Press-Hardening process with TTT approach, a Gleeble-3180 system has been used (Fig. 4a). The temperature has been controlled by four Ni/Cr–Al thermocouples, which have been positioned by spot welding on the specimens' surface (Fig. 4b).

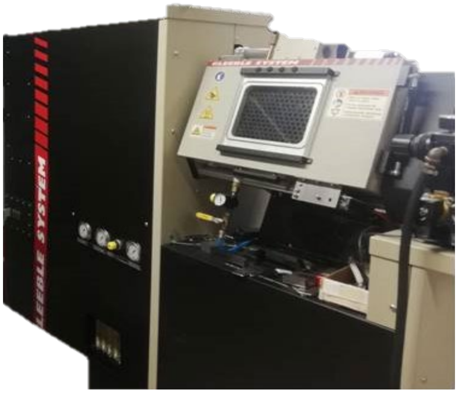

Fig. 4a. Gleeble-3180 system

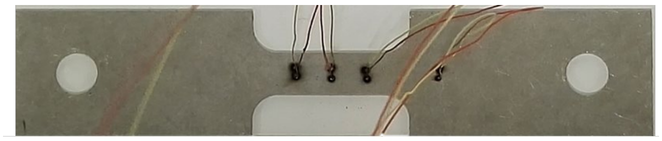

Fig. 4b. Specimen in USIBOR®2000 with thermocouples welded on its surface

In the Gleeble system, the specimen is heated by Joule effect and the current flow is modulated by a proportional–integral–derivative (PID) closed loop controller able to minimize the difference between the target temperature and the one acquired by the piloting thermocouple, which is the one welded in the specimen center.

The imposed thermo-mechanical cycle includes:

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

To physically simulate also the drawing phase, hydraulic piston has been connected to the grip system. Moreover, a L-strain transducer has been adopted to measure the length change within the specimen zone characterized by uniform thermal gradient and a strain control mode has been imposed.

During physical simulation tests the specimens are clamped by cooled jaws; therefore, the temperature decreases moving from the center towards the grips. A parabolic temperature distribution is present along the specimens. As a consequence, only in the area where there is a uniform thermal gradient (about 4 °C/mm) the recorded thermal cycle coincides with the set one. The width of this area is approximately equal to 10 mm. Then, beyond this zone, the temperature profiles are different from set ones. Because of the aim is to verify the influence of thermo-mechanical cycles, for different quenching parameters, on the mechanical properties, hardness tests have been carried out only in the uniform gradient area. Furthermore, due to the operating principle of the Gleeble system, the different thermal cycles along the axial direction of the specimen lead to a different final microstructure. If the same specimen geometry adopted for physical simulation tests is used for the tensile tests, the specimens would always break in the ferritic-pearlitic zone, i.e., in the zone where the thermal cycle has not altered the material microstructure (near cold grips). To avoid this problem, a notched tensile specimen has been adopted (Fig. 2). In this way, plastic deformation is forced exactly in the central specimen zone.

For hardness tests the fully automatic Qness Q10+ hardness tester with load of 2 kg and dwell time of 5 s has been adopted, while for tensile tests Instron 4485 universal testing machine (200kN load cell) has been used. In order to analyze the local strain distribution, the optical strain measurement system ARAMIS of the company GOM has supported the tensile tests (Fig. 5).

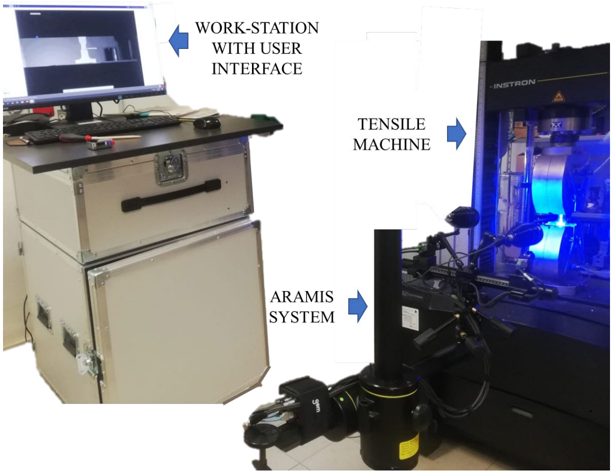

Fig. 5. Experimental setup for tensile tests assisted by a digital image correlation system

Results and Discussion

FE-thermomechanical cycles

The FE model has been developed for the numerical simulation of the Press-Hardening process of the automotive commercial B-Pillar which must present two soft zones to dissipate energy during possible impacts and a hard central zone to avid intrusion (Fig. 6). The FE numerical simulations are aimed at obtaining thermo-mechanical cycles during the process on the soft zone for different values of quenching time and temperature of heated tools. AutoForm software, in fact, allows to evaluate the variation of the temperature and plastic strain of a specific element during the simulation. In this study, the history plot of temperature and plastic strain during the process simulation are considered in the second soft zone (soft zone II in Fig. 6).

