

Determination of Material and Process Characteristics for Hot Stamping Processes of Quenchenable Ultra High Strength Steels with Respect to a FE-based Process Design

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ABSTRACT

For lightweight construction, besides the conventional lightweight materials like aluminium and magnesium, ultra high strength steels are being increasingly used in the automotive industry. For example the quenchenable ultra high strength steel 22MnB5 is applied for the production of complex crash relevant components. The processing of the boron micro-alloyed steel 22MnB5 is carried out in an innovative, non-isothermal hot sheet metal forming process, which combines forming and quenching in one process step. The process itself as well as the experimental determination of relevant process parameters like thermal and mechanical material properties with respect to a more reliable numerical process design will be introduced and explained.

INTRODUCTION

Nowadays the automotive industry has to face with one main conflictive challenge. On the one hand it has to meet the customers' demands with respect to more and more powerful, but saver vehicles with a higher extend of operating and handling comfort like navigation systems, air condition and entertainment systems etc., which lead inescapably to an increase of the vehicles weight. But on the other hand the engineers have to find a way of simultaneously reducing the fuel consumption with regard to the aspect of lowering the CO₂ air pollution and due to the fact of the permanent increasing oil price let the fuel costs exploded in the last years world wide. In order to be able to accomplish these conflictive objectives besides the conventional lightweight materials more and more components made of high and ultra-high strength steels find their application in modern car concepts [1, 2]. Due to the higher strength with those kinds of new steel grades components with a reduced sheet thickness could be produced, whereby a reduction of weight, particular in the body in white (BIW), could be achieved [3]. But the use of high strength steels leads also to some disadvantages like for example a decreasing formability and a high spring back tendency. Therefore as a

consequence of the limited formability of such materials new forming technologies like for example hot stamping of quenchenable boron-manganese steels had to be developed to tap the full potential of these new high strength steel grades as structural parts in the body in white. Hot stamping, also called press hardening, is an innovative, non-isothermal forming process for sheet metals, which combines forming and quenching in one process step. Thus it is possible to manufacture high strength components with a final tensile strength up to 1500 MPa with complex geometric shapes in one single stroke. The hot stamped parts currently find applications as crash relevant components like reinforcement parts, front bumper beams, anti-intrusion bars, sills, door-beams, A and B-pillars, etc, in the automotive industry (compare figure 1).

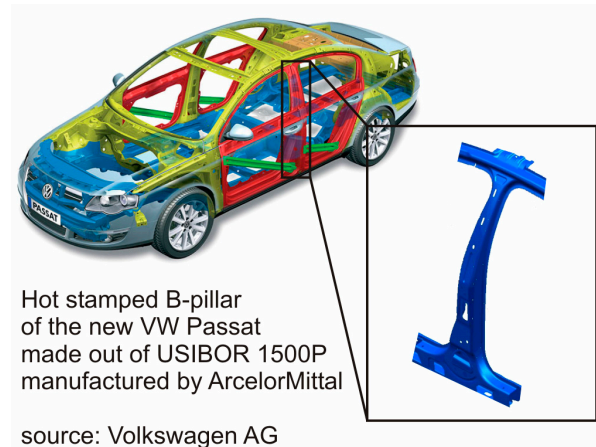


Figure 1: Body in white of the new VW Passat with a hot stamped B-pillar made out of 22MnB5 manufactured by Arcelor [4]

As standard material for hot stamped parts the micro-alloyed boron-manganese steel 22MnB5 is commonly applied in the automotive industry. Compared to the usage of conventionally high strength steels like MS-W 1200 or CP-W 800, for example it had been possible to realize a front bumper of the Peugeot 607 with a sole weight reduction of 2 kg, by reducing the

sheet metal thickness of about 10 % [5]. For a mid class car with a body in white weight of approximately 300 kg using hot stamped components will hence lead to a final weight reduction up to 30 kg [6].

