

Numerical Study to Promote the Residual Stresses Development during ISF Process with Improvement in Two Point Incremental Die Forming

Muhammad Junaid Afzal^{1,a*}, Johannes Buhl^{1,b}

¹Chair of Hybrid Manufacturing, Brandenburg University of Technology, Cottbus - Senftenberg,
Konrad – Wachsmann – Allee 17, Cottbus D-03046, Germany

^aafzal@b-tu.de, ^bjohannes.buhl@b-tu.de

Keywords: Disc springs; Martensite transformation; Residual stresses; Cooling channels; Incremental sheet forming; Austenite phase.

Abstract. Metastable austenitic stainless steel (MASS) has been the material of choice for the fabrication of disc springs employing incremental sheet forming (ISF) processes due to its high creep, fatigue, and chemical resistance, as well as its good surface quality. Previous research has shown that the presence of martensite enhances the formation of beneficial compressive residual stresses. However, if the ISF is accelerated to improve efficiency, the rise in temperature during ISF operation suppresses the deformation that causes martensite transition (DIMIT). In essence, the cooling channel shapes are developed with numerical assistance such that its impact on residual stress induction is low. Variation in ISF process parameters, such as tool diameter, tool step-down, and contact force, as well as variation in cooling channel size, are used to construct the computational analysis. To analyze the finally produced residual stresses in the disc spring, the non-linear isotropic/kinematic hardening combined with the TRIP formulation is simulated. According to the comparison, the channel size must be between 0.8 and 1.2 mm in radius to minimize residual stress fluctuation. Additionally, when moving across the die with cooling channels, the force-controlled ISF produces more consistent results. Based on the numerical findings, it is conceivable to greatly enhance the ISF process speed and dissipate process heat by cooling the sheet on sides, allowing residual stresses and martensite content to be adjusted in a stable manner. As a result, the ISF process may be greatly expedited, making it more appealing for industrial applications.

1. Introduction

The DIN 2093 standard defines disc springs as shallow conical components often employed in industries that need high spring forces with limited spring travel [1, 2]. Under operating tensile loads, disc springs must have better fatigue resistance. In high cycle fatigue (HCF) testing, the induction of compressive residual stresses in tensile stressed regions may delay the nucleation and propagation of fatigue cracks [3, 4]. Shot peening is the traditional technique of embedding compressive stresses to disc springs [5]. During this process, tiny, round metal or ceramic beads are hurled at the component surface. This causes local plastic deformation at the surface layer of the specimens, changing residual stress, and strain hardening [6]. However, it may affect the spring's geometry and surface topography and reduce heavily shot-peened components durability and service life [7, 8]. Therefore, because of their resistance to stress relaxation and good mechanical characteristics, metastable austenitic stainless steels (MASS) are the most frequently used for disc spring production. MASS is often referred as transformation induced plasticity (TRIP) because they undergo austenite (γ)-to-martensite (α') transition. This transition is based on the material's critical free energy state, with austenite stable at higher temperatures and martensite stable at lower temperatures [9]. However, these transitions may also be aided by mechanical driving forces, resulting in increased $\gamma \rightarrow \alpha'$ phase transformation with increased plastic deformation at ambient temperature. As a result, the plastic work during the forming or service loading of the MASS can be utilized to enhance the α' –martensite phase transformation.

Incremental sheet forming (ISF) has been developed to take the role of shot peening. It is suitable for small batch production to selectively increase the tangential residual compressive

stresses in disc springs and improve the industrial manufacturing process [10]. In terms of ISF processes, there are two major types: single-point incremental forming (SPIF) and two-point incremental forming (TPIF). High residual stresses are developed during the localized forming process. Numerous researches have been conducted to determine the development of this residual stress in ISF [11, 12]. However, the localized contact between the forming tool and component surface increases the temperature at changing forming rates. Turski et al. [13] investigated the development of residual stresses in the subsurface of AISI 301LN and AISI 316L steel components using various surface treatment process parameters. Wick et al. [14] presented the influence of the shot peening temperature on the behavior of residual stresses in steel AISI 4140. He depicted that the increase in temperature during peening leads to relaxation of the residual stresses. Mordyuk et al. [15] studied the residual stresses and martensite fraction in the peened samples of 321-stainless steel. He reported that the absence of the martensite was attributed to the presence of the increased localized temperature during the ablation process. In his work, he suggested using running water during peening to have better-transformed martensite and residual stresses.

