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Control-Oriented Characterization of Product Properties during Hot Hole-Flanging of X46Cr13 Sheet Material in a Progressive-Die

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Abstract: Robust and versatile production is enabled by a closed-loop control of product properties. This essentially relies on the characterization of the interaction between properties and available degrees of freedom to control the process. In particular, this work examines the setting of collar height, thinning, curvature, and hardness during hot hole-flanging of X46Cr13 sheet material with simultaneous heat treatment to identify approaches for a closed-loop property control in hot hole-flanging during multi-stage hot sheet metal forming. To scrutinize the adjustability of the hardness of X46Cr13 sheet material by heat treatment with rapid heating and short dwell times, quenching tests with austenitizing temperatures from 900 to 1100 °C and dwell times from 1 to 300 s were carried out. A hardness between 317 and 680 HV10 was measured. By analyzing the force-displacement curve and the contact situation between tools and blank during hot hole-flanging, an understanding for the process was established. To determine the adjustability of geometrical collar properties and the hardness of the collar, collars were formed at punch speeds between 5 and 100 mm/s and at different temperatures. Here, a dependency of the geometry of the collar on temperature and punch speed as well as setting of the hardness was demonstrated.

Keywords: hole-flanging; product properties; press hardening; progressive-die; hot forming; process control; closed-loop control; martensitic chromium steel; X46Cr13

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1. Introduction

Hot sheet metal forming by multiple consecutive forming operations combined with press hardening in multi-stage tools enables the production of hardened components while facilitating advanced shaping capabilities [1]. An implementation of a progressive-die hot stamping process for producing automobile seat belt buckles [2] and a progressive-die plate forging of tailored high strength gear parts [3] was realized. However, even within a single press hardening stage, the thermal and mechanical interactions are complex to assess [4]. Still, the realization of a zero-defect production represents one of the major challenges in press hardening [5]. Hence, to deduct a functional process window for a process chain with multiple consecutive hot forming steps requires extensive modelling [6]. The targeted setting or, moreover, the batch-dependent variation of product properties therefore represents an additional challenge. To allow for a robust and versatile production in forming processes, a closed loop control can be employed [7]. Here, process variables and product properties are measured, fed back to the system by means of a controller, and set by variation of process parameters using real-time capable models. First approaches for a sole closed-loop control of springback [8], microstructure [9] or strength [10] in hot sheet metal bending in a progressive-die were developed.

From a systems and control perspective, controllability and observability are key enablers for the design of property-related control concepts. Loosely speaking, the term controllability refers to the availability of a suitable number of degrees of freedom (inputs) such as temperature, process speed, dwell time, holding pressure, or other press related parameters to eventually adjust the thermo-plastic process in a desired way. Observability addresses the ability to reconstruct the in general spatial-temporal process evolution based on the availability of appropriate sensor data in conjunction with a process model. Controllability and observability are intrinsically interconnected with actuator and sensor selection and placement and give rise to the need to identify and control the interaction between the available inputs, the sensory outputs, and the product properties. This, however, requires adequate control-oriented process models capturing the process dynamics combined with the characterization of the product properties depending on the process evolution and the input history.

As one of the essential steps towards the development of fundamental approaches for the property control in multi-step hot forming process, hot hole-flanging is investigated in this work, whereby the boundary conditions given by an implementation in multi-stage forming within a progressive-die are considered. During hole-flanging, a punch is moved into a pre-hole in a sheet. With progressing punch-feed, the hole is expanded and the material folds sideways around the punch. Optionally, a blank holder is used. In temperature-assisted hole-flanging or hot hole-flanging, the sheet is additionally heated either during or before forming. This allows for the expansion of process limits and a simultaneous heat treatment. Groche and Erhardt [11] demonstrate an enhancement of the expansion ratio during laser assisted warm (~200 °C) hole-flanging of magnesium and aluminum sheets as well as a difference in strain hardening between the inner and the outer surface of the collar. Motaman et al. [12] improved the expansion ratio during laser-assisted warm (~250 °C to 400 °C) hole-flanging of DP1000 sheet material in a progressive-die by taking advantage of dynamic strain aging. Cheng [13] developed a one-step hot stamping-forging method that enables the hole-flanging of high strength quenchable steel sheet 15B22. Despite the ongoing research, a control-oriented analysis of the relationships between the product properties and the process parameters during hot hole-flanging with simultaneous heat treatment is not known. Likewise, the force-displacement curve during hot hole-flanging and its implementation in process control has not yet been assessed. To derive approaches for a control of product properties, knowledge of these yet unknown relationships is required.

In this contribution, influences of process parameters on the product properties during hot hole-flanging of X46Cr13 sheet material within the frame of closed-loop controlled multi-stage forming in a progressive-die are revealed. In particular, the influence of the austenitization parameters and the punch speed on the geometry of the collar (thickness, curvature) and the hardness distribution are analyzed. The adjustability of X46Cr13 sheet material hardness by rapid heating and quenching is examined. Hot hole-flanging tests are carried out where the force-displacement curve as well as geometric properties and the hardness of the formed collar are analyzed. The relationships revealed results in approaches for a closed-loop control of product properties during hot hole-flanging, which is applicable in multi-stage hot sheet metal forming. As a matter of convenience, Table 1 represents the nomenclature of this paper.

Table 1. Nomenclature.

