Characterisation of Phase Transformation and Induced Residual Stresses in Incrementally Formed Disc Springs - An Experimental and Numerical Study

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Abstract

Disc springs are shallow, conical components suitable for a broad application spectrum in the industry. They need to have a reliable and long service life. However, operational tensile stresses can limit their lifetime. Traditionally, their performance can be improved by inducing compressive residual stresses using shot peening which causes additional time and cost in the production process. In this study, the incremental sheet metal forming (ISF) approach was employed for an integrated and targeted induction of residual compressive stresses in the disc springs manufacturing process. The springs were produced using AISI 301 stainless steel sheet blanks. The roles of various process parameters such as forming tool diameter, tool step down, feed rate and initial sheet blank condition on the characteristics of induced residual stresses were studied experimentally and numerically. Residual stress measurements were carried out using the X-ray diffraction method. With the help of the ISF method, the compressive residual stress induction could be integrated into the forming process of disc springs. As a result, additional post-forming treatments could be omitted. Forming tool diameter and forming temperature significantly influenced the induced residual stress characteristics. In addition, the martensite formation of metastable austenitic steels showed an important contribution to the residual stress properties. Furthermore, the developed numerical approach could precisely predict the formation of the residual stresses and can be applied for the design of the disc springs with the targeted residual stress properties.

1 Introduction

Disc springs are defined by DIN 2092 as shallow conical elements and are often used in industries where high spring forces with low spring travel are required [1-3]. Disc springs are required to exhibit high resistance to fatigue under operational tensile stresses. Induction of compressive residual stresses in tensile stressed areas can postpone the nucleation and propagation of fatigue cracks in high cycle fatigue (HCF) tests [4-6]. The conventional method for induction of compressive stresses in disc springs is shot peening [7]. In this process, small, ball-shaped and extremely hard metal or ceramic beads are shot at high velocity onto the component surface. As a result, the specimens experience local plastic deformation at their surface layer which modifies their residual stress property, strain hardening and surface topography [8, 9]. The drawbacks of using conventional processes, such as shot peening, are an overall increase in manufacturing cost and time. In addition, it may adversely influence the spring features, i.e. its geometry and its surface topography, and even shorten the durability and service life of heavily shot-peened components [10, 11]. In addition, the shot peening process has a stochastic character and therefore a repeatable adjustment of the residual stress properties of the treated components is not possible.

The preferred steels used in the disc spring industry are metastable austenitic stainless steels (MASS). Their ductility, high strength, and resistance to stress relaxation and corrosion make them ideal for such applications. During the forming step and operating stage, MASS undergo plastic deformation and can be subjected to strain-induced phase transformation from γ-austenite having a face-centered cubic structure to α'-martensite having a body-centered tetragonal structure [12, 13]. As a result, the formation of α'-martensite improves the component properties made of MASS such as ductility and work hardening [14, 15].

The conventional shot peening method was replaced by the incremental sheet forming (ISF) technique to selectively induce residual compressive stresses within the disc springs. In the ISF technique, a CAM program creates a trajectory for the forming tool to travel along and shape the blank incrementally into the desired form. Due to the fact that the deformation mechanism in ISF is local, it is possible to exceed the conventional forming limit curves for workpieces with the alike geometries and therefore having high residual stresses is characteristic for the ISF process [2, 6, 16]. Formed components pass through various post-processing operations to reduce their residual stresses to increase their performance [17]. In this study, it is planned to utilize the deformation-induced residual stresses for improving the spring properties.

To the author's knowledge, characteristics and adjustment of residual stresses induced by ISF have not yet been extensively investigated for MASS. Katajarinne et al. investigated the dependency of martensitic formation in MASS on ISF process parameters such as forming temperature, feed rate, and wall angles. As a result, they could present a novel approach to adjust material properties such as ductility and strength for parts manufactured using incremental sheet metal forming through regulating their deformation-induced austenite-martensite transformation [18]. In another research, Turski et al. examined the evolution of compressive stresses in the surface layer of AISI 304L components due to different surface treatment processes. Their results indicate the importance of the utilized surface treatment on the specimens' topography and residual stress characteristics [19]. Moreover, Kleber and Barroso reported a direct correlation between the strain-induced martensite content and the amount of the residual compressive stresses in components made of AISI 304 L steel that were treated by shot peening [20]. Fragas et al. studied the fatigue strength of parts made of AISI 301 LN having the surface treated by shot peening. Their findings indicated a higher fatigue life for cold road parts [21]. The effect of a single laser shot on the characteristics of the residual stresses in parts manufactured from AISI 304 MASS was a subject of a study conducted by Halilovic et al. Their findings indicated that at lower temperatures, martensitic phase transformation plays the main role and at higher temperatures, plastic deformation is the major factor in generating the residual stresses [6].