Previous works have proven that the presence of martensite improves the buildup of the favorable compressive residual stresses [1, 2, 10]. However, if the ISF is accelerated to improve efficiency, the rise in temperature caused by the ISF operation suppresses the deformation-induced martensite transition (DIMIT) [16]. In essence, the geometry of the cooling channels are orchestrated with numerical assistance so that their effect on the induction of residual stresses are reduced to an absolute minimum and the material of the sheet blank do not flow into those channels. The changes in ISF process parameters, such as tool diameter, tool step-down, contact force, and the deviation in cooling channel size, are used to build the computational analysis. The numerical model [17] is used to perform the computational analysis, which includes phase transformation as a component. The UMAT combined with the TRIP formulation [18] is simulated to assess the residual stresses generated in the disc spring at the end of the simulation. Furthermore, the contrast of tool movement controlled by displacement vs. force is investigated.

2. Material and Geometry

The stainless steel EN.1.4310 (AISI 301) with austenitic properties is used to create the incremental disc springs. In the present work, the disc spring of thickness 1mm was used to find out the influence of the die hole on the induced residual stresses. The chemical composition of the steel we selected is depicted in Table 1. Figure 1 shows the standard geometry of a disc spring. External diameter, internal diameter, thickness, and free height of the disc spring are represented by D_e , D_i , t and l_0 , respectively.

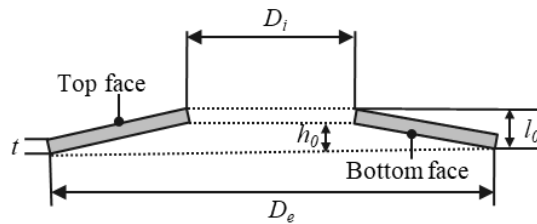


Fig. 1. Schematic representation of the examined disc springs.

Table 1: Chemical composition of AISI 301 (Alloying elements (wt. %))

C	Si	Mn	P	S	Cr	Ni	Mo	N	Fe
0.07-0.15	1.0	2.0	0.045	0.03	17.5-19.5	6.5-8.0	-	0.1	Bal.

3. Manufacturing Disc Springs by ISF Technique

The incremental sheet forming (ISF) method was used to fabricate the disc springs used in the experiments. This technique may be classified as either single-point incremental forming (SPIF) or

two-point incremental forming (TPIF), depending on whether or not a die is present during the ISF operation. The use of TPIF with a negative die, according to previous research, mimics the deep rolling effect and produces better results when it comes to inducing compressive residual stresses onto the inner surface of produced disc springs. These residual stresses result from plastic deformation of the contact surface in addition to martensite transformation.

The forming process converts approximately 90% of the deformation energy into heat. In addition, energy dissipates due to friction at the contact points of tool and sheet metal, which, however, leads to a local temperature increase; see Figure 2. The locally introduced heat is distributed in the spring via heat conduction and conducted away via the forming tools or released into the environment by convection. To measure the temperature during the forming process, a thermocouple is attached to the underside of the sheet metal blank so that the temperature can be recorded depending on the ISF process parameters tool diameter, tool distance, speed, and contact force. To ensure that the temperature effects do not suppress the development of the residual stresses, the sheet should be cooled with compressed air on the top and underside. The cooling channels in the die transform the two-point process locally to a one-point ISF. Simulations are used to investigate different outlet openings of the cooling channels (round, elliptical, angular) and to determine the maximum possible dimensions for which the ISF process does not change for the residual stresses. In addition, the influence of the cooling channel spacing on the residual stress development is investigated for the round exit shape.