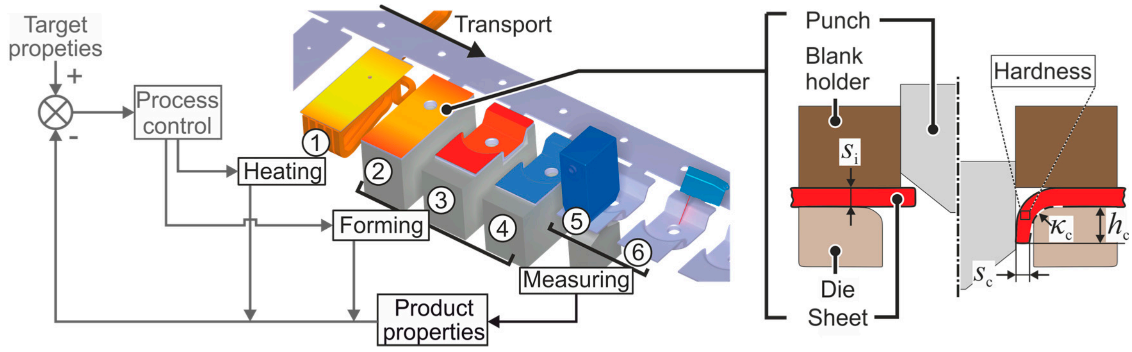
α_P	Cone angle of the punch	[°]
κ_c	Curvature of the collar	[1/mm]
$\kappa_{c,ou}$	Curvature along the outer developed length of the collar	[1/mm]
D_d	Diameter of the hole in the die	[mm]
D_i	Diameter of the pre-hole in the sheet	[mm]
D_p	Diameter of the punch	[mm]
F_p	Force acting on the punch	[N]
f_p	Feed of the punch	[mm]
h_c	Height of the collar	[mm]
l	Length	[mm]
$l_{c,in}$	Developed length along the inner side of the collar	[mm]
$l_{c,ou}$	Developed length along the outer side of the collar	[mm]
l_{gap}	Length of the gap between the tools during heating	[mm]
M_s	Martensite start temperature	[K]
R_d	Radius of the edge of the hole in the die	[mm]
r_c	Cooling rate	[K/s]
r_h	Heating rate	[K/s]
s	Thickness	[mm]
s_c	Thickness of the collar	[mm]
s_i	Initial thickness of the sheet	[mm]
Δs_c	Thinning of the collar wall	[%]
T	Temperature	[K]
T_γ	Austenitization temperature	[K]
t_γ	Dwell time of austenitization temperature	[s]
v_p	Velocity of the punch	[mm/s]
w	Width	[mm]
x	Distance to the water surface	[mm]

2. Materials and Methods

2.1. Process Setup and Product Properties

For the characterization of product properties towards the realization of product-oriented multivariable control, hot hole-flanging within a closed-loop controlled multi-stage hot sheet metal forming process with rapid heating and short dwell times in a progressive-die was assumed (Figure 1a). The sheet is pre-punched, heated by means of induction heating, and formed in several stages with simultaneous quenching by tool contact. Compared to conventional furnace heating, inductive heating of the blank inside the progressive-die extends the number of directly controllable process parameters by those of the austenitization. Actual product properties are measured after forming and, in addition to other data from the ongoing process, such as forming forces and temperature distribution, serve as input for process control. Target product properties are then set by adjusting the kinematic of the press and the austenitizing parameters. For the sake of simplicity, it was assumed that the hot hole-flanging investigated here takes place in the tool stage after the heating stage. In addition, it was presumed that the forming steps following the hot hole-flanging affect the product properties of the collar only through quenching. A superimposed strain hardening or forming of the collar in the third and fourth tool stage was therefore neglected. Similar conditions are to be expected, when a bending and a calibration operation are carried out subsequent to the hot hole-flanging.

The main geometrical product properties of the collar that are considered within the framework of control are the height of the collar h_c as well as the distribution of the wall thickness s_c and the curvature κ_c along the collar wall (see Figure 1b). In addition to the geometry, the hardness set by the heat treatment and forming is considered. The issues of control are addressed in [14] by taking into account an extended Kalman filter for the real-time reconstruction of the spatially and time-varying sheet temperature distribution during forming, based on suitable reduced-order process models. Here, it is shown that the interaction between forming, heat treatment, and estimated temperature evolution enables the reconstruction of the spatial-temporal distribution of product properties, when their control-oriented characterization is available. The latter is the topic of the present paper.



(**a**) (**b**)

Figure 1. (**a**) Process design for multi-stage hot sheet metal forming in a progressive-die with a closed loop control of product properties; (**b**) Principle of hot hole-flanging and product properties: collar height h_c, thickness of the collar s_c, curvature of the collar κ_c, and hardness.

2.2. Material

For the examined process, the martensitic chromium steel X46Cr13 was chosen. Possible industrial applications of hardened martensitic chromium steels range from cutting blades to parts in automotive crash applications [15]. Conventional press-hardening steels (e.g., 22MnB5) require a coating or the use of inert gas serving as protection against the formation of scale during heating. Established AlSi-coatings necessitate a certain diffusion time and have a melting point below that of the base material [16]. Similar boundaries are given when using Zn-coatings [17]. Moreover, during induction heating of AlSi-coated 22MnB5, undesirable local accumulations of the coating layer caused by the magnetic field forces can be observed [18]. Therefore, conventionally coated press hardening steels are not suitable for heating with high heating rates (>100 K/s) and short dwell times (<20 s), which is a requirement within the frame of the analyzed process. The utilization of X46Cr13 allows for rapid heating within the progressive die as no coating is required, enabling an aggressive control of the austenitizing parameters as well as high stroke rates. In addition, the hardness after heat treatment of this air-hardening steel has a minor sensitivity towards the cooling rate as the critical cooling rate for obtaining a fully martensitic structure is in the order of 1.3 to 2.2 K/s [19]. This is simplifying process control.