Nowadays hot stamped parts are almost implemented in the body in white at all main global car manufactures like Volkswagen VW, Peugeot, Audi, BMW, DaimlerCrysler, Ford, Citroen, Renault etc. [7]. For example the body in white of the new VW Passat, which achieved the maximum of five possible stars at the European NCAP crash test, consists of approximately 85 % of high strength steels, whereof 15 % belong to hot stamped components like for example the B-pillar as shown in Figure 1 [4]. With respect to a numerical process design the quality of the implemented process relevant material and process characteristics as well as the applied material models play an important role regarding the reliability of the results of the finite element analysis (FEA). Therefore among the others the accurate determination of the material's thermal and thermo-mechanical properties under process related conditions is a basic requirement and represents a much bigger experimental challenge for the hot stamping technology in comparison to cold forming processes. Within the scope of this paper a short overview about the research work at the Chair of Manufacturing Technology, on the topic of hot stamping with the focus on the experimental determination of the thermal and thermo-mechanical material and process characteristics will be presented. Besides the introduction and the description of the different experimental setups and analysis procedures some fundamental experimental results acquired during the research work are illustrated as well. Exemplarily results will be shown with respect to the process window, the heat transfer coefficient between blank and die in dependency of the contact pressure. Furthermore results concerning the characterization and the modelling of the mechanical flow properties of 22MnB5 in dependency of the hot stamping process influencing parameters like temperature, strain and strain rate etc. will be presented and discussed.

HOT STAMPING OF BORON-MANGANESE ULTRA HIGH STRENGTH STEELS

TECHNOLOGY

The development of the so called hot stamping process was carried out empirically according to the trial and error principle at the end of the nineties for some quite simple automotive components like door and bumper beams. But the potential that is related to the new forming technology and the new high strength steel grades respectively let the process and its meaning for the automotive industry develop very quickly. Today exist several kinds of different complex structural parts for the usage of the body in white with the focus on crash relevant components as mentioned before. In the industry two methods are nowadays commonly used,

namely the direct and indirect hot stamping. A schematic illustration of the procedure of both hot stamping methods is shown in Figure 2.

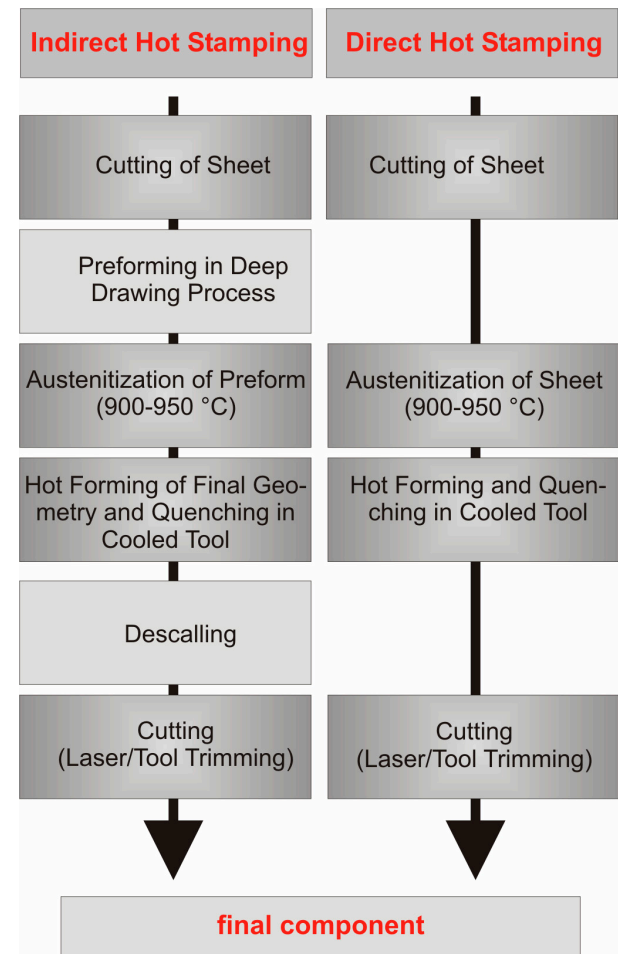


Figure 2: Principles of the indirect and the direct hot stamping process according to [8]

