

# Influence of process parameters on the hot stamping of carbon-martensitic chromium steel sheets

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**Abstract.** Hot-stamped components are an important part in steel-intensive automobile lightweight design in which the use of the heat-treatable steel 22MnB5 has been established. However, the field of application is limited by the low elongation at break in the hardened state. In order to improve ductility and consequently the crash-performance, the formation of martensite can be locally suppressed. This process known as tailored tempering is accompanied by decreasing tensile strength. Regarding its lightweight potential, 22MnB5 is reaching its limits and new materials come into focus. Promising potential to fulfil the mentioned demands is offered by carbon-martensitic chromium steels. Besides improved tensile strength and elongation at break, this material series has further advantages. Due to its low critical cooling rate, the formation of martensite is achieved in the hot stamping process as well as by cooling at ambient temperature. Moreover, the low martensite-start-temperature allows the use of thin material sheets. However, the process management required to achieve the respective demands for automobile applications is not trivial. Considering the materials X20Cr13 and X46Cr13, this study investigates the influence of varying process parameters on mechanical properties. In order to comprehend the relationship between solution annealing and tempering parameters, a design of experiments has been performed by means of tensile tests. In addition, miniature tensile tests were conducted to obtain flow curves at varying forming temperatures and to examine the effects of varying cooling and strain rates.

## 1. Introduction

So far, hot stamping has been used for crash-relevant structural components in automotive construction, particularly in order to achieve weight reduction [1]. The rough calculation to be applied here is that a weight reduction of 100 kg results in a fuel consumption which is between 0.25 and 0.5 l/100 km lower. Since the vehicle body accounts for about 40 % of the total weight, there is significant potential in reducing the weight of this component [2]. The most commonly used material in this process is boron alloyed steel containing manganese, 22MnB5 (material number 1.5528) [3]. Regarding lightweight design this steel grade exhibits tensile strengths slightly higher than 1,500 MPa in the hardened state and an elongation at break ranging from 5 to 7 % [1]. An increase in ductility by means of tailored properties with varying methods in order to enhance crash performance is always



accompanied by a loss in strength [4]. Thus, the lightweight potential of 22MnB5 is limited and attention is given to alternative materials. In order to fulfil the material-specific demands of increased strength and ductility, materials must be identified and examined in closer detail. Heat-treated carbon-martensitic chromium steels meet these demands and show adequate corrosion resistance [5]. The heat treatment of common hot stamping processes consists of solution annealing followed by quenching. When processing carbon-martensitic chromium steel grades for automotive applications the solution annealing temperature needs to be higher compared to boron alloyed steels in order to dissolve existing chromium carbides. Furthermore, the process should be supplemented by a subsequent tempering step for martensite relaxation and austenite stabilization in order to increase ductility [6]. Various combined steel grades like X12Cr13 (1.4006), X20Cr13 (1.4021), X30Cr13 (1.4028) are analysed in the literature as to the effect of thermal treatment on mechanical properties and corrosion resistance [5,6,7,8]. However, especially the type X46Cr13 (1.4034) became the focus of attention [5,9,10] for automotive applications due its combined high tensile strength of 1,800 MPa and at least 10 % elongation at break after solution annealing at 1,100 °C for 300 s and tempering at 400 °C with a dwell time of 300 s [11]. The present study expands the existing knowledge about the materials X46Cr13 and X20Cr13, focused on automotive application. Since no coating is required, the ability of resistance heating for X46Cr13 is examined with respect to varying heating dwell times. Also, heat flow curves are recorded and the effect of varying cooling rates on the mechanical properties is investigated. Finally, the results of a conducted design of experiments are presented in order to comprehend the relation between solution annealing and tempering parameters on the mechanical properties of X20Cr13.

## 2. Experimental procedure

### 2.1. Materials

In this study the materials X20Cr13 and X46Cr13 are investigated regarding various hot-stamping process parameters influencing the mechanical properties. In Table 1 the chemical compositions of the investigated materials can be seen, measured by spark spectroscopy.

**Table 1.** Chemical compositions of investigated materials

Grade	Thickness (mm)	Chemical composition (mass-%)			
		C	Cr	Si	Mn
X46Cr13	0.8	0.46	13.84	0.47	0.52
X46Cr13	1.2	0.43	13.97	0.28	0.67
X46Cr13	1.5	0.43	13.00	0.56	0.60
X20Cr13	0.8	0.19	12.77	0.49	0.64

Compared to X46Cr13, the material X20Cr13 contains less carbon. This results in a lower strength and ductility in the hardened and tempered state, but is beneficial for corrosion resistance [5]. However, the determined chemical compositions are within the range specified by DIN EN 10088-1.