Experiments are carried out with heat-treated, cold-rolled X46Cr13 (DIN EN 10088-2: finish 2B) coil material. The width and sheet thickness of the coil is 200 mm and 2 mm with a tolerance according to DIN EN ISO 9445-2. To produce samples, the coil is unwound and straightened. An overview of the delivery condition is given in Table 2.

Table 2. Delivery condition of the X46Cr13 coil material according to mill certificate in conformity with EN 10204/3.1.

Yield Strength $R_{p0,2}$ in MPa	Hardness in HV	Chemical Composition in wt%						
		C	Si	Mn	P	S	Cr	Fe
372	245	0.443	0.37	0.55	0.026	0.001	13.76	84.85

2.3. Quenching Test—Heat Treatment with Rapid Heating and Short Dwell Times

For the sole investigation of the heat treatment of the virgin X46Cr13, sheet material by rapid heating and short dwell times quenching test were performed. Hereby, the heating stage of the progressive-die was emulated with an exclusion of the influence of forming on the quenched microstructure. Specimens in the form of metal strips (dimensions: 180 mm × 20 mm × 2 mm) were heated by means of combined induction and conduction [20] (Figure 2a) with a heating rate r_h of ~1000 °C/s to austenitizing temperatures T_γ between 900 °C and 1100 °C. T_γ was held for dwell times t_γ of 1, 5, 20, or 300 s (Figure 2b). Subsequently, the specimen was quenched on one end by raising a water basin with a pneumatic actuator. The applied heating method is allowing for a rapid as well as homogenous heating. The heating device was coupled to a generator TruHeat MF7040 (TRUMPF Hüttinger, Freiburg, Germany) with an output of 40 kW at 600 V via a coaxial transformer. Depending on the distance to the water surface x, differing cooling rates r_c arise in the specimen. These were reversibly determined by evaluating thermal images recorded during the quenching with TIM M-1 (Micro-Epsilon Messtechnik, Ortenburg, Germany) from 1200 °C to 450 °C and VarioCam HD head 680 S (InfraTec, Dresden. Germany) from 450 °C to 50 °C. In this investigation, the cooling rates r_c were calculated as a mean cooling rate between the austenitizing temperature and the martensite start temperature M_s. Based on Yuan [21], a mean martensite start temperature M_s of 295 °C was assumed. The austenitizing temperature and dwell time were controlled with the program Sensor Tools (Sensortherm, Sulzbach, Germany), whereby the temperature was measured by a pyrometer Metis M308 (Sensortherm, Sulzbach, Germany) focused on the center of the heated specimen. As described in Section 2.5.1, hardness measurements were carried out on the surface of the specimens generated with different parameter sets.

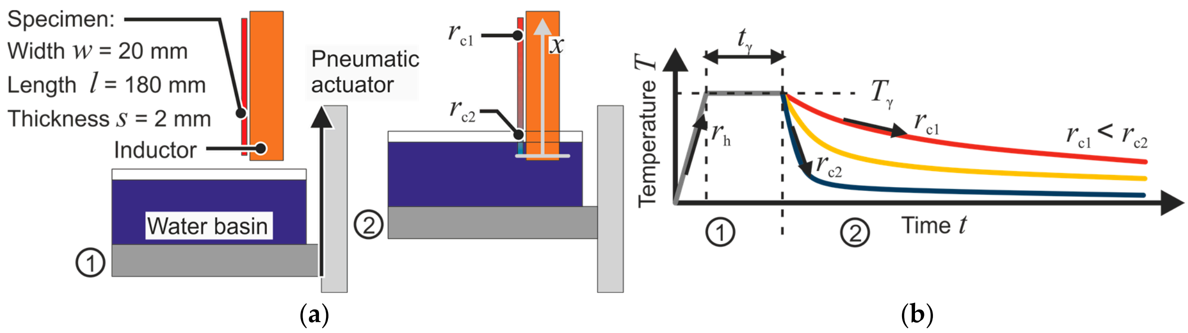


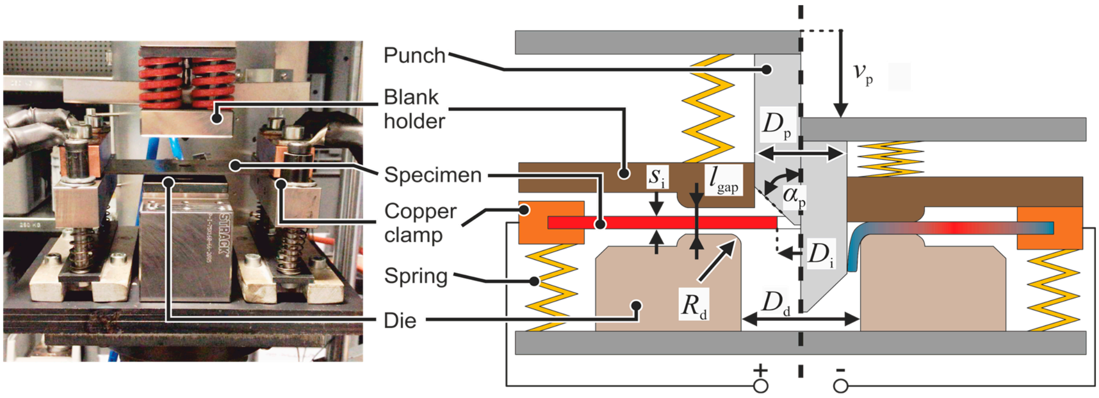
Figure 2. (**a**) Design of the quenching test with adjustable austenitizing temperature T_γ and dwell times t_γ and variating cooling rates r_c [22]; (**b**) Schematic time-temperature curves during heat treatment by rapid heating and short dwell times.