This study aims to investigate the influence of ISF process parameters i.e. forming tool diameter, feed rate and step down as well as the sheet metal initial condition, in particular the martensite content, on the targeted induced residual compressive stresses within the disc spring made of MASS. The residual stress characteristics and microstructural evolution of the incrementally formed disc springs were studied by X-ray diffraction and optical microscopy. In addition, a numeric model was developed to describe the dependence of deformation-induced martensite content and mechanical behavior of the incrementally formed disc springs on ISF process parameters.

2 Materials and methods

2.1 Materials and geometry

Disc springs were produced from AISI 301 stainless steel sheet blanks. Part of the disc springs was produced from sheet blanks in the as-received condition. Others were manufactured from blanks that were annealed at 1060°C and undergone hot rolling processes at 80°C, 150°C, and 300°C. In this way, it was possible to study the effects of the initial material condition and, in particular, the martensite content on the evolution of the residual compressive stresses of the springs due to the forming process. The chemical composition of the as-received blanks can be found in Table 1.

Table 1: Chemical composition of AISI 301 stainless steel, in weight %, with Fe balance

AISI 301	C	Si	Mn	P	S	Cr	Ni	Mo	N
X10CrNi18-8	0.07	1.0	2.0	0.045	0.015	17.5	8.0	-	0.1

The geometry of the produced springs is sketched in Fig. 1.

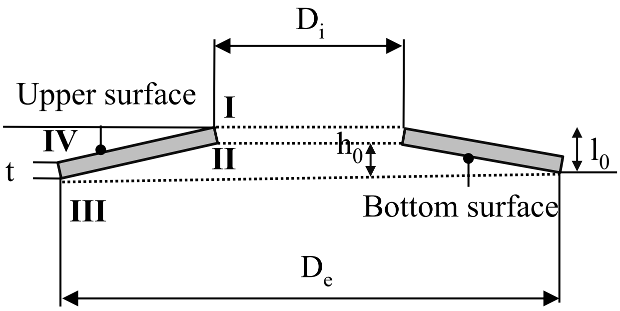

Fig. 1 - Schematic illustration of the examined disc springs

L_0 and h_0 denote the cone height and free height of the springs, and the external and internal diameters of the springs and their thicknesses are represented by D_e, D_i, and t, respectively.

2.2 Manufacturing of disc springs using the incremental sheet forming

Disc springs were manufactured using the incremental sheet forming (ISF) technique. Depending on the presence or absence of a die at the ISF setup, this method can be subcategorized as single point incremental forming (SPIF) or two-point incremental forming (TPIF). Previous studies have shown that the application of TPIF with a negative die replicates the deep rolling effect and provides better results in inducing compressive residual stresses into the inner surface of formed disc springs [10]. Part of these residual stresses is produced due to the martensitic phase transformation and others due to plastic deformation in the contact surface. Therefore, the TPIF method was employed for all forming processes in this study. Fig. 2 shows the test setup for the two-point incremental forming (TPIF) process.

Disc springs were produced with various combinations of forming parameters. The diameter of the forming tool, feed rate and the tool step down were considered as forming parameters. Furthermore, as mentioned earlier, both as-received and annealed and hot-rolled sheet blanks were taken for the forming of disc springs. The aim was to investigate the influence of the forming process parameters on the residual stress characteristics of the disc springs.