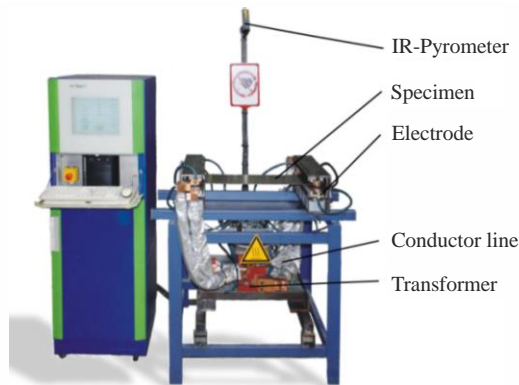
### 2.2. Experimental setups

The tests are conducted at the Institute for Forming Technology and Machines (IFUM) in Hanover and Volkswagen AG in Wolfsburg. In the following sections, the experimental setups are described in detail.

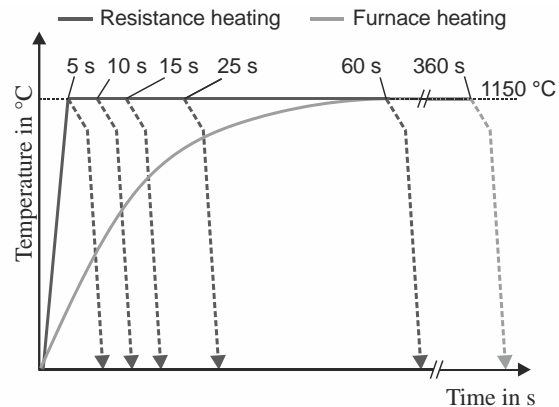
#### 2.2.1. Resistance heating of X46Cr13

In order to examine the feasibility of using resistance heating for the hot stamping of chromium martensitic steels as a cost-effective alternative to roller hearth furnaces, a test rig developed at the

IFUM was used. The test rig consists of electrodes transferring current to the sheet, a transformer converting the main voltage to a safe level and a thyristor power stage to vary heating power. Furthermore, a regulation system is implemented consisting of an infrared pyrometer and a control unit with integrated interfaces for the online monitoring of the temperature. The test rig can be seen in Figure 1.



**Figure 1.** Test rig for resistance heating

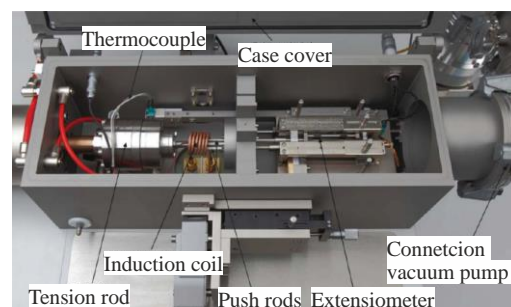


**Figure 2.** Schematic temperature profile

By means of this test rig, sheet specimens of X46Cr13 with the dimensions of 290 mm x 95 mm x 1.2 mm are heated up to 1,150 °C within 5 s. After a varying holding time of 0 to 60 s the sheets were manually transferred into a plate tool and quenched down to room temperature. As a reference, specimens with the same dimensions were heated up to 1,150 °C in a chamber furnace by Nabertherm GmbH for 360 s. The schematic temperature development can be seen in Figure 2. All tests are conducted without a protective atmosphere. Subsequently, the specimens are analysed regarding scale formation and hardness.

### 2.2.2. Flow curves and varying cooling rate effects of X46Cr13

In the mass production of hot-stamped components, the blanks cool down to a specific temperature when being transferred from the furnace to the tool, depending on material properties, initial and surrounding temperature, sheet thickness and transfer time. In order to determine flow curves in this approximated temperature range, hot tensile tests on X46Cr13 (sheet thickness: 1.5 mm) are carried out on a dilatometer by BÄHR-Thermoanalyse GmbH (model: 805A/D+T) at the IFUM, which can be seen in Figure 3. A detailed description of the system and specimen dimensions can be seen in [12]. The specimens are heated up to 1,100 °C by an induction coil and kept at this temperature for 300 s. Then they are cooled down to 700 °C, 800 °C and 900 °C within 10 s and subsequently pulled at this temperature with a tensile rate of 0.2 s<sup>-1</sup>. Additionally, the influence of a lower strain rate of 0.05 s<sup>-1</sup> is investigated for 800 °C and room temperature.