2.4. Hot Hole-Flanging

The experimental design shown in Figure 3 was deployed for emulating the heating stage and the hot hole-flanging stage in a progressive die during hot sheet metal forming. For precise setting of the lower speed range (punch velocity v_p from 5 to 10 mm/s), the tooling system is installed in a universal testing machine Zwick Z250 (Zwick, Ulm, Germany), also measuring the force-displacement curve during the forming process. To examine the mean and upper speed range (v_p equal to 50 and 100 mm/s), the same tooling system was operated in a servo press MSD2-400 (Schuler, Göppingen, Germany). All tool elements were water-cooled and made of hardened hot work tool steel Böhler W360 (Voestalpine, Linz, Austria). Dimensions are given in Table 3.

Table 3. Characteristic values of the hot hole-flanging setup.

ID.	Value	ID.	Value
α_p	45°	l_{gap}	20 mm
D_d	19.1 mm	R_d	2 mm
D_i	10 mm	s_i	2 mm
D_p	14.9 mm	v_p	5 mm/s to 100 mm/s



(a) (b)

Figure 3. (**a**) Implementation of hot hole-flanging in a Zwick Z250 universal testing machine; (**b**) Schematic setup of hot hole-flanging.

First, a sheet metal plate (dimensions: 190 mm × 60 mm × 2 mm) with a pre-hole was heated to the austenitizing temperature in ~15 s by a DC power source with a maximum output of 44 kW. Shorter heating times were not aimed for to avoid overheating at the edges of the pre-hole. The sheet was heated to austenitization temperatures between 900 °C and 1100 °C. After 5 s of dwell time, a homogeneous temperature distribution in the forming zone with a deviation of ±20 K was observed. Then, heating was interrupted, and after a delay of 1 s, the tool was engaged with the velocity v_p. This delay emulates the transfer between the heating stage and the forming stage in the progressive-die. After reaching the bottom dead center and a holding time t_h between approximately 3 s, the tool movement was reversed. This was intended to prevent the collar from shrinking onto the punch. In addition, the high-temperature lubricant Fenella Fluid F 505 (Houghton, Dortmund, Germany) was used to reduce the friction. Setting the heating as well as the evaluation of the temperature distribution was carried out analogously to Section 2.3. For the analysis of the influence of the preparation method of the pre-hole on thinning, curvature, and collar height during hot hole-flanging, the specimens were prepared by laser cutting as well as by drilling and reaming.

2.5. Analysis of the Product Properties

2.5.1. Hardness Measurements

The hardness of the specimens from the quenching test was assessed directly on the flat side of the heat-treated sheet metal strips ($w \times l$ in Figure 2a). For those specimens, hardness measurements were executed with a universal testing machine Dia Testor 2 RC (Wolpert (Buehler), Esslingen am Neckar, Germany) according to HV10 (test force 98.07 N) with a holding time of 10 to 15 s. Three measurements were conducted for each parameter set consisting of a certain austenitizing temperature, cooling rate, and dwell time. Hot hole-flanging samples were cut orthogonal to the direction of current flow during heating (short sample side with 60 mm width) through the middle axis of the collar. On the cut and then polished surface, hardness tests were carried out along the inner and outer arches of the formed collars with a distance to the sheets surface of 100 µm. These measurements were executed according to HV0.5 (test force of 4.903 N) with a holding time of 10 s with a Micro-Vickers-hardness tester HMV-G (Shimadzu Europa, Duisburg, Germany). The evaluation of the imprint of HV10- and HV0.5-testing from a pyramid-shaped indenter (dihedral angle of 136°) was done manually.

2.5.2. Geometry Measurements

The geometry of samples from hot hole-flanging was evaluated by digitizing samples with the strip light projection system Atos Triple Scan (GOM, Braunschweig, Germany) and assessing them within GOM Inspect (GOM, Braunschweig, Germany). The optics of the measuring system were calibrated to a measuring volume with an edge length of 170 mm. Within GOM Inspect, 12 cutting planes running through the center axis of the digital collar at a 30° angle to each other were generated. Thinning Δs_c of the collar was determined by calculating the distance of curves resulting from the intersection of the cutting planes with the digitized model on the inside and the outside of the collar. The evaluation of the curvature was carried out analogously to the evaluation of thinning along curves resulting from the intersection of planes with the digitized samples. To determine the collar heights, the mean distance between the surface of the everted collar edge and the lower surface of the sheet metal was measured.

3. Results and Discussion

3.1. Hardness of X46Cr13 with Rapid Heat Treatment

The hardness set by heat treatment of the X46Cr13 sheet material with a variation of the austenitizing parameters at different cooling rates was examined. Only the parameter range relevant for an application in a progressive-die was analyzed with a limiting dwell time t_γ of up to 20 s for a possible two-stage heating setup. Within the considered parameter range, the hardness can be set between 317 and 680 HV10 (Figure 4). The hardness of the heat-treated X46Cr13 increases with the austenitizing temperature and dwell time. The averaged difference of the minimal and maximal hardness for cooling rates from 8 to 512 K/s is approximately 34 HV10. Therefore, the dependence of the hardness upon the cooling rate r_c is subordinate to that of the austenitizing temperature, underlining the air-hardening properties of the material.