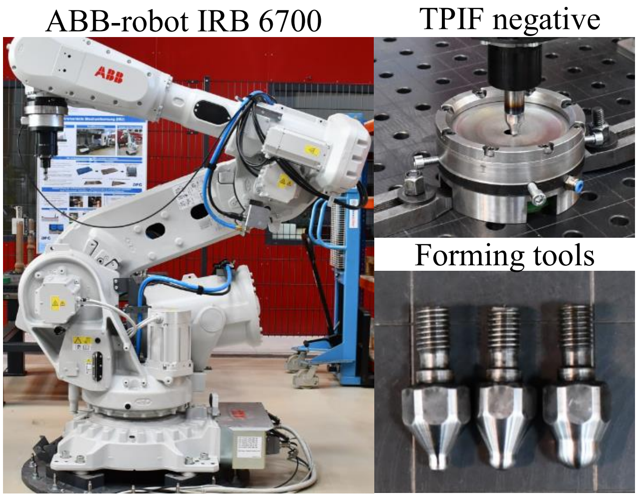

Fig. 2 – Experimental setup for two-point incremental forming (TPIF)

2.3 Residual stress examinations

The residual stresses were measured along the tangential direction of the disc springs and in the sheet blanks' rolling direction. The X-ray diffractometer Bruker D8 Discover

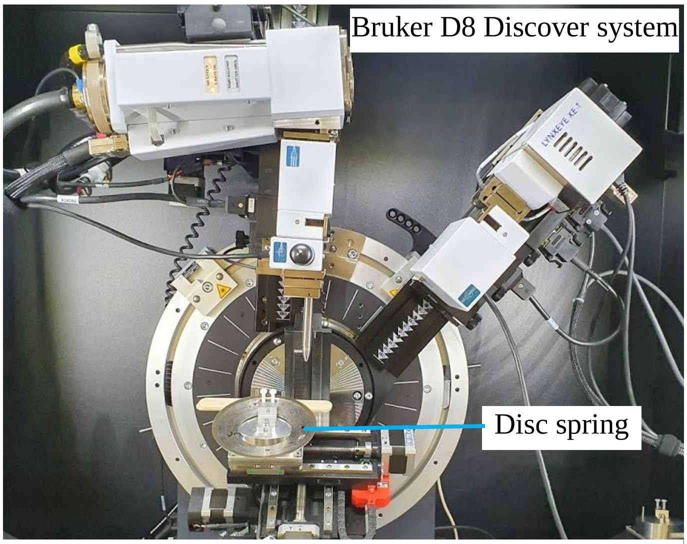

Fig. 3: Experimental setup for X-ray measurements

(XRD) was utilized for this purpose. It works based on the $\sin^2 \theta$ method. Five measurement angles [0; 11.25; 22.5; 37.75; 45°] were selected for the analyses by using Cu radiation having a current of 40 mA and a voltage of 40 kV. The 2θ range covered from 112° to 123° having a diffraction peak at 118.194°. Hence, the diffraction plane was {400}. A step size of 0.1° was applied, and measurement time was 20 s per measurement point. The collimator diameter was 2 mm, and the azimuth positions φ were 90° and 270°. Detailed measurement parameters are presented in Table 2.

Table 2. Parameters for X-ray diffraction measurements of AISI 301 stainless steel

Target	-	Cu	Young's modulus	GPa	220
Wavelength $k_{\alpha 1}$	Å	0.1540549	Poisson ratio	-	0.28
Diffraction plane {hkl}	-	Fe-α {400}	Collimator Ø	mm	2
Current	mA	40	θ -angle	°	(0; 11.25; 22.5; 37.75; 45)
Voltage	kV	40	Φ-angle	°	(90; 270)

2.4 Metallographic characterization

The metallographic investigations were carried out on the cold-rolled and hot-rolled sheet blanks. The aim was to study the effects of near-surface martensite presence in sheet blanks on the residual stress evolution of incrementally formed disc springs. Samples were etched using Beraha-II etchant and their microstructures were analyzed by light microscopy.

3 Material and mechanical modeling

A constitutive model that precisely describes the residual stresses quantitatively was modeled to takes into account the process mechanics and material behavior more accurately. The ISF process involves a continuous cyclic bending/unbending deformation mechanism and material, i.e. AISI 301 exhibits the TRIP response. The non-linear isotropic/ kinematic hardening law according to [22, 23, 24] with integrated Oslen-Cohen model was developed to provide a complete understanding of the phase transformation during deformation and helps in studying sub-surface residual stresses. The constitutive model considers:

i) the austenite of volume fraction $(1 - f_{\alpha'})$ and

ii) ii) the martensite which forms from the austenite having a volume fraction of $f_{\alpha'}$. The model was implemented as a material subroutine (UMAT) in the commercial FE-software Abaqus/Implicit.