Initially the base material 22MnB5 exhibits a ferritic-pearlitic microstructure with a yield and tensile strength of about 400 MPa and 600 MPa respectively. After passing through the hot forming process, the component finally consist of a martensitic microstructure with a yield strength of 1200 MPa and a tensile strength of about 1500 until 1700 MPa [9]. In order to achieve the aspired martensitic microstructure and following the mechanical properties, therefore the blank has to be austenitized for at least five to eight minutes in a furnace at temperatures higher than the according A_{c3} -temperature to assure a complete homogenous austenitization of the microstructure as pre-condition for an aspired complete martensitic phase transformation. After having received the wanted microstructure the blank will be transferred to a water cooled die as quick as possible using a robot or feeding system. This procedure usually takes three seconds. Afterwards the blank will be formed at high temperatures between 850 °C down to 650 °C [10]. Within this temperature window the boron-manganese

steel 22MnB5 exhibits an excellent formability as a consequence of the reduced flow stress at elevated temperatures, wherefore rather complex geometric shapes could be realized in a single stroke. The quenching leads to a microstructural phase transformation from austenite to martensite and to the significant increase of the final strength of the part which is a consequence of the established contact of the blank with the water cooled die absorbing the heat from the hot blank. Following the continuous time temperature transformation (TTT) diagram in Figure 3, a cooling rate of at least 27 K/s is essential for preventing bainitic phase transformation and to achieve a full martensitic microstructure. The critical value of 27 K/s is only valid for material not subjected to plastic deformation. But within hot stamping the sheet metal in austenite state is subjected to plastic deformation that increases the internal energy of the material, which leads to an increase of the minimum cooling rate required for martensite transformation for hot stamped parts up to 35 K/s [11]. As a result of the full metallic contact between blank, die and punch, during the quenching cooling rates between 50 K/s and 100 K/s can be realized. Thus components with homogeneous mechanical properties at a final high tensile strength level of above 1500 MPa and a sufficient remaining ductility of 6-8 % uniform elongation could be manufactured as well [10].

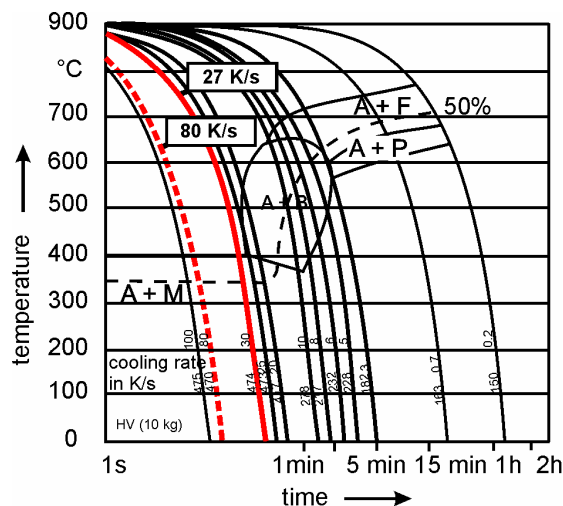


Figure 3: TTT-diagram of 22MnB5 (USIBOR 1500P) according to Arcelor [12]

After the forming and cooling operation the part exits the hot stamping line at a temperature of around 150 °C to 200 °C. The entire forming cycle time including transfer, stamping and quenching in the closed die lies somewhere in between 15 s to 25 s. In order to prevent the blank from decarburization and oxidation in the form of developing a scale layer during the heat treatment and the transfer from the furnace to the die, for the direct hot stamping method blanks pre-coated with an protecting aluminum-silicon layer have to be used. During the heating in the furnace up to austenitization temperature

due to diffusional processes the Al/Si-coating will transform to an Al-Si-Fe alloyed layer system with a continuously increasing content of Fe. This leads to a simultaneously increase of the melting temperature of the ternary coating layer resulting in a prevention of the base material from corrosion and decarburization.