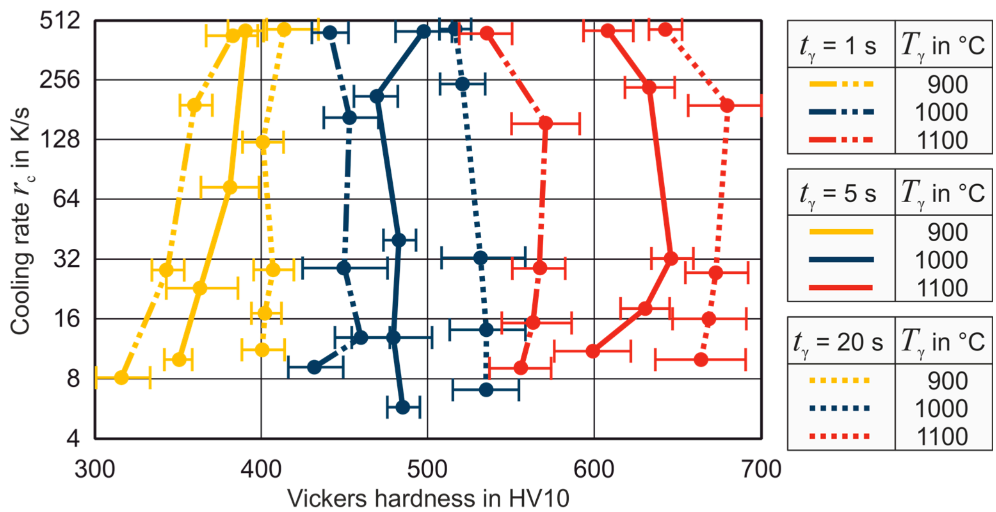


Figure 4. Hardness of X46Cr13 determined from the quenching tests with variation of the austenitizing temperature T_γ, dwell time t_γ, and cooling rate r_c.

According to Garcia et al. [23], who examined a constant dwell time t_γ of 60 s and austenitizing temperatures between 1000 °C and 1250 °C for X45Cr13, the increase in hardness with rising T_γ can be traced back to the accompanying decrease in carbide volume fraction. Hereby, the amount of carbon dissolved in the austenite increases together with the tetragonality of the martensite after quenching, improving the final hardness. Analogously, Barlow and Du Toit [24] are describing these mechanisms for the heat treatment of the AISI 420 with a chemical composition comparable to that of X46Cr13 (t_γ of 15 min and T_γ between 1000 °C and 1200 °C). As the carbide dissolution increases, the martensite start temperature drops and the amount of residual austenite in the quenched micro-structure increases. This mechanism causes a drop in hardness when a threshold austenitizing temperature is exceeded. This threshold value of T_γ decreases with rising dwell time t_γ from 1120 °C at 60 s [23] to 1075 °C at 15 min [24]. To evaluate whether the mechanism described is the basis for the observed increase in hardness, quenching tests were also carried out with T_γ = 1100 °C and t_γ = 300 s. Here, an average hardness of 571 HV10 was determined, which is approximately 13% below the hardness at a dwell time of t_γ = 20 s (Figure 4). Accordingly, the increase in hardness at high heating rates can also be attributed to a carbide dissolution that increases with temperature and dwell time until reaching a threshold, out of range for the application in a progressive-die when T_γ is limited to 1100 °C.

3.2. Forming Force and Contact Situation

The forces acting on the punch are divided into those that occur during forming (engage) and demolding (retract) (Figure 5a). Within the displayed parameter range examined in the Zwick Z250, the austenitizing temperature T_γ has a slight influence (up to 10% difference with const. v_p) on the forming force F_p. The punch speed v_p has a greater influence on the force F_p (up to 60% difference with const. T_γ). In principle, the force increases with lower forming temperatures, which can result from lower austenitizing temperatures or lower punch speeds, since the contact time with the tool and therefore the cooling time is longer here.

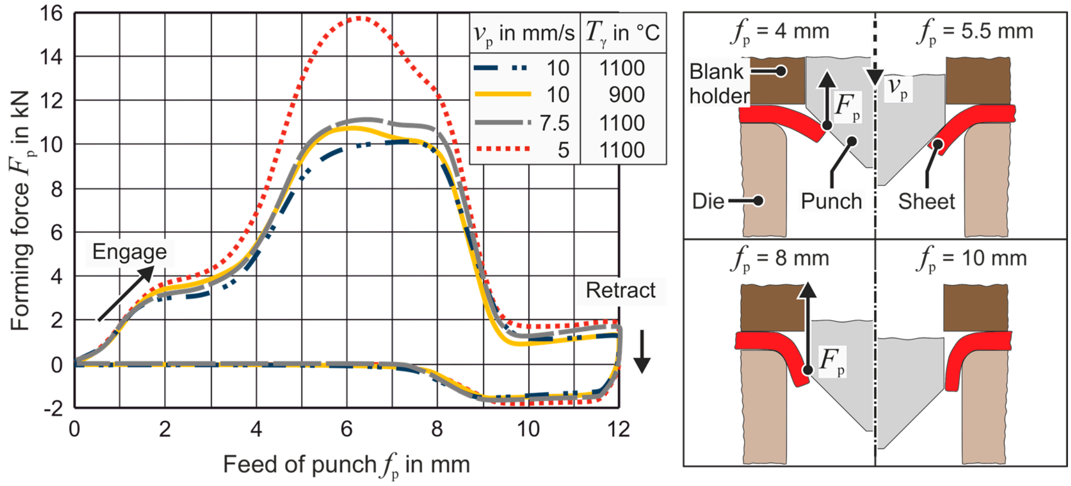
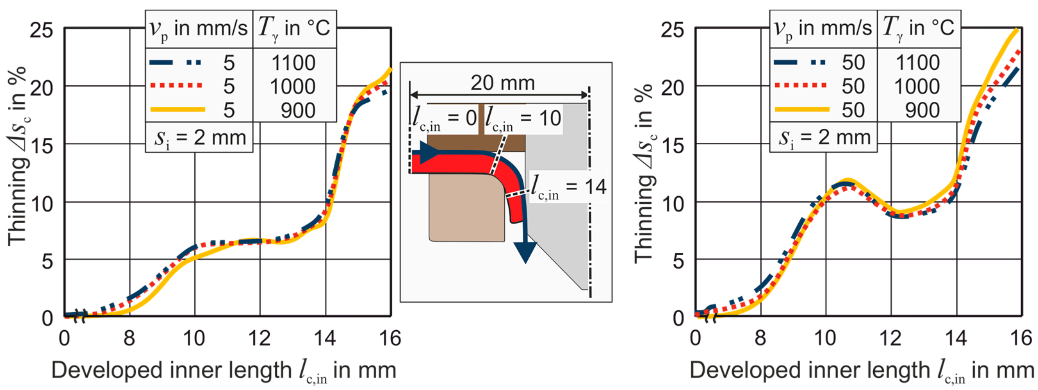