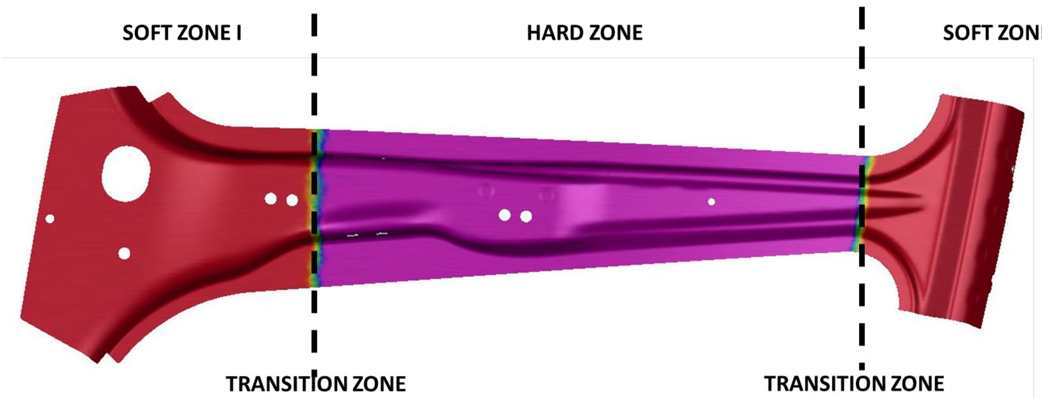

Fig. 6. B-Pillar modeled in AutoForm environment with desired ductile and resistant zones

Figure 7a and Figure 7b show, respectively, the thermal history and the plastic strain history of a point in the second soft zone for different temperature of heated tools values and quenching times. In Figures 7a and 7b, for example, the thermal and deformation histories of only three cases are shown; obviously for each investigated values of heated tools temperature and quenching time these curves have been obtained. From Figure 7b, no differences in the plastic strain values for the three cycles are observed; in fact, the thermal and deformation histories have all been extrapolated in the same point of the second soft region. Instead, from Figure 7a, differences in thermal history are noted, because the quenching parameters affect only the temperature.

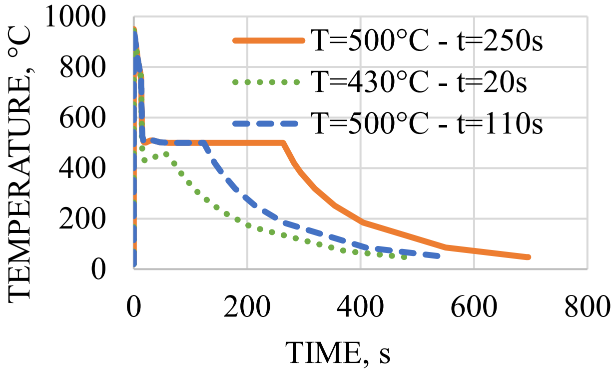

Fig. 7a. History plot of temperature during process simulation in one point of second soft zone

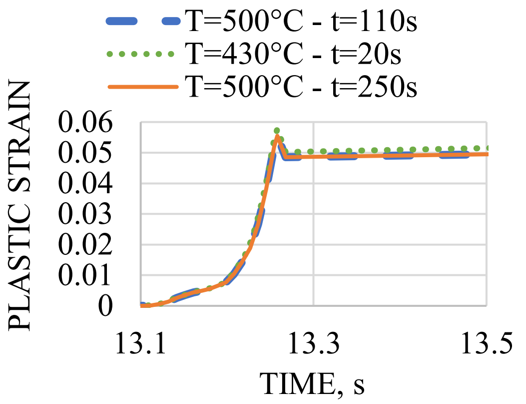

Fig. 7b. History plot of plastic strain during process simulation in one point of second soft zone

Process window – ANN results

The numerical thermo-mechanical cycles have been set in the Gleeble system and reproduced on specimens in USIBOR®2000. After physical simulation tests, specimens have been subjected to the micro-hardness and tensile tests. The mean value of experimental results obtained in terms of hardness, tensile strength and rupture deformability have been used for training the ANN to develop a process window that expresses the relationship between quenching process parameters and the mechanical properties of the component at the end of Press-Hardening process.

