REVIEW

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Concept for controlled adjustment of residual stress states in semi-finished products by gradation extrusion

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Abstract The residual stress distribution in extruded components and wires after a conventional forming process is frequently unfavourable for subsequent processes, such as bending operations. High tensile residual stresses typically occur near the surface of the wire and thus limit further processability of the material. Additional heat treatment operations or shot peening are often inserted to influence the residual stress distribution in the material after conventional manufacturing. This is time and energy consuming. The research presented in this paper contains an approach to influence the residual stress distribution by modifying the forming process for wire-like applications. The aim of this process is to lower the resulting tensile stress levels near the surface or even to generate compressive stresses. To achieve these residual compressive stresses, special forming elements are integrated in the dies. These modifications in the forming zone have a significant influence on process properties, such as degree of deformation and deformation direction, but typically have no influence on the diameter of the product geometry. In the present paper, the theoretical approach is described, as well as the model set-up, the FE-simulation and the results of the experimental tests. The characterization of the residual stress states in the specimen was carried out by X-ray diffraction using the $\sin^2\psi$ method.

Keywords Impact extrusion · Residual stress modification · FE-simulation · Residual stress measurements by X-ray diffraction · Mechanical properties of materials

1 Introduction

The most common production processes for elongated components are impact extrusion and drawing methods. In the forming zone, a combination of tensile and compressive stresses occurs for both processes while the cross section is reduced. After the forming process, residual stresses remain in the material. Impact extrusion as forming operation with a compressive force application is preferably used for larger diameters and higher deformation. Wire forming with a tensile force application is used for smaller dimensions and smaller cross-sectional changes. These residual stresses influence the forming properties in further forming steps of the semi-finished products and the mechanical application behaviour, e.g. of the wire and its lifetime [1]. An innovative approach for influencing the near-surface layer during the forming process is the application of the gradation extrusion method. This method combines the impact extrusion process with severe plastic deformation (spd) in areas near the surface of the material as a result of additional geometric elements in the dies [2]. The

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spd-elements do not affect the final workpiece geometry but generate a severe plastic deformation locally as well as gradients in microstructure, strain gradient and strength across the workpiece cross section. The grain sizes near the surface can be refined to below one micrometre and affect local properties for the investigated aluminium alloy [3]. The elements also generate changes in the forming direction. As shown in the example in Fig. 1, their size compared to the overall specimen initial diameter of 16 mm is relatively small. Each spd-element causes a diameter reduction of 1.5 mm.

As a result, a high degree of deformation occurs in the material volume near the surface of the workpiece. The material near the surface undergoes an equal channel angular pressing (ECAP)-like deformation. The total effective strain is calculated by summing up the values for impact extrusion steps i and ECAP forming steps j . The applicable Eqs. (1) to (4) are presented in Table 1. The effective strain decreases in radial direction from subsurface towards the centre. A gradient is generated over the cross section [4]. The final workpiece geometry is not affected by the spd-elements.

The previous work on the development of the process gradation extrusion aimed primarily at the modification of local microstructure with resulting local property changes [3].

By specifically influencing the residual stress state during forming of the semi-finished products, broader implications of subsequence processes are possible. A favourable residual stress state increases the economic efficiency of the forming process by eliminating the need for subsequent (heat- or shot peening) treatments. Furthermore, compressive residual stresses at the near-surface layer enable, e.g. smaller bending radii of torsion bars springs due to an increase of the resistibility against cracks compared to conventionally produced semi-finished products. The findings of the studies presented in this paper from gradation extrusion process will be subsequently transferred to a process with only tensile load conditions, like, e.g. wire drawing, in further investigations. Wires are semi-finished products for manufacturing torsion bar springs. In the present work, the mechanisms of gradation extrusion [5] will be examined regarding the possibilities for influencing residual stress distributions as result of the modified forming dies without subsequent heat and mechanical treatment. The residual stress state of extruded products depends on the forming process, which was also part of different investigations. In [6, 7], results are presented where the opening angle of the die in extrusion processes influence the residual stress states of the specimens. A smaller opening angle causes a uniform forming velocity in the cross section and leads to a decrease of the residual stresses. The tensile residual stresses on the surface of the specimens can be reduced due the adjustment on the die geometry. Franceschi et al. demonstrated in [8,