3.1 Constitutive law

The macroscopic flow stress is a combination of each constituent phase calculated as:

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

where $\sigma_{y,\gamma}$ and $\sigma_{y,\alpha'}$ are the flow stress of the austenite and martensite respectively. The elastoplastic behavior is achieved in each phase by using von-Mises with non-linear hardening.

The yielding is described as follows:

$$F = \sigma_{eq} - \sigma_0 - R \tag{2}$$

in Eq. (2), σ_{eq} represents equivalent von-Mises stress, σ_0 indicates the initial yield stress and R is the isotropic hardening parameter. σ_{eq} is derived as:

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

Here, s_{ij} is the deviatoric part of the stresses. X represents the kinematic hardening terms defined as a function of the plastic strain, ε_{ij}^P and its strain equivalence ε_{eq}^P such as:

$$R = Q_o(1 - e^{-b\varepsilon_{eq}^P}) \tag{4}$$

$$dX_{ij} = \frac{2}{3}\chi d\varepsilon_{ij}^p - \omega X_{ij} dp \tag{5}$$

Q_o, b, ω and χ are material constants depending on the constituents and dp define the cumulated plastic strain. The plastic multiplier was calculated as:

$$d\forall = \sqrt{\frac{2}{3} d\varepsilon_{ij}^p d\varepsilon_{ij}^p} = \frac{3\mu\left(s_{ij} - X_{ij}\right)d\varepsilon_{ij}}{\sigma_{eq}(3\mu + \chi + H) - \frac{3}{2}\sigma_{eq}\,\omega\left(s_{ij} - X_{ij}\right)X_{ij}} = A_{ij} d\varepsilon_{ij}\,, H = Q_o b e^{-b\varepsilon_{ij}^P} \tag{6}$$

The stress increment was calculated using the following equation [24].

$$d\sigma_{ij} = \sum_{ijkl}\left(d\varepsilon_{kl} - d\varepsilon_{kl}^p\right) = \sum_{ijkl}\left(d\varepsilon_{kl} - \frac{3}{2}\frac{(s_{kl} - X_{kl})}{\sigma_{eq}} A_{mn} d\varepsilon_{mn}\right) \tag{7}$$

In equation (7), $\sum$ is the elastic stiffness tensor and μ is a shear coefficient. The term β is dependent on the yield function, $\beta = 1$ if $F \geq 0$ or $\beta = 0$ if $F < 0$. The mix-hardening law has the elastic-plastic modulus l_{ijmn} with $\sigma_{ij} = l_{ijmn} d\varepsilon_{mn}$

$$l^{ep}{}_{ijmn} = \sum_{ijkl}\left(l_{ijmn} - \frac{3}{2}\frac{(s_{kl}-X_{kl})}{\sigma_{eq}}A_{mn}\right) \tag{8}$$

3.2 Martensite formation criterion

The Olson-Cohen model (referred to as OC-model) is extensively employed to fit the data of the strain-induced martensite formation. This sigmoidal function relates the martensitic volume fraction and the plastic strains as [19]:

$$f_{\alpha'} = 1 - \exp\{-\beta_0(1 - \exp(-\xi\varepsilon)^n)\} \tag{9}$$

The rate of the shear-band formation is controlled by the parameter ξ with increasing strain and is dependent on the stacking fault energy. The variation of parameter β_0 controls the probability of martensitic embryo generation. It is governed by the chemical driving force of the transformation $\gamma \rightarrow \alpha'$. The term n acts as a fitting parameter and can be taken as a maximum value of 2 for TRIP steels [4]. The transformation rate for this model is mathematically represented as:

$$\frac{df_{\alpha'}}{d\varepsilon} = -\frac{n\xi(1 - f_{\alpha'})ln(1 - f_{\alpha'})}{\exp(\xi\varepsilon) - 1} \tag{10}$$

To determine the optimized set of material parameters, the standard tensile tests with on-site Feritscope measurements, tension-compression test and an inverse FE-approach based on a systematic variation of the material parameters are utilized. The predicted parameters for material response are depicted in Table 3. A good match is found by using the single 8 node linear brick element (C3D8) to avoid computational efforts, Fig. 4 (a-c). The numerical setup (Fig. 4 (d)) included a disc spring and a rigid die with dimensions 112/57/1 mm, and a forming die with a diameter of 5 mm. The tool increment was assumed to be 0.1 mm.