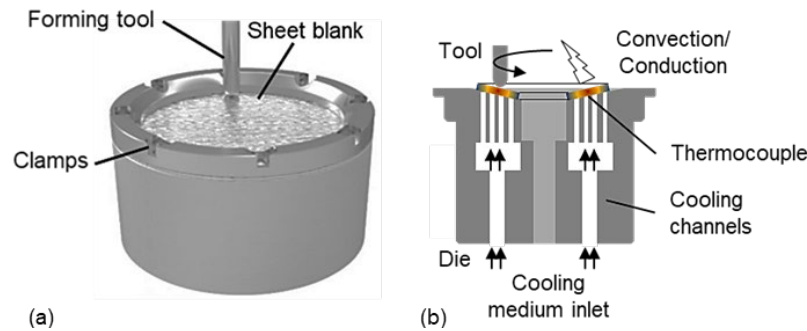


Fig. 2. Illustration of the ISF process (a) and the proposed cooling of the spring (b).

4. Numerical Model

A constitutive model that adequately captures the quantitative residual stresses has been developed for the process mechanics and material behavior. AISI 301 shows the TRIP behavior when subjected to the deformation during ISF process, characterized by a continuous cyclic bending/unbending deformation mechanism. Following [17, 19], a non-linear isotropic/kinematic hardening law with an integrated Oslen-Cohen model [18] was created to give a comprehensive knowledge of phase transition during deformation and to aid in the analysis of sub-surface residual stresses. The constitutive model takes into account the austenite (γ) of volume $(1 - f_{\alpha'})$ and the martensitic (α') that is formed out of the parent γ -phase having volume of $f_{\alpha'}$. The macroscopic flow stress is a composite of each component phase computed as:

$$\sigma_f = \sigma_{y,\gamma}(1 - f_{\alpha'}) + \sigma_{y,\alpha'}f_{\alpha'} \quad (1)$$

where, $\sigma_{y,\gamma}$ and $\sigma_{y,\alpha'}$ are the flow stress of the austenite and martensite respectively. Using von-Mises with non-linear hardening, each phase exhibits elastoplastic behavior. The yield behavior is characterized as follow:

$$\sigma_y = \sigma_{eq} - \sigma_0 - R \quad (2)$$

in Eq. (2), σ_{eq} present the von-Mises stress, σ_0 is initial yield and R is the isotropic hardening:

$$\sigma_{eq} = \sqrt{\frac{3}{2}(s_{ij} - X_{ij})(s_{ij} - X_{ij})} \quad (3)$$

Here, s_{ij} is the deviatoric part of the stresses. X represents the kinematic hardening terms. The detailed formulation is provided in [17]. For fitting data on strain-induced martensite formation, the Olson-Cohen model (OC-model) is often used. Plastic strain and martensitic volume fraction are related by this sigmoidal function as:

$$f_{\alpha'} = 1 - \exp \{-\beta_0(1 - \exp(-\xi\varepsilon)^n)\} \quad (4)$$

The parameter ξ with increasing strain controls the rate of shear-band development and is reliant on the stacking fault energy. The β_0 parameter variation governs the likelihood of a martensitic nucleation forming from the embryo and it is controlled by the chemical driving force of the process i.e. $\gamma \rightarrow \alpha'$. Standard tensile tests with online feritscope measurements, tension-compression tests, and an inverse FE technique based on systematical change in the numerical parameters are used until excellent match with experimental data is obtained to predict the development of the martensite composition with strain. The predicted parameters for material response are depicted in Table 2. To reduce computational efforts, a feasible match is established by utilizing a single 8-node linear brick element (C3D8), Fig. 3 (a, b).