Fig. 1 Gradation extrusion principle: ECAP-like deformation within gradation extrusion die [2]

Table 1 Calculation of effective strain [2]

Effective strain of impact extrusion step φ_{viE}	$\varphi_{viE} = \ln(1 + \varepsilon_A) \varepsilon_A = \frac{D_1^2 - D_0^2}{D_0^2} \quad (1)(2)$ <p> ε_A logarithmic strain D_0 diameter before the impact extrusion step D_1 diameter after the impact extrusion step </p>
Effective strain of ECAP-like step φ_{viECAP}	$\varphi_{viECAP} = \frac{2}{\sqrt{3}} \cdot \cot\left(\frac{\Phi}{2}\right) \quad (3)$ <p> Φ angle of the geometric element </p>
Summation effective strain near-surface φ_v	$\varphi_v = \sum \varphi_{viE} + \sum \varphi_{vjECAP} \quad (4)$

9] a tool set-up with active counter-punch. During the extrusion process, the ejector is actively controlled. Consequently, an axial force on the workpiece is generated and the material flow between centre and the surface of the workpiece is influenced. Because of the control of the counter-force, lower tensile residual stresses are achieved on the near-surface layer of the extruded specimens. In [10], the residual stresses are not adjusted during extrusion but in the ejection process step with a specific pre-stress of the die. The pre-stress is changed due to a segmented sleeve which is in contact with the die. By using an additional drive to vary with the sleeve the pressure on the die the internal diameter of the calibration zone of the die is affected. In combination of experiments and FE-simulations, it was shown that after forming an ejection with decreased or increased pre-stresses of the die influence the residual stresses of the specimens compared to conventional pre-stress of the die. A decreased pre-stress (diameter calibration zone + 25 μm) causes higher tensile residual stresses, but with increased pre-stress of the die (diameter calibration zone – 25 μm), compressive residual stresses on the surface of the specimens can be obtained. The investigations on the process limit had shown that the positive effect is dependent on the condition that the plastic deformation only occurs on the surface of the specimens during ejection. If the pre-stress is too high and the plastic limit is reached of the cross section of the specimen, it becomes like a second extrusion, which is unfavourable for the residual stress state.

By modifying the forming process using special forming elements inside the dies, the degree of deformation and deformation direction can be influenced. This enables the residual stress state to be favourably adjusted, which is important for further processing.

2 Materials and methods

The investigations presented in this paper are divided into experimental and FE-simulations parts. For the experimental tests at 20 °C, cylindrical specimens of an austenitic steel 1.4301 with uniform initial conditions are used. The chemical composition of the austenitic stainless steel 1.4301 is given in Table 2. This material is almost metastable austenitic in the annealed initial state. Due to plastic strain during forming, the metastable austenitic phase is transformed to the martensitic phase in the deformation zone. This results in a significant increase in strength.

Among other materials, the material 1.4301 is used for technical springs. These components are subject to complex load conditions over their lifetime. For the basic investigation, only the rod-shaped cylindrical part was initially examined for the residual stress characteristic and the possibilities of modification. A bending process is not part of the experiments.

Special dies are developed on the basis of the results presented in [11] and the experiences of the gradation extrusion process. The tool set-up of the experimental device for the impact extrusion process includes interchangeable specific dies with additional convex or concave geometric elements. Three different die geometries are investigated in FE-simulations and experimental set-up. The main geometric dimensions of the tools are identical. Based on [5, 12], a diameter reduction of the specimen from $\varnothing$ 12 to $\varnothing$ 10.8 mm was selected. The geometric elements incorporated in the forming zone cause a high degree of plastic deformation during the forming process, which also change the residual stress distribution of the material. However, the final diameter is the same as in the conventional forming process. The variant of the conventional die geometry represents the reference process without additional spd-elements. The convex geometry includes one convex forming element and the concave geometry a concave forming element. The specific elements affect a modified material flow. In Fig. 2, the geometry variants with the special geometric elements and dimensions which are used for the investigations are presented.