**Figure 3.** Deformation dilatometer

In order to examine the effect of varying cooling rates on X46Cr13 further dilatometer tests have been conducted with modified specimen geometry, see Figure 7. The critical cooling rate for the formation of a martensitic structure of this material is between 1.3 and 2.2 K/s. Thus, with the applied heat-treatment parameters of a solution annealing temperature of 1,150 °C and a dwell time of 300 s, the investigated cooling rates from 3 K/s to 100 K/s should always result in a fully martensitic

structure. However, different cooling rates may affect ductility, since strongly strained structures obtained by faster cooling rates may influence the formation of retained austenite during annealing. Therefore, hardness measurements are carried out on hardened and annealed specimens at 400 °C for 300 s.

Subsequently, the test conditions are transferred to a near production scale experimental setup in order to examine the effect on ductility. Therefore, a non-water-cooled sheet die, mounted in a hydraulic press by Eitel KG (model: EZ 60B), is used for reproducible process-specific cooling. As in the dilatometer tests, the sheet specimens (thickness 1.5 mm) are heated up to 1,100 °C in a chamber furnace by Nabertherm. The tool is equipped with ejection pins to prevent preliminary contact between tool and sheets during insertion. Forming pressures from 1 MPa to 40 MPa were used and air, oil and water are considered as further cooling media. The temperature development is measured by sheathed thermocouples. All test sheets are subsequently tempered at 400 °C for 300 s. The mechanical properties are analysed in accordance with DIN EN ISO 6892-1 using a tensile testing machine by Zwick/Roell AG (model: Z100). The tensile specimens are cut out in dog-bone shape H by laser-beam cutting based on DIN 50125.

### 2.2.3. Influence of heat treatment parameters on X20Cr13

In contrast to X46Cr13, the material X20Cr13 has a lower carbon content and, as a consequence, a lower strength in hardened or tempered state. However, with comparable strength, this material exhibits a higher elongation at break than 22MnB5 and therefore is an interesting material for automotive applications. In order to find suitable heat treatment parameters, a design of experiments (DOE) has been conducted. Time and temperature of solution annealing and tempering process have been varied and analysed by tensile tests. The schematic structure of the DOE can be seen in Figure 4 and the varied parameters are listed in Table 2. A chamber furnace by Nabertherm has been used for solution annealing and a convection furnace by Schwartz for tempering. After solution annealing, sheet specimens in the dimension of 310 mm x 300 mm x 0.8 mm were manually transferred into a water-cooled sheet die, mounted into a hydraulic press by Dunkes and quenched to room temperature. Subsequently, tensile specimens based on DIN 50125 are cut out in dog-bone shape H by water-jet cutting.