The obtained material characteristics were utilized to build up a numerical simulation of the disc spring with a hole in the die to determine the optimum size for the cooling channel in the die such that the residual stresses are no more reliant on these channels. For the numerical analysis, the disc spring of dimension 112/57/3mm ($D_e/D_i/t$) was used. In addition, the tool path was imported into Abaqus as respective co-ordinates in the x, y and z-axis from the commercial CAD program Pro/e Creo®. The numerical model is presented in Fig. 3c.

Table 2: Identified computational material model parameters [17]

$\sigma_{y_0,\gamma}$	$Q_{o,\gamma}$	b_γ	E_γ	ν_γ	vol_{γ_0}	χ_γ	ω_γ
856 MPa	302.7 MPa	19.97	178 GPa	0.3	90%	11680.5 MPa	450
$\sigma_{y_0,\alpha'}$	$Q_{o,\alpha'}$	$b_{\alpha'}$	$E_{\alpha'}$	$\nu_{\alpha'}$	$vol_{\alpha'_0}$	$\chi_{\alpha'}$	$\omega_{\alpha'}$
1460 MPa	1005 MPa	10.22	210 GPa	0.28	9.5%	11680.5 MPa	450

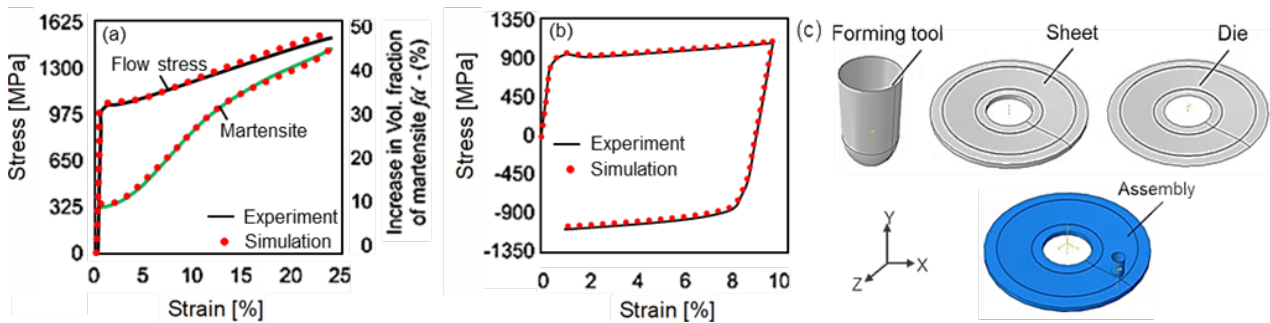


Fig. 3. A comparison of numerical and experimental curves: (a) Stress and martensite development against plastic strain, (b) Cyclic response of stress-strain. (c) Mechanical set-up for numerical study.

5. Results and Discussion

The main goal of the current study is to enhance the formation of the targeted residual stresses during the forming operation of the disc springs. Fig. 4 (a) depicts the measured temperature at the time of contact on the top surface of the disc spring. It is observed that with an increase in the feed rate during ISF operation, the temperature is raised above 100 °C for the highest feed rate without

lubrication. With lubrication the rise in local temperature decreases but for highest ISF feed rate it is above 80 °C, which suppresses the martensite development and deters the residual stress induction; see Fig. 4 (b, c). Such observations are also reported in the literature [15, 16].