The experimental tests were carried out using cylindrical samples (diameter 12 mm, height 32 mm), which were annealed at 1050 °C for 15 min and then cooled outside the furnace in still air. The applied heat treatment serves to achieve uniform initial conditions before forming.

A solid lubricant (LOCTITE LB 8191) was applied to each of the samples and additionally lubrication with high-alloyed drawing oil was used during forming. In order to investigate the generation of residual stresses

Table 2 Chemical composition alloy X5CrNi18-10 (1.4301) according DIN EN 10,088–3

Element		C	Si	Mn	P	S	Cr	Ni	N
Content [wt.%]	Min	–	–	–	–	–	17.5	8.0	–
	Max	0.07	1.0	2.0	0.045	0.03	19.5	10.5	0.1

Fig. 2 Geometry variants of the dies with special geometric elements

Fig. 3 Tool principle—interchangeable dies with different geometry variants

during the forming process, an experimental device was modified for extrusion. In Fig. 3, the tool design is presented. Five specimens for every die variant were pressed through. Each follow-up specimen pushes the predecessor completely through the die. For the evaluation, in each case, the three middle samples were used, which were formed under steady conditions. The first and last samples were not evaluated. An ejection process was therefore deliberately avoided, as this again affects the residual stresses, which was analysed by Jobst et al. [13].

Surface-near sections of the formed samples were examined by X-ray diffraction methods (XRD) and compared to the initial state. The measurements of the residual stresses were performed in the middle zone of the specimen length. The determination of the residual stress states was carried out in order to study the influence on the residual stress state by varying the tool geometry. XRD allows a phase-specific analysis of residual stresses, as the differences in the crystal lattices of the austenite and martensite phases result from different Bragg angles and each phase can be analysed by their reflections. In the case of angle-dispersive X-ray diffraction, monochromatic X-ray radiation and Ω - 2θ mode are used. The residual stress state has been analysed by the X-ray diffraction technique using the $\sin^2\psi$ method [14]. For this analysis, the austenitic-reflection 311 and the martensitic-reflection 211 were selected. Using Co-K α radiation (penetration depth = 6 μm), the reflection profiles were measured in the 2θ angular range of 108.3° – 114.3° for austenite and 96.7° – 102.7° for martensite, respectively, with a step size of $\Delta 2\theta = 0.05^\circ$ and a counting time of 15 s per step. The measurements are performed using a round collimator with a diameter of 2 mm. The diffracted beam is collimated with a 0.4° -Soller and a LiF monochromator. The reflection profiles were acquired for 9 ψ tilts ($\pm 63.435^\circ$, $\pm 50.787^\circ$, $\pm 39.232^\circ$, $\pm 26.565^\circ$ and 0). To determine the residual stresses, the diffraction elastic constants (DEK) $s_1 = 1.77 \cdot 10^{-6}$ MPa; $\frac{1}{2} s_2 = 7.11 \cdot 10^{-6}$ MPa (for austenite) and $s_1 = 1.27 \cdot 10^{-6}$ MPa; $\frac{1}{2} s_2 = 5.8 \cdot 10^{-6}$ MPa (for martensite) were used, respectively [15].

Fig. 4 Flow stress and extrapolation for the material 1.4301

2D axisymmetric, explicit FE-simulations have been implemented by using FE-Software Abaqus version 6.14.4 in order to estimate changes in residual stress distribution due to the die geometry designs. The tools are defined as rigid bodies with combined friction model of Coulomb and factor model according to Tresca ($\mu = 0.2$, $m = 0.1$ [16]). The flow curves for the material 1.4301 applied in the FE-simulations were determined experimentally by compression tests on the Gleeble System 3800 for different temperatures and strain rates and were extrapolated for higher degrees of deformation and isotropic work hardening effect using the Swift-approach. In Fig. 4, the flow curve and the extrapolation for higher plastic strains are illustrated by a strain rate of 0.1 1/s. From the plastic strain φ 0.25 up to the end of the measured data, the variables were determined. Up to φ 0.35, the flow curve is represented with the measured values and further by means of the extrapolation with the values C_1 1220.352, C_2 -0.225 and C_3 0.104 for the Swift-approach. The phase transformation is not yet considered in the material model and will be part of further developments and adjustments of the FE-simulations.