Table 3: Identified material parameters [23]

$\boldsymbol{\sigma_{y_0,\gamma}}$	$\boldsymbol{Q_{o,\gamma}}$	$\boldsymbol{b_\gamma}$	$\boldsymbol{E_\gamma}$	$\boldsymbol{v_\gamma}$	$\boldsymbol{vol_{\gamma_0}}$	$\boldsymbol{\chi_\gamma}$	$\boldsymbol{\omega_\gamma}$
850 MPa	302.7 MPa	19.97	188 GPa	0.3	90%	11680.5 MPa	450
$\boldsymbol{\sigma_{y_0,\alpha'}}$	$Q_{o,\alpha'}$	$b_{\alpha'}$	$E_{\alpha'}$	$v_{\alpha'}$	$vol_{\alpha'_0}$	$\chi_{\alpha'}$	$\omega_{\alpha'}$
1460 MPa	1005 MPa	10.22	217 GPa	0.28	9.5%	11680.5 MPa	450

The tool path is generated using the commercial CAD program Pro/e Cero.

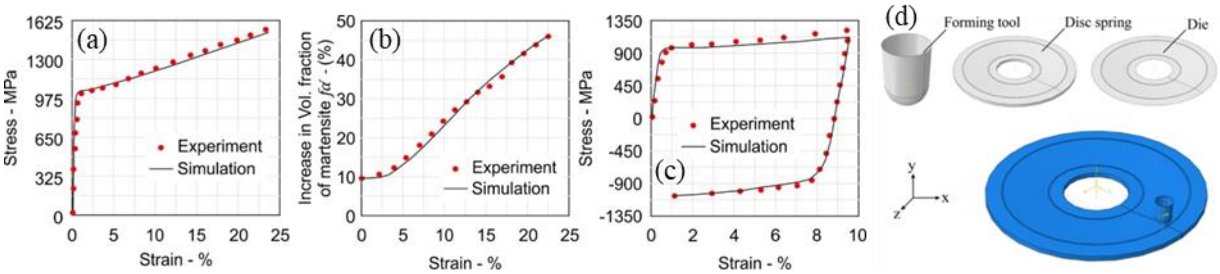

Fig 4 - Numerical and experimental curve comparison: (a) Tensile test data, (b) Martensite evolution as a function of plastic strain, (c) Cyclic stress-strain response, (d) Numerical set-up for the ISF process

4 Results and discussion

4.1 Residual stress investigations in the tangential direction

As shown in Fig. 5, incrementally formed springs were demonstrated considerably higher compressive residual stresses compared to conventionally formed springs. The forming tool diameter had the biggest effect on the magnitude of induced stresses. In addition, increasing the tool step down, decreases the residual stress induction. Feed rate variation did not make a considerable effect on the residual stress characteristics. In addition, increasing the initial sheet blank rolling temperature has decreased the martensitic transformation. For this reason, disc springs that produced from sheet materials rolled at higher temperatures have demonstrated a smaller amount of compressive residual stresses.