Figures 8a, 8b and 8c show, respectively, the process window to predict hardness, tensile strength and rupture deformability of low strength region for investigated quenching parameters. It has been found that the hardness decreases as the quenching time increases, in agreement to the results of Palmieri et al. [15] and Kim et al. [14]. Moreover, for low values of the quenching time, the hardness decreases as the temperature of the heated tools increases. The trend of tensile strength follows the hardness one. In particular, the ratio between tensile strength and hardness is on average 2.6 (Fig. 8b). On the contrary, the rupture deformability decreases with the reduction of the quenching time and the temperature of the heated tools (Fig. 8c).

These results are justified by a generation of bainite microstructure with the increase of tool temperature and quenching time. In fact, the bainite microstructure is characterized by greater toughness and ductility compared to martensite one, formed for low quenching time and tool temperature.

For quenching times between 150 s and 250 s, all three process maps show a plateau. Within this plateau, the maximum rupture deformability (between 20 % and 24 %), the lowest tensile strength (between 800 MPa and 900 MPa) and the minimum hardness (between 300 HV2 and 350 HV2) are obtained. On the other hand, in correspondence with lowest quenching time (20 s) and lowest heated tools temperature (430 ° C), a hardness slightly higher than 600 HV2, a tensile strength between 1500-1600 MPa and a rupture deformability less than 10 % are recorded. These values are typical of a fully martensitic microstructure.

A measurement of how well neural network has fit the data is the regression analysis and the error histogram. Figure 9a shows the regression plot, instead, Figure 9b shows the error histogram. For a perfect fit, the data should fall along a 45-degree line, where the network outputs are equal to the responses. For this problem, as it is possible to see in Figure 9a, the fit is good with an R-value equal to 0.9951. The error histogram in Figure 9b shows how the error sizes are distributed. The blue bars represent training data, the green bars represent validation data, and the red bars represent testing data. It is possible to observe that most errors are near zero, with very few errors far from that.

Effectiveness of process window for mechanical properties prediction has been verified. New values for quenching time and tool temperature, within the investigated range, are chosen and imposed for FE-simulations. Once new thermo-mechanical cycles are obtained, physical simulation tests are carried out. Finally, experimental results of hardness and tensile tests have been compared with neural network prediction.

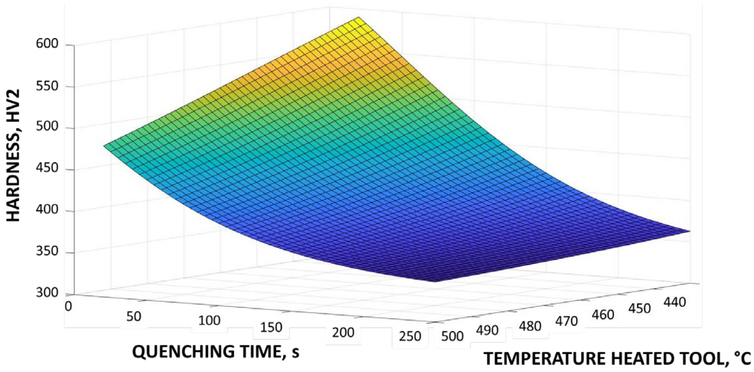

Fig. 8a. Process window to predict hardness of low strength region as a function of heated tool temperature and quenching time

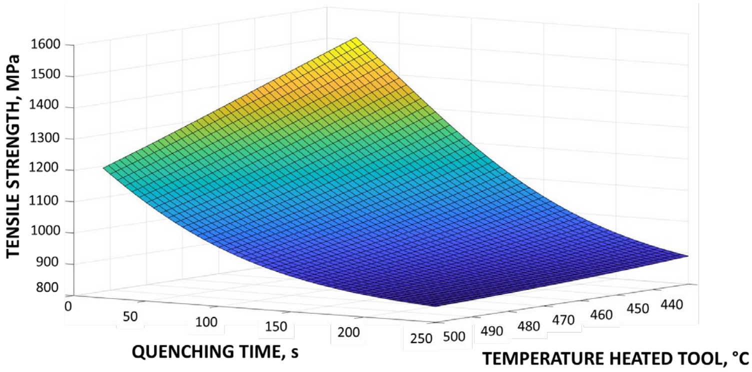

Fig. 8b. Process window to predict tensile strength of low strength region as a function of heated tool temperature and quenching time