The samples were simplified defined with an initial state free of residual stress on the macro scale. For the evaluation of the forming induced residual stresses, an implicit calculation after unloading of the specimen was implemented. The specimen was meshed with an element length of the mesh by 0.1 mm. In order to equalize the mesh during forming the Abaqus method “ALE Adaptive Mesh” was used. According to this, a remeshing is not necessary. The tools were modelled both as rigid or elastic objects as well. To investigate the influence of the modelling of the dies on the residual stress distribution of the specimen, selected variants are compared. Due to the very small size of the specific geometric element (0.25 mm), the mesh size in this zone of the tool needs to be very fine. The element length of the mesh was reduced to 0.02 mm in this area. Surface to surface contact was defined as kinematic contact with finite sliding, contact controls were not added.

3 Results and discussion

3.1 Results of experiments

The evaluation of the experimental investigations shows that deformation-induced martensite is formed in the peripheral zone for all variants due to increased plastic strain and shear stress. Figure 5 visualizes the colour separation of the deformation-induced martensite edge zone (green) and austenite (brown) in the cross sections of a specimen formed in the convex die. The XRD phase analysis confirms this result. It can be seen that the deformation-induced transformation of the austenite to martensite at the near-surface zone of the specimen is inhomogeneous across the specimen surface. Residual austenite components and intermediate phases caused by deformation (presumably ε' martensite) can be observed in the diffractogram belonging to the near-surface area. Additionally, at the measuring position 180°, the amount of the martensite phase is weaker compared to the measuring position 0°, which can be seen in a decreasing green colour of the etching. The martensitic zone varies in thickness over the circumference of the specimens and corresponds on average to about 16 μm .

The near-surface residual stress state for the martensite and austenite phases differ depending on the individual dies, which are presented in Fig. 6. Therefore, each residual stress value shown originates from one measurement location at the surface. The martensite phase in the tangential direction shows significant residual compressive stresses when using the convex die of up to -490 MPa, whereas significant residual tensile stresses of $+400$ MPa were determined using the conventional die in the tangential direction. The

Fig. 5 Colour etching and X-ray phase analysis of the deformed specimen with convex die, cross section, near-surface area, measuring point 0° (a) and measuring point 180° (b), 100 × magnification

Fig. 6 Residual stresses corresponding to the reflex positions on the lateral surface of the deformed specimens as a function of the die (geometric element) and the measurement location

highest residual compressive stresses in the martensite phase with -540 MPa are generated by the convex die in axial direction.

However, the residual stress states determined for the martensite and austenite are not homogeneous over the circumferences. Minor variances such as material inhomogeneity, different stress state distributions from pre-processing, manufacturing tolerances of the dies and small variations in processing conditions can be the cause of the nonhomogeneous distribution mentioned. For instance, the manufacture of the special contours by EDM drilling with shaped electrodes in the impact extrusion dies, which have small dimensions ($L \times W$ 0.25 mm $\times$ 0.5 mm; $R = 0.1$ mm) are also difficult to access and can only be carried out with relatively large tolerances up to 50 μ m.

3.2 Results of FE-simulations

In order to investigate the effective strain and differences in residual stress distribution over the cross-section, FE-simulations are performed. Additional FE-simulations with elastic dies illustrate that the diameter of the dies decreases by 0.04 mm when pressed into the reinforcement. Due to the load occurring during forming,

Fig. 7 Tool and specimen deviation from initial radius after forming by elastic modelling of the die

the diameter increases to 10.8 mm (Fig. 7). Thus, the specimens' final diameter is the same diameter as with a rigid die definition. The residual stresses of the specimens do not show any significant differences when the specimen is pushed through the elastic or rigid die. To transfer the results in additional analyses to wire drawing the specimen were complete pushed through the die in the investigated impact extrusion process. From the comparison of the residual stress curves with regard to the elastic and rigid modelling of the dies, it was possible for the application case that the dies are defined in the FE-simulation as rigid.