Besides the direct hot stamping process a second method exists, which is called indirect hot stamping. For this type of forming process the uncoated blank will be pre-formed at room temperature until 90 to 95 % of its final geometry. The austenitization has to be performed afterwards under inert atmospheric conditions to prevent the sheet metal from oxidation. The quenching is carried out in a final calibration step where the blank is formed to its final shape. After the process the surface has to be treated with various methods for improving its quality for post processing. The indirect hot stamping process is applied in the automotive industry as well taking advantage of higher realizable draw depth in comparison to the direct method. Typically applications of indirect hot stamped components are for example tunnels, roof rails etc.

Contrary to the direct and indirect hot stamping method the steel manufacture voestalpine has invent a comparably hot forming technology of 22MnB5 steels, namely HT1500PS and HT1500PS(+), using a protecting zinc coating layer. The voestalpine-PHS technology is a combination of direct and indirect press hardening trying to use the advantages of each method. Within the voestalpine process chain the Zn-coated boron-manganese blank is cold formed and cut to its final shape. Afterwards it will be austenitized and quenched in one final process step [13]. According to voestalpine the hot stamped component does not need any kind of further treatment with respect to post processing steps. Currently no publication regarding the industrial application for this technology at any automotive manufacture is known. For more details concerning this hot forming technology it should be referred to the literature [13, 14].

PROCESS DESIGN

For cold forming processes the numerical modelling of the forming process design via finite element simulation is state of the art. With regard to a reliable FE-based design of hot stamping operations, besides the tribological conditions the knowledge of the thermal material properties as well as the knowledge of elastic and plastic mechanical material characteristics like Young's moduls, Poisson ratio, yield locus, flow curve, anisotropy coefficients etc. in dependency of the process influencing parameters is required. In Figure 4 the relationship and the interaction between the thermal and the thermo-mechanical properties within the press hardening process is schematically illustrated [15, 16, 17].

The time-temperature characteristic, which the forming blank has to pass through, is besides the austenitization condition like temperature and duration, primarily

effected by the contact condition between blank and water cooled die within the forming process. The heat transfer resulting from the established contact between blank and tool consequently rules the cooling of the blank, which is on the one hand responsible for mechanical properties during the forming process as a result of the temperature dependency of the flow behavior. On the other hand it hence determines the occurring microstructural phase transformation due to the transformation kinetic of the material. The heat transfer between hot blank and water cooled die itself is mainly effected by the occurring contact conditions like for example the established contact pressure, the surface properties of the contact partners and the temperature difference of the contacting surfaces and partners. For a more detailed summary of all influencing and interacting and interdependent parameters, which have to be considered regarding a complete numerical modelling of the hot stamping process chain, it should be referred to the following publications [10, 18].

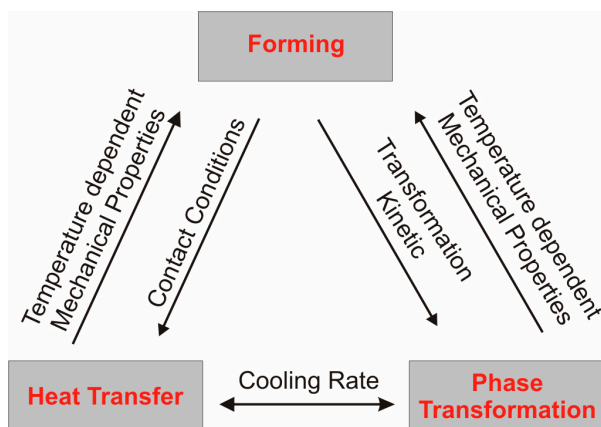


Figure 4: Schematic illustration of the interaction between forming, heat transfer and phase transformation [19]

EXPERIMENTAL DETERMINATION OF PROCESS RELEVANT MATERIAL AND PROCESS CHARACTERISTICS

MATERIAL

In the automotive industry weather for direct and indirect hot stamping as well as for the voestalpine press hardening PHS-technology the quenchenable, boron-manganese steel with the alloying composition 22MnB5 is used as standard material. Within the scope of this work a cold-rolled strip with a sheet thickness of 1.75 mm manufactured by Arcelor was used. The boron-manganese micro-alloyed steel, so called USIBOR 1500P, consists of a fine grained, ferritic-pearlitic microstructure with a hardness of 171 HV10 and a yield and tensile strength of approximately 400 MPa and 600 MPa [20]. In order to prevent the blank from oxidation and decarburization during the heat treatment and the