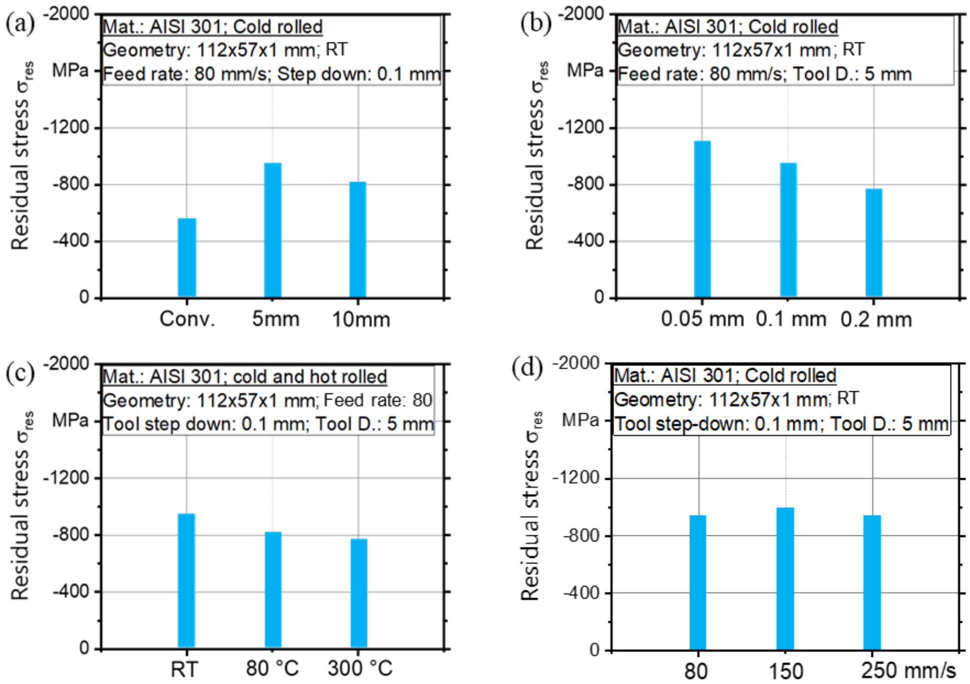

Fig. 5 - Compressive residual stress magnitudes at: (a) Various tool diameters, (b) Various tool step down, (c) Various initial material rolling temperatures, (d) Various feed rates

4.2 Microstructural characterization

Fig. 6 displays the micrographs of AISI 301 stainless steels sheet blanks.

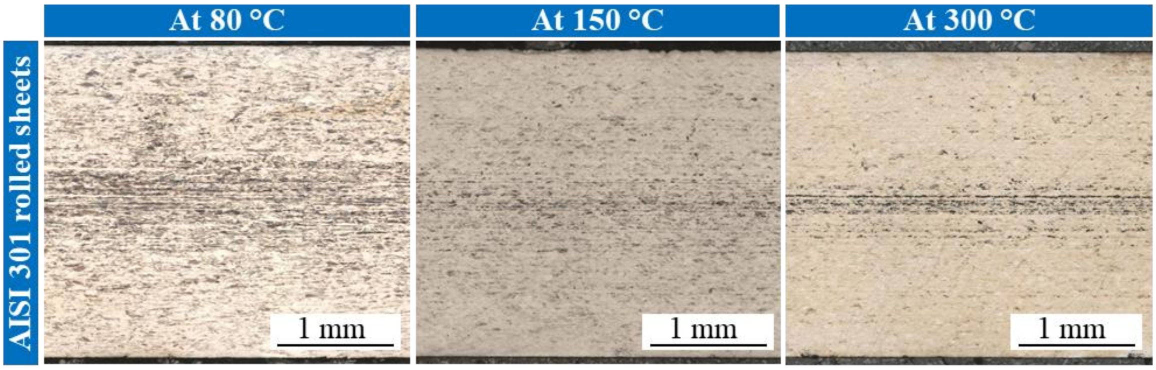

Fig. 6 - Micrographs of cross-sections of stainless steel AISI 301 after rolling at 80°C, 150°C and 300°C

They were characterized by light microscopy after being hot-rolled at 80 °C, 150 °C and 300 °C. As a general trend, deformation-induced martensite formation was decreased with increasing the rolling temperature. However, martensite lathes can be observed in all samples, especially in the central area (black parts in the micrographs).

4.3 Material and mechanical modeling

Numerical simulation is performed to quantitatively measure the residual stresses concerning the martensite fraction in the incrementally formed springs. Subsequently, the spring back simulation is conducted. The computed residual stresses and developed martensite volume fraction for a tool step-down of 0.1 mm, corresponding to 12 loops in total, are depicted in Fig 7 (a, b). Fig. 7 (c) presents the residual stress and martensite faction along the section placed on the bottom face of the disc spring as marked in Fig. 7 (a, b). The valleys in the plots correspond to the regions where the forming tool does not pass. Furthermore, the destruction of residual stresses and martensite is not constant over the whole surface of the disc spring due to the displacement-controlled movement of the forming tool. Moreover, to validate the numerical simulation, the XRD method was used to measure the respective stresses at the specified point of the disc spring and exactly the same way martensite is calculated. The experimentally measured values are marked as a line in Fig. 7 (c). Based on the comparison, it can be concluded that for a given martensite content, the numerical model shows the residual stresses in close approximation to the experimental values. Additionally, more martensite was observed in regions where residual stresses are highest.