Figure 5. (**a**) Force acting on the punch F_p during engaging and retracting at different punch velocities v_p and austenitizing temperatures T_γ; (**b**) Schematic contact situation during forming (engaging) between sheet and punch for progressing feed f_p.

The characteristics of the force-displacement curve are related to the contact situation between the sheet and the tools for progressing feed of the punch f_p (Figure 5b). After the punch comes into contact with the sheet (f_p = 0 mm), the edge of the pre-hole is bent. The lever arm for bending becomes smaller with increasing feed of the punch f_p, since the point of application of force moves towards the die, which results in an increase in the punch force. This matter is superimposed by the gain in forming force due to strain hardening caused by the expansion of the pre-hole. For 5.5 mm < f_p < 8 mm, the collar is expanded around the transition between the cone and the cylindrical section of the punch. Here, a difference in shape and magnitude of the force-displacement curve at a punch speed of 5 mm/s compared to higher punch speeds occurs. This is an indication that a phase transformation from austenite to martensite has already taken place in parts of the flange and bend area of the collar, which locally inhibits material flow. When the cylindrical punch section is pushed through the formed collar (10 mm < f_p < 12 mm) and retracted, clamping forces act on the punch. These are due to the elastic springback and the thermal shrinking of the collar onto the punch. As the temperature decreases with the punch speed and the austenitizing temperature, the absolute value of clamping force increases during retracting of the punch. By assigning a characteristic force-displacement curve to each parameter set consisting of a temperature and a punch speed, a soft sensor can be established allowing for a reversible determination of the temperature during and after forming, subserving as input for process control.

3.3. Geometry of the Collar

The thinning values calculated according to Section 2.5.2 are assigned to the inner developed length $l_{c,in}$ (Figure 6b). $l_{c,in}$ is set to zero at the outer edge of the contact zone between the sheet metal and the blank holder, which corresponds to a distance of 20 mm from the center of the collar. The collar edge ($l_{c,in}$ > 16 mm) is not evaluated due to its macroscopic roughness and the associated measurement uncertainties. Thinning averaged from three samples per parameter set was analyzed dependent on the austenitizing temperature T_γ (Figure 6a,c) and dependent on the punch speed v_p (Figure 7). The average deviation of thinning calculated along the inner developed length for each parameter set is less than ±1%.



(**a**) (**b**) (**c**)

Figure 6. (**a**) Effect of the austenitizing temperature T_γ on thinning of the collar Δs_c with a constant punch speed v_p of 5 mm/s; (**b**) Definition of the developed inner length $l_{c,in}$; (**c**) Effect of austenitizing temperature T_γ on thinning of the collar Δs_c with a constant punch speed v_p of 50 mm/s.

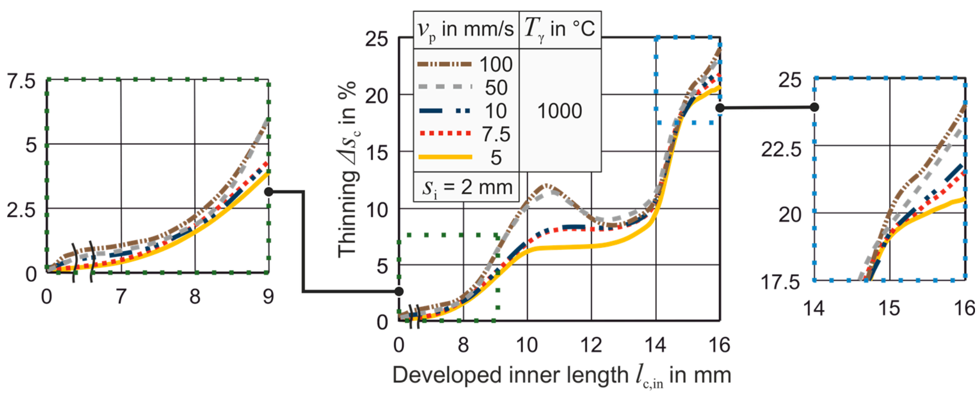
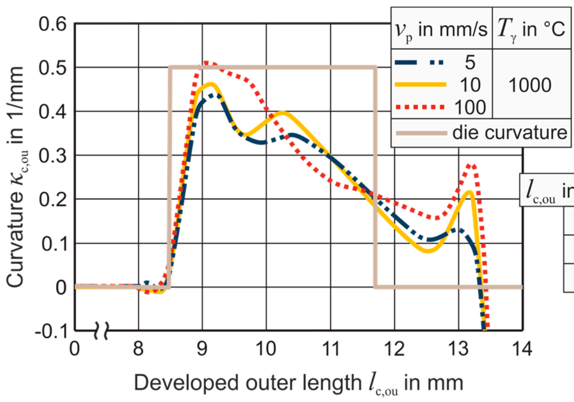


Figure 7. Effect of the punch speed v_p on thinning of collar Δs_c for a constant austenitizing temperature T_γ of 1000 °C.