transfer from the furnace to the die, USIBOR 1500P is pre-coated with an aluminum-silicon-based layer. The thickness of the coating usually lies in a range between 23 μm and 32 μm according to Arcelor (Figure 5). To obtain the required homogeneous austenitic microstructure before quenching, the steel producer recommends a furnace dwell time higher than at least five to eight minutes [12]. Furthermore an austenitization temperature of 900 to 950 $^{\circ}\text{C}$ is recommended. Regarding the resulting microstructural evolutions during the hot stamping process as a result of the occurring quenching during the forming operation the continuous time temperature transforming (TTT) diagram in Figure 3 has to be considered.

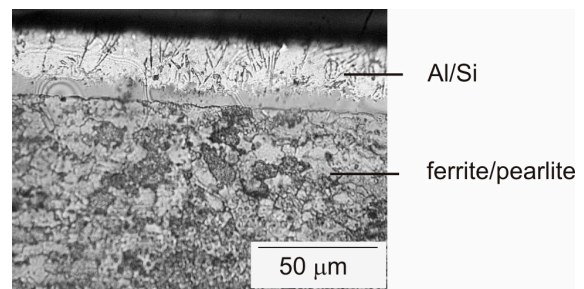


Figure 5: Micrographs of Al/Si-pre-coated 22MnB5 (USIBOR 1500P) as-delivered

DETERMINATION OF THE THERMAL INFLUENCING PARAMETERS

For the determination of the process relevant thermal influencing parameters like interaction between austenitization temperature and time on the mechanical properties as well as the heat transfer coefficient between blank and die in dependency of the contact pressure, one within the project P644 at the Chair of Manufacturing Technology at the University of Erlangen-Nuremberg constructed tool had been implemented in a universal mechanical testing machine (SchenkTrebel RM 400) with a maximum normal force of 400 kN (Figure 6). The tool mainly consists of two 10 mm exchangeable water cooled contact plates, on which the rectangular specimens with a dimension of 58 mm x 168 mm will be placed manually on four spring-seated pins after heat treatment in a furnace under atmospheric conditions. By using a set-point testing software the specimen can be loaded with a defined contact pressure with respect to both side full metallic contact during hot stamping. Simulating non metallic contact conditions a defined gap between die and blank can also be realized. Within the test the temperatures of the blank and of both contact plates are recorded using integrated Ni/Cr-Ni-thermocouples. In order to minimize the loss of heat before the tool is completely closed the four pins are embedded in the lower contact plate and disappear during the test. Thus the heat transfer coefficient and the corresponding cooling rates can be determined in dependency of the contact conditions either using numerical or analytical analysis methods.

The described experimental set-up has been used for two different investigations [15, 16]: In order to characterize the austenitization behavior of the quench-able high strength steel 22MnB5 (USIBOR 1500P) with regard to the determination of the process window of the hot stamping process, annealing tests have been carried out in dependency of the austenitization temperature. To evaluate the heat transfer coefficient α quenching tests have been performed in dependency of various contact pressures p_c as well as different gap distances. Within this paper results will be shown later with respect to the process window for austenitization and heat transfer coefficient as a function of the applied load. The results regarding the influence of the gap distance at non metallic contact is objective of current investigation.

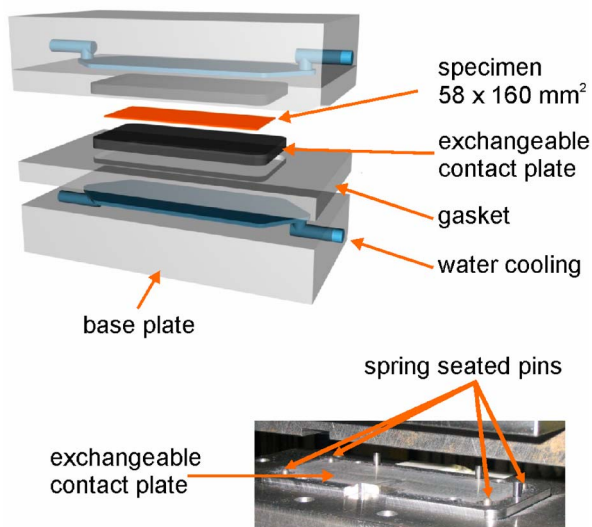


Figure 6: Sketch of the experimental set-up for determining the process relevant thermal material properties [15]