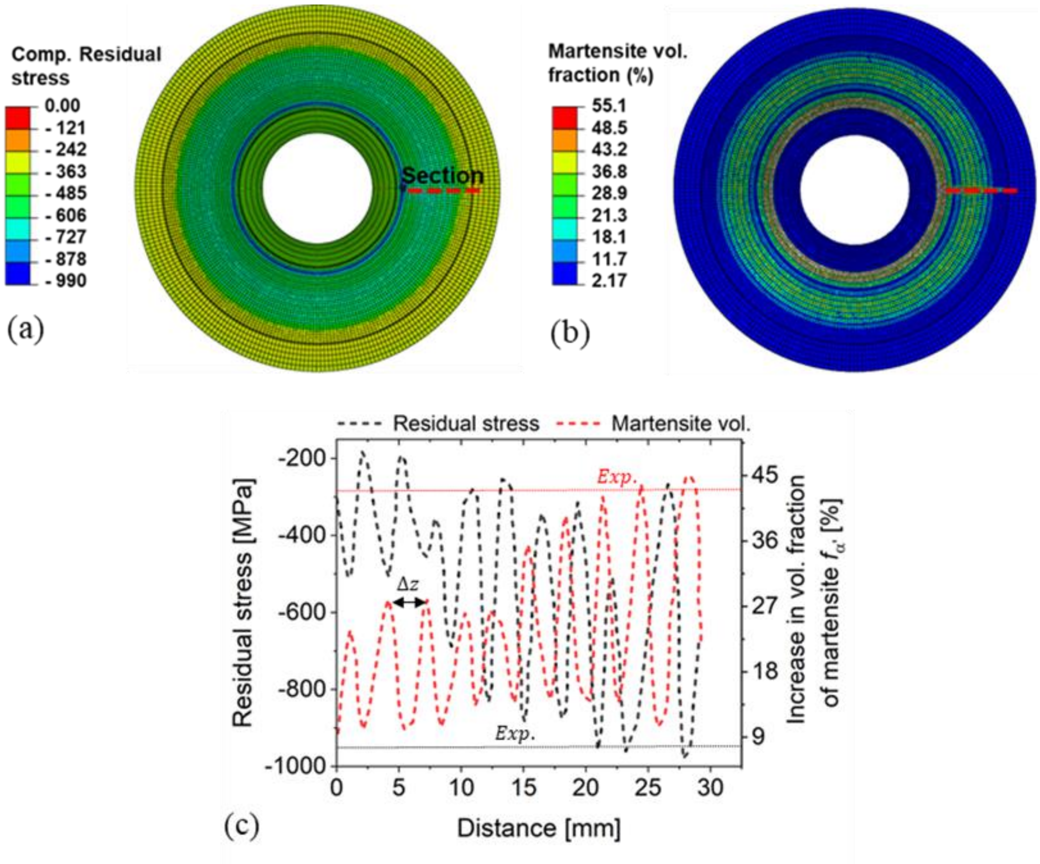

Fig. 7: (a) Residual stress and (b) Martensite volume fraction in incrementally formed disc springs (c) Residual stress magnitude and martensite volume fraction along the red dashed line in comparison to experimental results

5 Conclusions and outlook

The incremental sheet forming technique was used for manufacturing disc springs from as-received as well as annealed and hot-rolled sheet blanks. The aim was to investigate the influence of various ISF process parameters and initial sheet blank condition on the residual stress characteristics of the incrementally formed disc springs. The key findings can be summarized as following:

Considerable increases in the magnitudes of the near-surface compressive residual stresses were noted for incrementally formed disc springs compared to conventionally formed springs. Decreasing tool diameter increased the amount of compressive residual stresses. The feed rate variation did not have a noticeable effect on the induced residual stress characteristics. The rolling temperature of the blank material had a strong impact on the near-surface martensite formation that in return influenced the magnitude of residual stresses of incrementally formed disc spring. The developed numerical model can be further applied to investigate the influences of process parameters on the properties of the ISF-formed disc spring.

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References

[1] Maqbool F, Hajavifard R, Walther F, Bambach M. Engineering the residual stress state of the metastable austenitic stainless steel (MASS) disc springs by incremental sheet forming (ISF). Production Engineering, 2019, 13, p.139-148.

[2] Maqbool F, Hajavifard R, Walther F, Bambach M. 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, 2019, 29, p.12-20.

[3] Oberg E, Jones FD, Horton HL, Ryffel HH, Geronimo JH. Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman, toolmaker, and machinist. South Norwalk, Connecticut: Industrial Press, 2016.