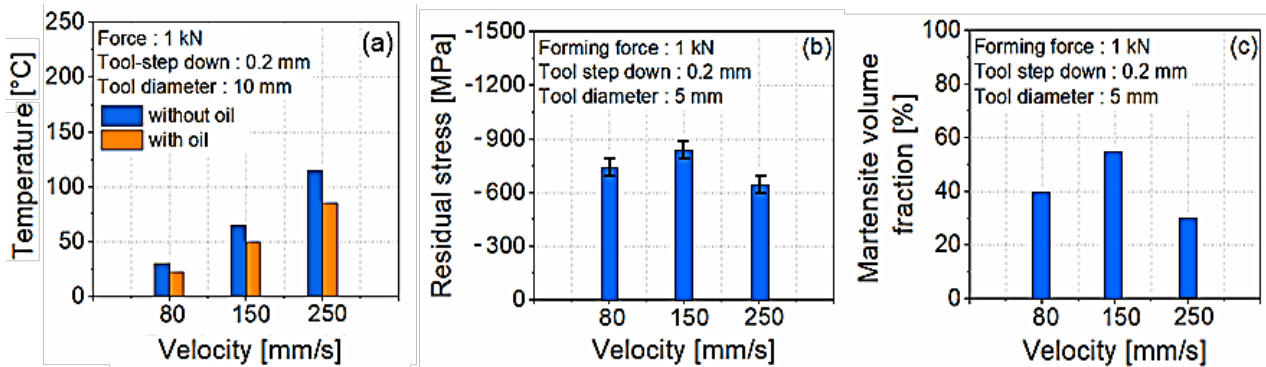


Fig. 4. Measurement of ISF frictional temperature (a), residual stress (b), and martensite fraction based on the process parameter (c).

In this regard, a numerical study was conducted to better design the forming die with cooling channels to induce residual stress. The displacement-controlled tool movement was adopted to evaluate the residual stresses over these cooling channels. The simulations were performed with different geometric shapes (square, ellipse and circle) specified by the edge length of the square L , the length of the ellipse m and the diameter of the circle d . The results show that for a constant area of the channels, the most favorable tangential compressive stresses after spring back simulations occur with a circular geometry compared to a square and elliptical geometry, see Fig. 5. The circular shape cooling channels give the results in close approximation to the reference residual stress. With increasing the area, the localized favorable residual stresses were reduced. It was found that the distance (S) between the individual cooling channels must at least be 3 mm from the center of one hole to the other so that the induced residual stresses remain the same (Figure 5).

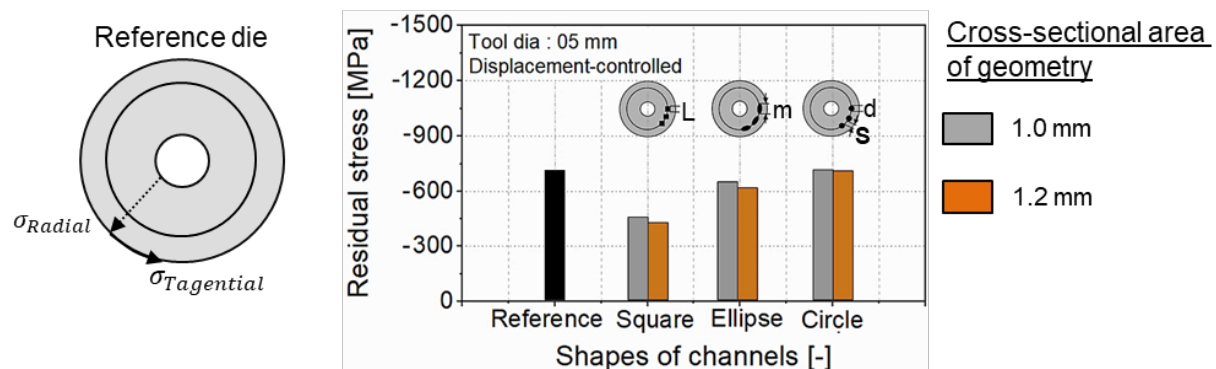


Fig. 5. Different geometric shapes of cooling channels and the resulting residual stresses

The circular cooling channels were examined in detail. For this purpose, bore diameters from 0.8 mm to 2.0 mm have been modelled (Fig. 6). The size of the cooling channel appears useful if the loss of residual stress is low and the surface profile on the upper side is unchanged. After spring back simulation, it was found that the residual stresses for cooling channels of size 0.8 mm, 1.0 mm and 1.2 mm develop approximately the same residual stresses in the spring as with a full die. However, as the cooling channel diameter increases beyond 1.2 mm, the sheet metal on top of the disc springs bends into the channels, resulting in a loss of compressive stress. This loss of stress is due to the lack of counterforce in the die.