DETERMINATION OF THE THERMO-MECHANICAL MATERIAL PROPERTIES WITHIN THE HOT FORMING PROCESS

The experimental challenge of determining the material's thermo-mechanical properties in dependency of the influencing process parameters like temperature, heating and cooling rate, true strain and strain rate etc. as required input data for the FE-based process design is difficult to meet with conventional mechanical testing systems. Therefore a Gleeble 1500 system, in particular the test chamber, has been modified at the Chair of Manufacturing Technologies. A picture of the adjusted test chamber of the servo hydraulic Gleeble 1500 system is displayed in Figure 7. In order to realize the typical time temperature characteristic with its required cooling rates higher than 27 K/s, two compressed-air nozzles have been integrated, which enable cooling rates up to 100 K/s. In Figure 8 the cooling period specimens are imposed during the thermo-mechanical test program of the hot conductive tensile test (Figure 9)

is exemplarily shown for an average cooling rate of approximately 80 K/s by using 5 bar of compressed air. According to the illustrated time-temperature characteristic it is obvious, that with the modified test system the typical, required cooling rates of the hot stamping process could be realized.

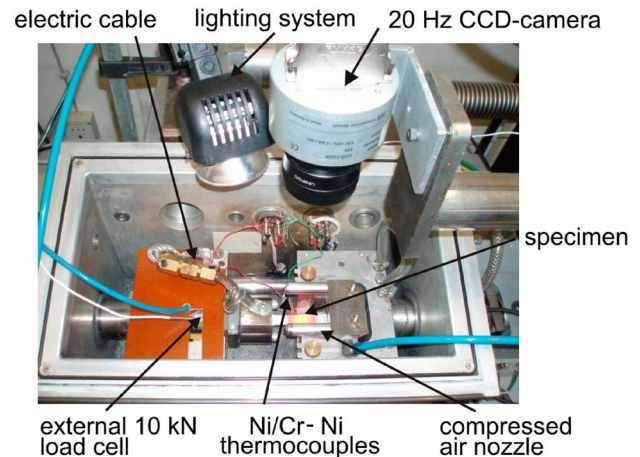


Figure 7: Look in the modified test chamber of the Gleeble 1500 thermo-mechanical physical simulator

By implementing the optical measuring system ARAMIS the deformation of the samples could be detected locally, which enables the determination of flow curves with respect to higher strains [21]. In order to obtain more precise force and following stress data, an external, more sensitive 50 kN load cell was implemented as well. Due to the usage of the additional equipment and with respect to improve the handling during the tests, the construction of an accordingly new clamping device including the load cell and cooling system had been constructed.

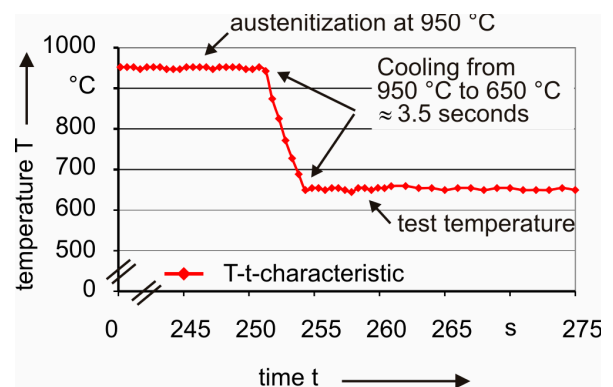


Figure 8: Cooling period specimens are faced with during the performance of the conductive hot tensile test program; 5 bar compresses air leading to cooling rate of circa 80 K/s

For determining the material's flow behavior at elevated temperatures the specimens have been imposed to the thermo-mechanical test program illustrated in Figure 9.