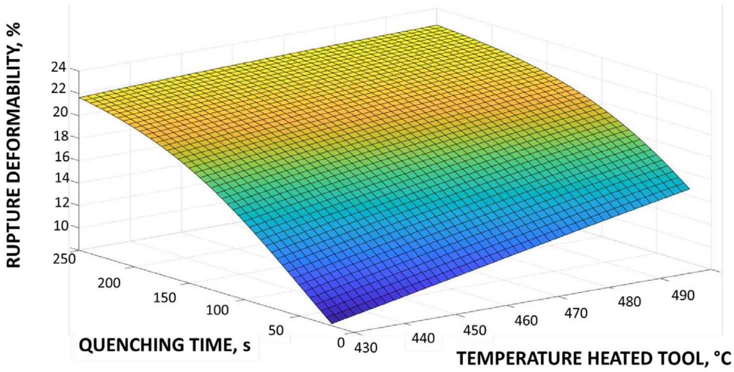

Fig. 8c. Process window to predict rupture deformability of low strength region as a function of heated tool temperature and quenching time

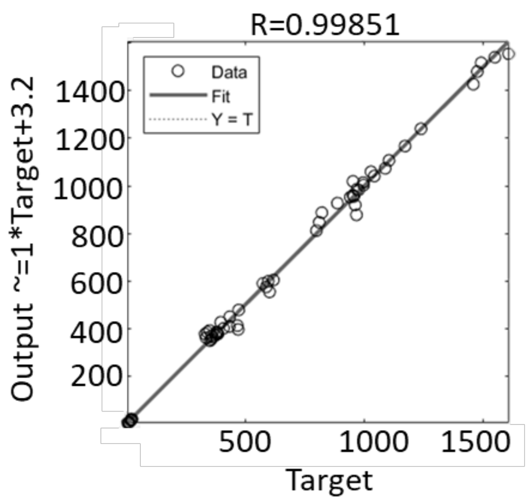

Fig. 9a. Regression plot that shows the neural network predictions (output) with respect to responses (target)

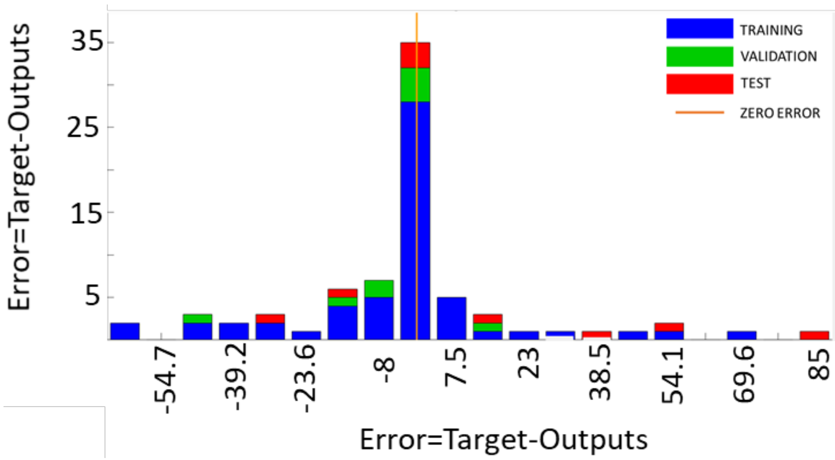

Fig. 9b. Error histogram for additional verification of neural network performance

Table 4 shows, for example, a comparison between the experimental results and the results estimated from the neural network model for a heated tool temperature of 500 °C and a quenching temperature of 50 s. From Table 4 it is observed that the maximum percentage errors are obtained for the results of the tensile strength and rupture deformability, however these values are within the experimental scatter. Therefore, the ANN model is reliable.

Table 4. Comparison between experimental and ANN model results

	Experimental results	ANN model results	Error, [%]
Hardness [HV2]	492	450	8.5
Tensile strength [MPa]	1281	11140	11
Rupture deformability [%]	15	16.7	11.3

Conclusions

In this work, the aim is the prediction of mechanical properties of the low-strength region of an automotive B-Pillar, manufactured by means of Tailored Tool Tempering Press-Hardening process, by using a process window. This process window has been developed through FE simulation coupled with tensile and hardness tests after physical simulation tests and an ANN model.