[4] Hajavifard R, Maqbool F, Schmiedt-Kalenborn A, Buhl J, Bambach M, Walther F. Integrated forming and surface engineering of disc springs by inducing residual stresses by incremental sheet forming. Materials, 2019, 12(10), p.1-19.

[5] Hajavifard R, Maqbool F, Bambach M, Walther F. Experimental and numerical studies on the use of incremental sheet forming to improve the austenitic disc spring characteristics through tailoring their microstructure and residual stress properties, IRF 2020, Proceedings of the 7th International Conference on Integrity-Reliability-Failure, 2020, p.247-258.

[6] Halilovic M, Issa S, Wallin M, Hallberg H, Ristinmaa M. 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, 2016, 111-112, p.24-34.

[7] Holweger W, Walther F, Loos J, Wolf M, Schreiber J, Dreher W, Kern N, Lutz S. Non-destructive subsurface damage monitoring in bearings failure mode using fractal dimension analysis. Industrial Lubrication and Tribology, 2012, 64(3), p.132-137.

[8] Llaneza V, Belzunce FJ. 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, 2015, 356, p.475-485.

[9] Schulze V. Shot peening. Wiley-VCH, 2003.

[10] Doman Y, Fujii T, Okubo K, He H. Influence of residual stress on the load-deflection curve of diaphragm springs for automobile clutches. JSAE Review, 2003, 24(2), p.197-203.

[11] Fathallah R, Laamouri A, Sidhom H, Braham C. High cycle fatigue behavior prediction of shot-peened parts. International Journal of Fatigue, 2004, 26(10), p.1053-1067.

[12] Baak N, Garlich M, Schmiedt A, Bambach M, Walther F. Characterization of residual stresses in austenitic disc springs induced by martensite formation during incremental forming using micromagnetic methods. Materials Testing, 2017, 59(4), p.309-314.

[13] Smaga M, Walther F, Eifler D, Deformation-induced martensitic transformation in metastable austenitic steels. Materials Science and Engineering: A, 2008, 483-484, p.394-397.

[14] Fahr D. Stress- and strain-induced formation of martensite and its effects on strength and ductility of metastable austenitic stainless steels. Metallurgical Transactions, 1971, 2(7), p.1883-1892.

[15] Talonen J, Hänninen H. Formation of shear bands and strain-induced martensite during plastic deformation of metastable austenitic stainless steels. Acta Materialia, 2007, 55(18), p.6108-6118.

[16] Allwood J, Shouler DR, Tekkaya AE. The increased forming limits of incremental sheet forming processes. Key Engineering Materials, 2007, 344, p.621-628.

[17] Behera AK, Ou H. Effect of stress relieving heat treatment on surface topography and dimensional accuracy of incrementally formed grade 1 titanium sheet parts. International Journal of Advanced Manufacturing Technology, 2016, 87(9-12), p.3233-3248.

[18] Katajarinne T, Louhenkilpi S, Kivivuori S. A novel approach to control the properties of austenitic stainless steels in incremental forming. Materials Science and Engineering: A, 2014, p.604: 23-26.

[19] Turski M, Clitheroe S, Evans AD, Rodopoulos C, Hughes DJ, Withers PJ. Engineering the residual stress state and microstructure of stainless steel with mechanical surface treatments. Applied Physics A, 2010, 99(3), p.549-556.

[20] Kleber X, Barroso SP. Investigation of shot-peened austenitic stainless steel 304L by means of magnetic Barkhausen noise. Materials Science and Engineering: A, 2010, 527, p.6046-6052.

[21] Fragas G, Roa JJ, Mateo A. Effect of shot peening on metastable austenitic stainless steels. Materials Science and Engineering: A, 2015, 641, p.290-296.

[22] Kubler RF, Berveiller S, Bouscaud D, Guiheux R, Patoor E, Puydt Q. Shot peening of TRIP780 steel: experimental analysis and numerical simulation. Journal of Materials Processing Technology, 2019, 270, p.182-194.

[23] Afzal MJ, Maqbool F, Buhl J, Hajavifard R, Walther F, Bambach M. 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, 2020, 47, p.1410-1415.

[24] Chaboche JL, Rousselier G. On the plastic and visco-plastic constitutive equations-part I: Rules developed with internal variable concept. Journal of Pressure Vessel Technology, 1983, 105, p.153-158.

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