Thinning of the collar flange (6 mm < $l_{c,in}$ < 9 mm) is amplified with rising austenitizing temperature T_γ (Figure 6) or also with rising punch speed v_p (Figure 7). The forming temperature increases with rising T_γ at constant v_p or converges to T_γ with rising v_p, leading a reduction in flow stress, facilitating the material flow out of the flange sheet thickness. In the bend area (9 mm < $l_{c,in}$ < 14 mm), thinning is affected by the increasing punch speed v_p by up to 5% (Figure 7). A reduction of the temperature gradient in the transition between the flange and the bend area ($l_{c,in}$ ≈ 9 mm) with rising punch speeds entails a decline in the gradient of temperature-dependent flow stress. The latter is leading to an increase of the curvature of the collar in the bend area promoting thinning. In the cylindrical collar area (14 mm < $l_{c,in}$ < 15 mm), thinning satisfies a linear function, showing a minor dependence of up to 2% on the set process parameters. Close to the collar edge ($l_{c,in}$ > 15 mm), rising punch speeds v_p also amplify thinning (Figure 7). Inversely, for higher punch speeds of 50 mm/s, a decrease in thinning of up to 4% with increasing austenitizing temperature can be observed here (Figure 6c).

Due to the principle of volume constancy, increased thinning corresponds to a change in collar height h_c or to a change in curvature κ. A change in curvature correlates with the expansion of the pre-hole and therefore with the material flow from the sheet thickness into the circumferential direction of the collar. Within the parameter range examined in the Zwick Z250 and the Schuler MSD2-400, collar heights h_c from 3.92 to 4.09 mm were determined. However, with three samples being evaluated for each parameter set, the range between the determined minimal and maximal h_c is even to the scatter within a parameter set itself. Therefore, a relation between thinning and the height of the collar cannot be established. To analyze the curvature of the collar, the developed outer collar length $l_{c,ou}$ is considered (Figure 8b). Based on the course of the curvature along the outside of the collar $\kappa_{c,ou}$, the external radial expansion and convergence of the collar to the contour of the die can be concluded. Above the developed inner collar, length $l_{c,in}$ is used, as it offers improved spatial resolution of thinning due to $l_{c,in} > l_{c,ou}$. An allocation of the inner to the outer developed collar length is given in Figure 8b. With increasing punch speed, up to 35 % greater curvatures $\kappa_{c,ou}$ are set in the transition from the flange to the bend area (8.5 mm < $l_{c,ou}$ <10 mm) (Figure 8a). This correlates with an increase in thinning Δs_c in the bend area as stated above. Due to a reduction of the equalization time with increasing punch speed, the temperature gradient within the sheet in the bending area decreases. This reduces the bending resistance in the transition area to the flange, which enables the collar to fit closer to the die contour. As the process speed increases, an up to 49% greater curvature is set in the area of the collar edge (12.5 mm < $l_{c,ou}$ <13.5 mm). Here, again, the reduction in the temperature gradient to the adjacent collar wall is the cause.



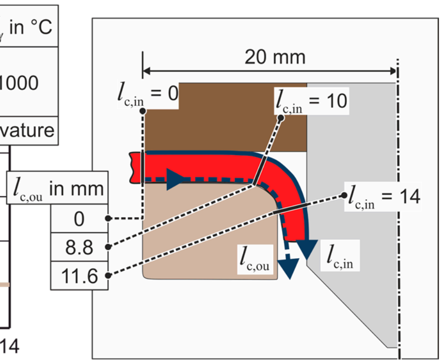


Figure 8. (**a**) Ideal curvature of the die and curvature κ along the developed outer length $l_{c,ou}$ for different punch velocities v_p; (**b**) Definition of the developed outer length $l_{c,ou}$.

With a variation of the austenitizing temperature and the punch speed, no influence of thinning, curvature, and collar height upon the preparation method of the specimens during hot hole-flanging was determined. To control the examined product properties, the cutting of the pre-hole must therefore not to be considered. The presented results were determined from specimens with laser-cut pre-holes.

3.4. Adjusting Hardness of the Collar

In addition to the prior investigated influence of the austenitizing temperature, dwell time, and cooling rate, the influence of forming on hardness could be present during hot hole-flanging with simultaneous heat treatment. Therefore, setting of the hardness in the formed collar was analyzed based on hardness measurements along the inside and the outside of the collar (Figure 9). For an austenitizing temperature T_γ of 1100 °C with a punch speed v_p of 10 mm/s and a dwell time t_γ of 5 s, the mean hardness in the collar is 625 HV0.5. By lowering the austenitizing temperature T_γ to 900 °C, the mean hardness decreases by 37.7% to 389 HV0.5, caused by a decrease in carbide dissolution (see Section 3.1). Through reduction of the punch speed v_p to 5 mm/s, the mean hardness decreases by 2.6% to 609 HV0.5, induced by a decline of the cooling rate. On average, the hardness on the inside of the collar is 2.1% higher than on the outside. Dissimilar cooling rates over the sheet thickness in the collar are to be expected due to a differing contact situation between the tools and the inner and outer collar (see Section 3.2), which can cause the described disparity. The hardness tends to increase by an average of approximately 10% from the flange area ($l_{c,in}$ = 8 mm) to the edge of the collar ($l_{c,in}$ = 16 mm) (Figure 9). Analogous to Section 3.1 and as shown above based on the variation of the punch speed, this tendency cannot be attributed to a difference in cooling rate. The main cause is the sensitivity of the hardness towards a spatial variation in austenitizing temperature. The current is constricted at the edges of the pre-hole, creating a temperature gradient in the examined plane (Section 2.5.1) with a temperature range of T_γ ±20 K and towards the edge of the pre-hole rising temperature. This is benefiting a rise of hardness towards the edge of the collar.