Based on the obtained results, the following conclusions can be drawn: (i)The physical simulation has proved to be an effective tool for the design of the Press-Hardening process with TTT approach for manufacturing a B-Pillar. In fact, through the Gleeble system, which made it possible to reproduce the thermo-mechanical cycles of the process for different temperature of heated tools and quenching time, specimens with different mechanical properties have been obtained. The hardness, tensile strength and rupture deformability values have been derived through microhardness and tensile tests. These results have been exploited to train a neural network model to develop a process window. (ii) In the process window has been observed that the increase of quenching time and heated tool temperature lead to a reduction in hardness, tensile strength and an increase in rupture deformability. For quenching time values between 150 s and 250 s, the tool temperature becomes less influential on the mechanical properties. (iii) The obtained process window can be applied to estimate the mechanical properties for other process parameters different from those used to train the ANN model; in fact, the error values between experimental and ANN-model results show a good reliability of ANN model. Moreover, the designed process window can be adopted to determine the process parameters to achieve required mechanical properties.

Acknowledgments

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References

[1] Karbasian, Hossein, and A. Erman Tekkaya. "A review on hot stamping." Journal of Materials Processing Technology 210.15 (2010): 2103-2118.

[2] Bian, Jian, et al. "Application potential of high performance steels for weight reduction and efficiency increase in commercial vehicles." Advances in Manufacturing 3.1 (2015): 27-36.

[3] Hu, Ping, Liang Ying, and Bin He. Hot stamping advanced manufacturing technology of lightweight car body. Springer Singapore, 2017.

[4] Naderi, Malek, et al. "A numerical and experimental investigation into hot stamping of boron alloyed heat treated steels." Steel Research International 79.2 (2008): 77-84.

[5] Merklein, M., and J. Lechler. "Investigation of the thermo-mechanical properties of hot stamping steels." Journal of materials processing technology 177.1-3 (2006): 452-455.

[6] Mori, Ken-ichiro. "Smart hot stamping of ultra-high strength steel parts." Transactions of Nonferrous Metals Society of China 22 (2012): s496-s503.

[7] Golling, Stefan, Rickard Östlund, and Mats Oldenburg. "Characterization of ductile fracture properties of quench-hardenable boron steel: Influence of microstructure and processing conditions." Materials Science and Engineering: A 658 (2016): 472-483.

[8] Merklein, Marion, et al. "Hot stamping of boron steel sheets with tailored properties: a review." Journal of materials processing technology 228 (2016): 11-24.

[9] Abdollahpoor, Amir, et al. "Sensitivity of the final properties of tailored hot stamping components to the process and material parameters." Journal of Materials Processing Technology 228 (2016): 125-136.

[10] George, R., A. Bardelcik, and M. J. Worswick. "Hot forming of boron steels using heated and cooled tooling for tailored properties." Journal of Materials Processing Technology 212.11 (2012): 2386-2399.

[11] Cui, Junjia, et al. "Predictions of the mechanical properties and microstructure evolution of high strength steel in hot stamping." Journal of materials engineering and performance 21.11 (2012): 2244-2254.

[12] Åkerström, Paul, and Mats Oldenburg. "Austenite decomposition during press hardening of a boron steel—Computer simulation and test." Journal of Materials Processing Technology 174.1-3 (2006): 399-406.

[13] Zhang, Pengyun, et al. "Study on Phase Transformation in Hot Stamping Process of USIBOR® 1500 High-Strength Steel." Metals 9.10 (2019): 1119.

[14] Kim, Jae-Hong, Seon-Bong Lee, and Byung-Min Kim. "Construction of process window to predict hardness in tailored tool thermomechanical treatment and its application."Metals 9.1 (2019): 50.

[15] Palmieri, Maria Emanuela, Vincenzo Domenico Lorusso, and Luigi Tricarico. "Investigation of material properties of tailored press hardening parts using numerical and physical simulation." Procedia Manufacturing 50 (2020): 104-109.

[16] Palmieri, Maria Emanuela, Francesco Rocco Galetta, and Luigi Tricarico. "Study of Tailored Hot Stamping Process on Advanced High-Strength Steels." Journal of Manufacturing and Materials Processing 6.1 (2022): 11.

[17] Hagenah, Hinnerk, et al. "Determination of the mechanical properties of hot stamped parts from numerical simulations." Procedia Cirp 33 (2015): 167-172.

[18] Information on https://automotive.arcelormittal.com/products/flat/PHS/usibor_ductibor.