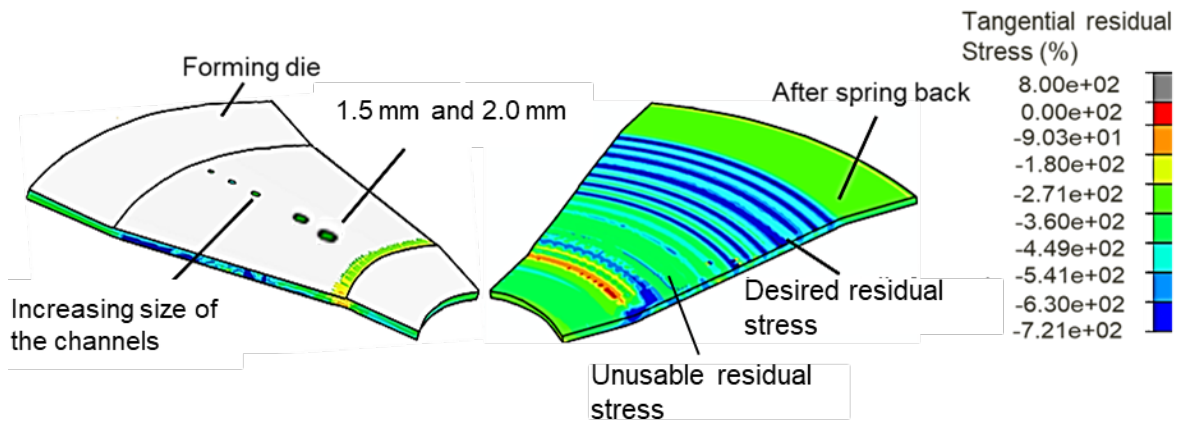


Fig. 6. Residual stress distribution in tangential direction for numerical analyses for cooling channel diameter 0.8 mm, 1.0 mm, 1.2 mm, 1.5 mm and 2.0 mm.

Fig. 7 (a) presents the tangential and radial residual stresses induced during the ISF simulation above the cooling channel. The tangential stress was higher on the tool contact side of the disc spring. Furthermore, the induced residual stress increases quantitatively with decreasing tool diameter, see Fig. 7 (b). In addition, the smaller tool generates a more concentrated deformation zone on the tool contact side, which leads to higher plastic strain. In return, the DMT is increased, resulting in more residual stresses.

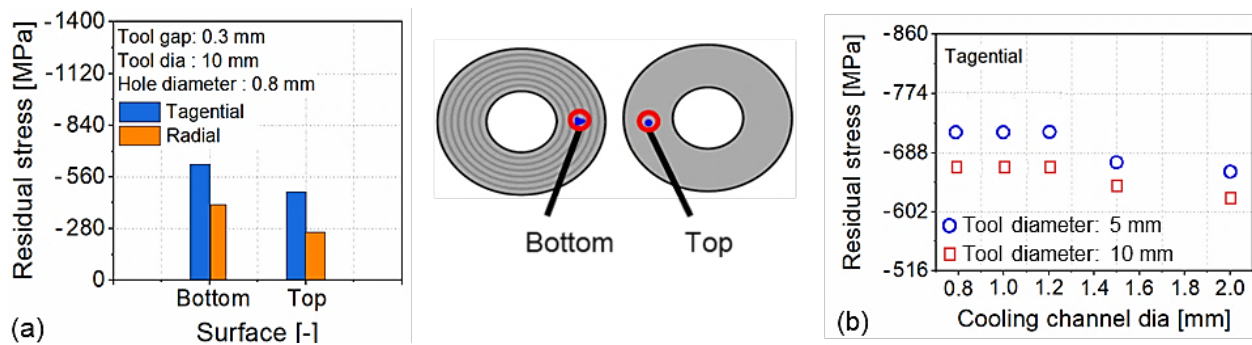


Fig. 7. Stresses on the top and bottom surfaces of the created disc spring above the die hole (a) and variation in tool diameter along cooling channel diameters (b).