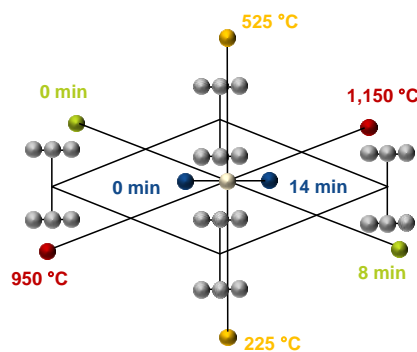


Figure 4. Schematic DOE

Table 2. Heat treatment parameters

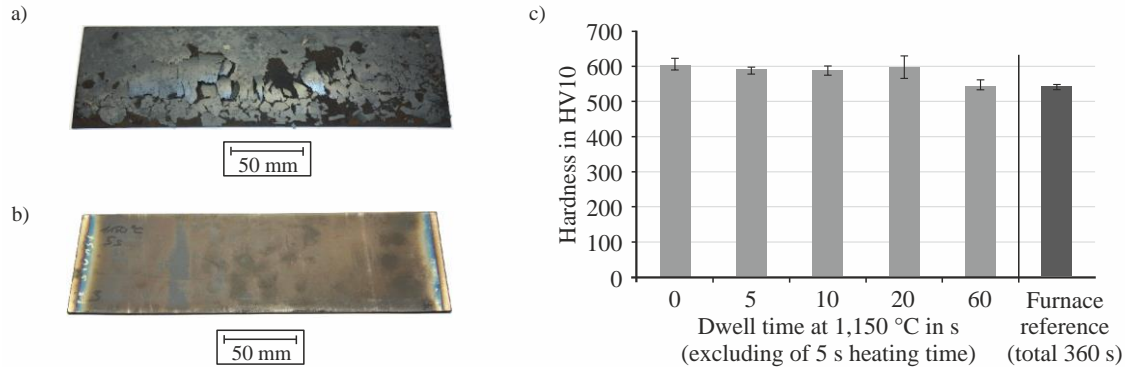
Sheet thickness (mm)	0.8
Solution annealing temperature (°C)	950; 1,000; 1,050; 1,100; 1,150
Solution annealing time (min)	0; 2; 4; 6; 8
Tempering temperature (°C)	225; 300; 375; 450; 525
Tempering time (min)	0; 3.5; 7; 10.5; 14

## 3. Results and discussion

### 3.1. Resistance heating

A strong scale formation resulting from furnace heating can be seen in Figure 5a. All specimens heated up fast by resistance heating show no scale formation which can be seen in Figure 5b. Furthermore, the results of the hardness measurements of hardened (but unannealed) specimens are given in Figure 5c. Using resistance heating and a holding time of 60 s, the specimens feature a hardness of 540 HV10 which corresponds to the hardness of the oven reference. The hardness values

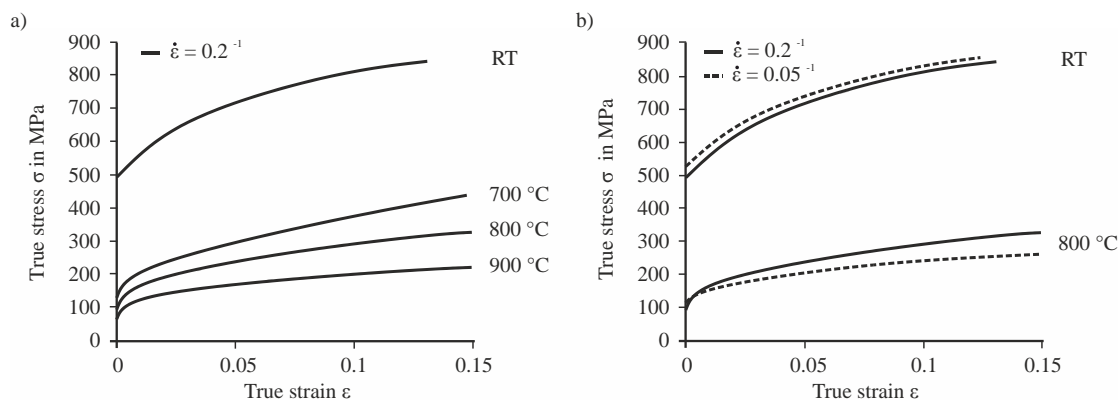
of resistance heated samples with holding times of 0 s to 20 s are approximately 600 HV10. The reason for the higher hardness may be a finer microstructure and finely distributed undissolved carbides. A possible increase in grain size is potentially avoided by the short holding times



**Figure 5.** (a) Specimens heated in furnace and (b) by resistance heating; (c) Results of hardness measurements

### 3.2. Determination of process limits during hot stamping and cooling

The influence of the temperature on the flow properties of material X46Cr13 in the rolling direction of 0° has been investigated for different temperatures and strain rates. Figure 6a is a plot of the flow curves at different temperatures. Here, specimens tested at room temperature are compared to specimens which have been solution-annealed at 1,100 °C for 300 s and afterwards cooled down to test temperatures of 700 °C, 800 °C and 900 °C.