The deviation of the average hardness values set by combined forming and quenching compared to those set by sole heat treatment with the same austenitizing parameters is below 3%. Accordingly, the influence of forming is neglectable and setting hardness by adapting the austenitizing parameters is also feasible for simultaneous forming and heat treatment of X46Cr13 sheet material.

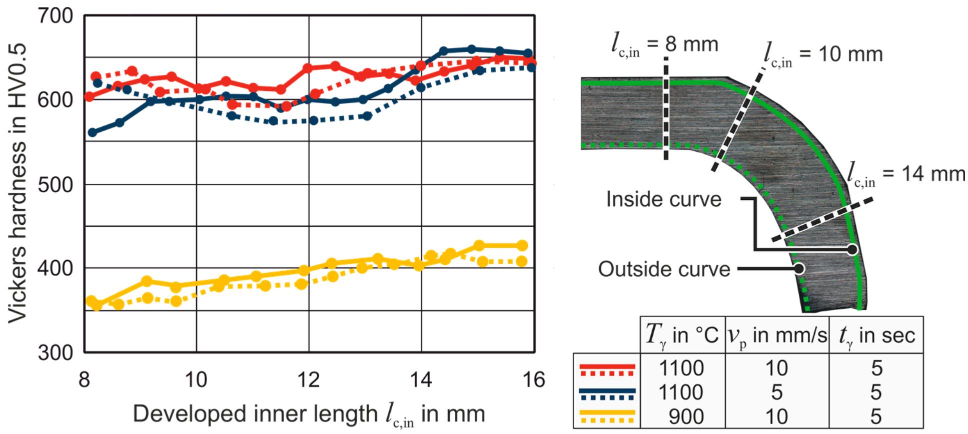


Figure 9. Distribution of hardness in the formed collar along the developed inner length $l_{c,in}$ with varying austenitizing temperature T_γ and punch speed v_p at a constant dwell time t_γ of 5 s.

3.5. Control of Product Properties

By rapid heating of the sheet metal blank inside the progressive-die with short dwell times, the austenitizing parameters in the multi-step hot sheet metal forming process can be controlled from stroke to stroke. Through adaption of the austenitizing temperature and the punch speed, the spatially as well as time-dependent temperature and cooling rate during hot hole-flanging are set. Hereby, thinning and the curvature partially are adjustable in the bend and at the outer edge area of the collar. Simultaneously, the dependency of the quenched hardness of X46Cr13 sheet material on the austenitizing temperature and the dwell time and reduced sensitivity towards the cooling rate allows for a setting of the final product hardness during hot hole-flanging. For a more precise control of the final product hardness, the applied method for heating of the blank with the pre-hole needs to be adapted. A targeted use of several electrodes similar to Mori et al. [25], or hot cutting in same stroke with hot hole-flanging comparable to Cheng [13], is conceivable. The latter allows a blank with a constant cross-section to be heated. Based on the in-situ force measurement during hot hole-flanging, a soft sensor can be established assessing the force-displacement curves with a real-time model to determine the temperature during and after forming in the collar. The model-based soft sensor design is addressed in [14] for the considered process. Besides process and product property monitoring with this, an additional input for the process control can be generated to realize robust closed-loop property control.

4. Conclusions

To establish models for property-controlled multi-stage hot sheet metal forming, relationships between product properties and the process parameters must be available. As one step towards the development of fundamental approaches for property control, hot-hole-flanging of X46Cr13 sheet material with simultaneous heat treatment with consideration of the boundary conditions of the multi-stage process was analyzed. Hereby, relationships between the process parameters (austenitizing temperature, dwell time, punch speed) and the product properties (geometry, hardness) were derived.

An examination of the sole heat treatment of X46Cr13 sheet material by means of rapid heating and short dwell times demonstrates that by adjusting the process parameters, austenitizing temperature (from 900 to 1100 °C) and dwell time (from 1 to 20 s) hardness values between 317 and 680 HV10 are set. A minor influence of the cooling rate is determined with an average difference of 34 HV10 between the minimal and maximal hardness for cooling rates ranging from 8 to 512 K/s. In the process window relevant for a progressive-die, the increase in hardness with rising austenitizing temperature and dwell time is traced back to an increasing dissolution of carbides into the austenite.

The analysis of the punch force in hot hole-flanging indicates the dependency upon the process parameters austenitizing temperature and punch speed with a maximum increase in force of up to 60 %. With this knowledge, a soft sensor can be developed, allowing for an in-situ determination of the forming parameters based on the forming force.

An evaluation of the formed geometry in hot hole-flanging at different punch speeds (from 5 to 100 mm/s) and austenitizing temperatures (from 900 to 1000 °C) reveals an increase in curvature of the bend area of up to 35%, correlating with an increase in thinning of up to 5%. Therefore, these relationships must be considered in control.

The hardness values set during pure heat treatment are reproduced during hot hole-flanging, where the influence of forming and spatially variating cooling rates is given. The minor sensitivity of the set hardness of the X46Cr13 sheet material towards the cooling rate and therefore the punch speed is facilitating control of hardness during forming.

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