Fig. 8 shows a comparison of a force- and path-controlled tool movement across the circular cooling channel with the diameter of 1.2 mm. The tangential stress component after springback is shown. 13.8 % more residual stress was observed with force-controlled process control than with displacement-controlled tool movement. This difference was due to the fact that the forming tool generated a high plastic strain even when passing over the holes under constant load. This effect is also reflected in the larger martensite fraction (Fig. 8 (b)).

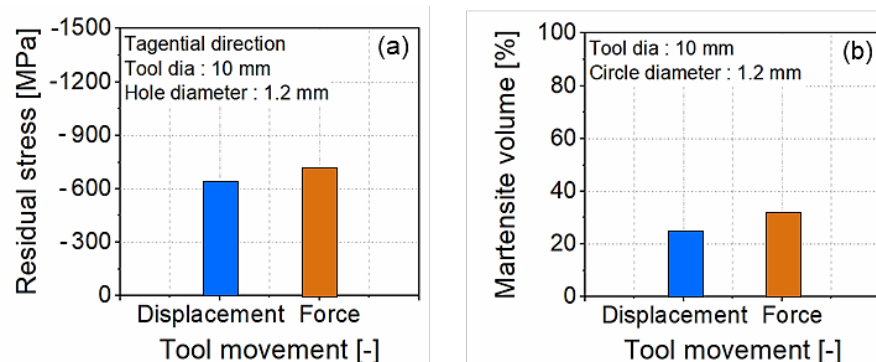


Fig. 8. Comparison between force controlled and displacement (a) and evolution martensite content (b) over selected cooling channel.

6. Conclusion

Previous studies have shown that martensite promotes the accumulation of beneficial compressive residual stresses. However, accelerating the ISF reduces the deformation-induced martensite transformation due to increasing process temperatures. Using a multiphase model with phase transformation, the MASS behavior is simulated and the cooling channels are dimensioned in such a way that the residual stress loss remains minimal. The circular opening of the channel resulted in higher residual stresses than the elliptical and triangular shapes. With a diameter of the cooling channel between 0.8 mm and 1.2 mm, approximately the residual stresses are achieved that also occur in the reference case without cooling channels. This means that for a sheet with a thickness of 1.0 mm, residual stresses are stably induced despite the cooling channels. With smaller tool diameters, an increase in residual stresses could be observed. In addition, the force-controlled ISF provides more reliable results when moving over the die with cooling channels. Based on the numerical results, it seems possible to significantly increase the ISF process speed and dissipate the process heat by cooling the sheet on both sides, thus adjusting residual stresses and the martensite content in a stable way. Thus, the ISF process can be accelerated significantly and also become interesting for industrial applications.

Acknowledgements

The authors would like to thank the German Research Foundation DFG for supporting the depicted research within the priority program ‘SPP2013’ through project no. ‘BU 3150/7-3’ and especial thank to Prof. Dr. Markus Bambach for his previous research contributions, on which this investigation was possible.