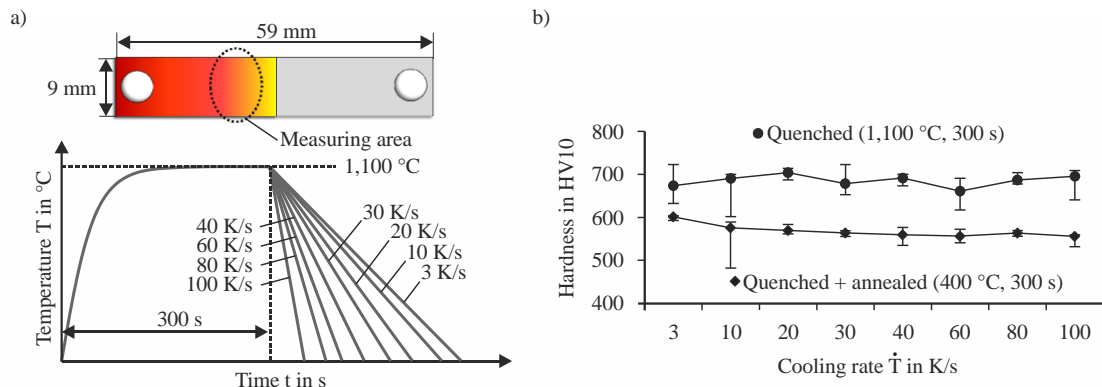
**Figure 6.** (a) Flow curves at varying temperatures and (b) strain rates of X46Cr13

The comparison indicates the temperature sensitivity of this material and the potential of better formability with increasing forming temperature. The decreasing stresses and hardening behaviour of the curves may be attributed to increased dislocation movement and recrystallisation processes with increasing temperature. For samples tested at room temperature and 800 °C, tests have been repeated with a lower strain rate of 0.05 s<sup>-1</sup> and compared in Figure 6b. At room temperature the lower strain rate shows no significant effect on the development of the flow curve while at 800 °C an influence on the degree of solidification is detectable. This can be explained by the fact that with lower strain rates more time remains for diffusion-controlled recrystallisation processes. Compared to the flow properties of 22MnB5 presented in [1, 13], X46Cr13 shows higher stresses and solidification during warm forming and a significantly higher onset of yielding at room temperature.

The effects of different cooling rates on X46Cr13 during hot stamping have been examined. The critical cooling rate between 1.3 K/s and 2.2 K/s for obtaining a fully martensitic structure always applies and therefore the material hardens regardless of the cooling process. However, fast cooling

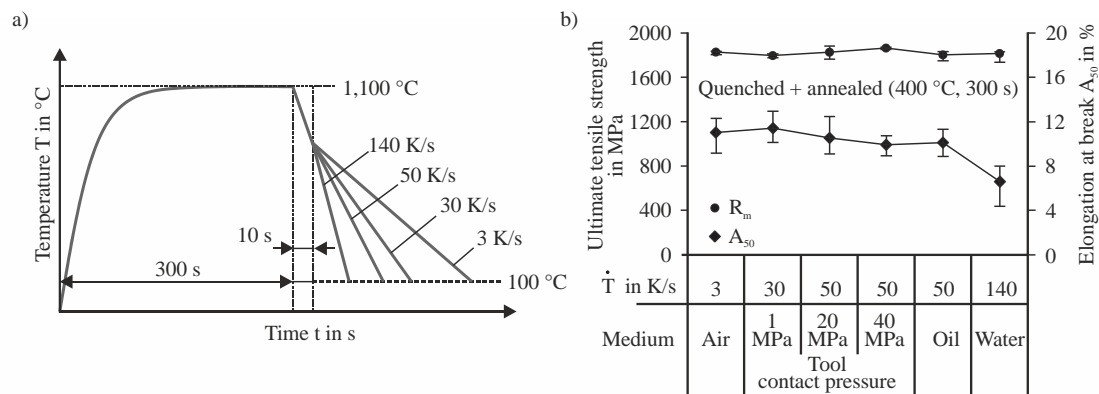


rates may lead to a formation of less retained austenite and, as a consequence, to a lower ductility after tempering. Figure 7a shows the temperature profile of the experiments and Figure 7b the results of different process-relevant cooling rates with respect to the hardness after quenching and additionally after tempering.



**Figure 7.** (a) Time-temperature profile and (b) hardness for quenched and quenched + annealed X46Cr13 specimens

It can be seen that the hardness is about 700 HV10 after quenching and 580 HV10 after tempering. The drop of approximately 120 HV10 indicates that the carbon previously enclosed in the martensitic structure is separating from the lattice structure. However, with respect to the hardness no difference between the cooling rates can be determined. In order to investigate the effect on ductility, the test setup has been transferred to experimental conditions close to mass production. Here, steel sheets are cooled down to room temperature at different cooling rates from 3 K/s to 140 K/s provoked by varying surface pressures in the tool and externally by cooling media. The temperature profiles can be seen in Figure 8a and the results are shown in Figure 8b.



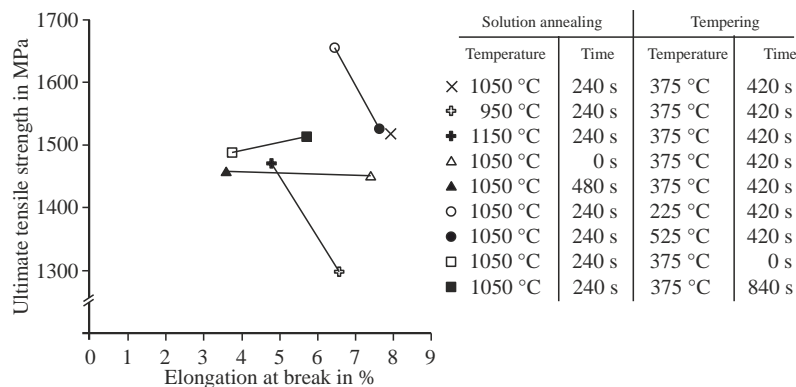
**Figure 8.** (a) Time-temperature profile and (b) ultimate tensile strength and elongation at break of quenched + annealed X46Cr13 specimens

As already evident from the hardness measurements, no significant effect is determined in tensile strength. But regarding the elongation at break, a noticeable drop can be obtained with increasing cooling rates. The highest ductility is determined for samples being cooled in the die with a low surface pressure of 1 MPa and a cooling rate of 30 K/s. After tempering, the material exhibits a strength of 1,800 MPa and an elongation at break of 11 % on average. In addition, other cooling media such as oil and water are listed, since these cooling methods exhibit even faster cooling rates. However, this is insignificant since the elongation at break considerably drops to approximately 5 %. In summary, it can be stated that a cooling rate of 30 K/s provoked by a surface pressure of 1 MPa is required to achieve the desired high mechanical properties. The difference between varying surface

pressures in relation to cooling rates has already been examined in [1]. Due to the fact that a high force is not necessary in this hot-stamping process, the cycle time can be reduced which consequently enhances capacity and productivity.

### 3.2.1. Influence of heat treatment parameters on X20Cr13

In order to investigate the effect of varying heat treatment parameters on the mechanical properties of X20Cr13, a design of experiments has been conducted. In Figure 9, the average results of three repetitions are shown for the principal effects. Here, only one parameter out of four has been varied compared to the central point which has been solution-annealed at 1,050 °C for 240 s and subsequently tempered at 375 °C for 420 s. With these parameters, the material exhibits a tensile strength of 1,520 MPa and an elongation at break of 7.9 % on average. It can be seen that upon varying these parameters, either tensile strength or ductility or both decrease. The same observation has been made when more than one parameter was varied within this DOE. In addition, the presented results show that a variation of the solution annealing or tempering temperature more clearly affects tensile strength, while a variation in time can lead to a higher effect on ductility. Low and high values for solution annealing and tempering reveal an opposite behaviour. The obtained effects can be explained by the solution of carbides and the associated provision of carbon.



**Figure 9.** Ultimate tensile strength and elongation at break for X20Cr13 with different heat treatment

## 4. Conclusion and Outlook

This study deals with the effect of varying hot-stamping parameters on the mechanical properties of the materials X46Cr13 and X20Cr13. The investigations concerning resistance heating showed positive results with regard to a potential industrial implementation. To a certain extent, the higher production costs caused by the material price of carbon-martensitic chromium steel grades and the additional tempering step may be compensated by the substitution of roller hearth furnaces, which are characterized by high energy consumption and space requirements.

The flow properties of X46Cr13 showed a similar behaviour compared to 22MnB5 with higher stresses and solidification for hot stamping and a significantly higher onset yielding at room temperature. In contrast to 22MnB5 the higher solution annealing temperature and subsequently associated higher tool insertion temperature for X46Cr13 has to be considered. With a higher forming temperature (approximately 50 °C to 100 °C), X46Cr13 may have a similar plastic deformation behaviour.

Furthermore, it is shown that the critical cooling rate for the formation of martensite is not relevant to serial hot-stamping processes, but it was shown that a low surface pressure – and the associated low cooling rate – can increase the elongation at break.

Moreover, the presented results of the X20Cr13 showed the effects of varying process parameters and give an impression of the wide associated scope of adjustment in terms of mechanical properties. In further investigations the design of experiments will be extended to X46Cr13. In addition, statistical evaluations will be carried out for both materials and microstructure investigations will be considered.

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