References

- [1] F. Maqbool, R. Hajavifard, F. Walther, M. Bambach, Engineering the residual stress state of the metastable austenitic stainless steel (MASS) disc springs by incremental sheet forming (ISF), *Prod. Eng. Res. Devel.* 13 (2019) 139–148.
- [2] F. Maqbool, R. Hajavifard, F. Walther, M. Bambach, Experimental investigation and finite element modelling of residual stress control in disc springs made of metastable austenitic stainless steel (MASS) using incremental sheet forming (ISF), *Procedia Manufacturing* 29 (2019) 12–20.
- [3] M. Halilović, S. Issa, M. Wallin, H. Hallberg, M. Ristinmaa, Prediction of the residual state in 304 austenitic steel after laser shock peening – Effects of plastic deformation and martensitic phase transformation, *International Journal of Mechanical Sciences* 111–112 (2016) 24–34.
- [4] R. Hajavifard, F. Maqbool, A. Schmiedt-Kalenborn, J. Buhl, M. Bambach, F. Walther, Integrated forming and surface engineering of disc springs by inducing residual stresses by incremental sheet forming, *Materials (Basel, Switzerland)* 12 (2019).
- [5] Y.F. Al-Obaid, A rudimentary analysis of improving fatigue life of metals by shot-peening, *Journal of Applied Mechanics* 57 (1990) 307–312.
- [6] L. Wagner, Shot Peening, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, FRG, 2003.
- [7] V. Llana, F.J. Belzunce, Study of the effects produced by shot peening on the surface of quenched and tempered steels: roughness, residual stresses and work hardening, *Applied Surface Science* 356 (2015) 475–485.
- [8] R. Fathallah, High cycle fatigue behavior prediction of shot-peened parts, *International Journal of Fatigue* 26 (2004) 1053–1067.
- [9] S. Curtze, V.-T. Kuokkala, M. Hokka, P. Peura, Deformation behavior of TRIP and DP steels in tension at different temperatures over a wide range of strain rates, *Materials Science and Engineering: A* 507 (2009) 124–131.

-
- [10] R. Hajavifard, K. Moehring, F. Walther, M.J. Afzal, J. Buhl, Characterisation of phase transformation and induced residual stresses in incrementally formed disc springs: an experimental and numerical study (2021).
 - [11] X. Shi, G. Hussain, S.I. Butt, F. Song, D. Huang, Y. Liu, The state of residual stresses in the Cu/Steel bonded laminates after ISF deformation: An experimental analysis, *Journal of Manufacturing Processes* 30 (2017) 14–26.
 - [12] C. Radu, C. Tampu, I. Cristea, B. Chirita, The effect of residual stresses on the accuracy of parts processed by SPIF, *Materials and Manufacturing Processes* 28 (2013) 572–576.
 - [13] M. Turski, S. Clitheroe, A.D. Evans, C. Rodopoulos, D.J. Hughes, P.J. Withers, Engineering the residual stress state and microstructure of stainless steel with mechanical surface treatments, *Appl. Phys. A* 99 (2010) 549–556.
 - [14] A. Wick, V. Schulze, O. Vöhringer, Influence of the shot peening temperature on the relaxation behaviour of residual stresses during cyclic bending, 1999.
 - [15] B.N. Mordyuk, Y. Milman, M.O. Iefimov, G.I. Prokopenko, V.V. Silberschmidt, M.I. Danylenko, A.V. Kotko, Characterization of ultrasonically peened and laser-shock peened surface layers of AISI 321 stainless steel, *Surface and Coatings Technology* 202 (2008) 4875–4883.
 - [16] M.J. Afzal, R. Hajavifard, J. Buhl, F. Walther, M. Bambach, Influence of process parameters on the residual stress state and properties in disc springs made by incremental sheet forming (ISF), *Forsch Ingenieurwes* 85 (2021) 783–793.
 - [17] M.J. Afzal, F. Maqbool, R. Hajavifard, J. Buhl, F. Walther, M. Bambach, Modeling the residual stresses Induced in the metastable austenitic stainless steel disc springs manufactured by incremental sheet forming by a combined hardening model with phase transformation, *Procedia Manufacturing* 47 (2020) 1410–1415.
 - [18] G.B. Olson, M. Cohen, A mechanism for the strain-induced nucleation of martensitic transformations, *Journal of the Less Common Metals* 28 (1972) 107–118.
 - [19] F. Maqbool, F. Maaß, J. Buhl, M. Hahn, R. Hajavifard, F. Walther, A.E. Tekkaya, M. Bambach, Targeted residual stress generation in single and two point incremental sheet forming (ISF), *Arch Appl Mech* 91 (2021) 3465–3487.