In the analysis of the FE-simulation results, it becomes clear that considerable differences of the degrees of deformation in the surface zone are achieved by the geometric elements in the die during impact extrusion. Due to the geometric elements convex and concave, the degree of deformation in the near-surface zone increases significantly. This basically corresponds to the results of gradation extrusion which are presented in [2]. However, this area of deformation is very small, which is illustrated in Fig. 8.

The radial component of the residual stress becomes zero at the surface. The curves for the axial (black) and the tangential (grey) residual stresses over the cross section are depicted in Fig. 9. The evaluation for the conventional geometry shows an increase of axial residual compressive stresses in the near-surface zone. Towards the centre, they change into tensile residual stresses.

The developments of residual stresses in axial direction for the convex and concave geometries show that residual compressive stresses can be generated in the near-surface zone. For the convex and concave variant used, compressive residual stresses occur. Residual stresses in tangential direction show a similar characteristic. These compressive residual stresses change to tensile residual stresses immediately on the surface. This residual stress state can be explained by the kinetic contact model in the FE-model. Further investigations and improvements of the FE-Simulation, also in combination with the material modelling of phase transformation, will be necessary for accurate validation.

Based on the FE-simulations and experiments performed, it can be demonstrated that the dies with the specific geometric elements in the forming zone have provable impact on the near-surface residual stress state as well as on the deformation-induced phase transformations from austenite to martensite. The FE-simulations and experiments indicate that the most significant influence on the near-surface residual stress state is achieved using a die with a convex geometric element in the forming zone. The experimental results confirm a shift from tensile residual stresses to compressive residual stresses due the geometric elements inside the dies. This finding is of advantage for further subsequent processing and final product properties. However, there are differences in the residual stress values between FE-simulations and experimental analyses due to current material modelling, especially phase transformation, which is part of further investigations.

Fig. 8 FE-simulation of impact extrusion—formation of the effective strain over the specimen cross section

Fig. 9 FE-simulation of impact extrusion—axial and tangential residual stresses over the specimen cross section as a function of the geometric elements

4 Conclusions

The investigation of the material 1.4301 revealed that the austenitic phase partly converts into a deformation-induced martensite in the near-surface zone due to high plastic strain. From the experimental tests, it can basically be concluded that the martensite phase tends to exhibit residual compressive stresses in the axial direction across the convex and concave die variants. The austenite phase, on the other hand, shows not such an intensive shift. Thus, the residual stress state and the phase fractions can be significantly influenced by the choice of the tool with the geometric element by means of a single deformation. The highest residual compressive stresses in the martensite phase are generated by the convex die with a value of -540 MPa. The possibility of the approach of gradation extrusion transferred to targeted residual stress modification has been demonstrated. The results of initial experiments indicate a considerable impact on the near-surface residual stress state. Because of the different near-surface residual stress states (X-ray measurement positions: 0° , 180°) further investigations have to be adapted which include the following issues: The special internal geometries of the dies, in particular the geometric elements, are to be recorded more precisely using a measurement methodology to be developed, preferably by means of optical and tactile measurement methods. The recorded geometries are to be implemented directly in the FE-simulations and the calculations validated by means of 3D-simulation models. The aim is to draw conclusions between the measured residual stresses and the

respective dimensions of the geometry element. The comparison of the near-surface residual stress state of experiment and FE-simulation showed deviations in the absolute stress values, which can be attributed not only to the manufacturing tolerances of the geometries but also to the specific phase formation. The aim for further investigations by means of the FE-simulation is to map the deformation-induced phase transformation on the microscale by programming and implementing subroutines. The tendency of the FE-simulations and the measured data by XRD show a good congruence in the present work. However, the absolute values of the residual stresses vary additionally because the measurement volume of the XRD analysis on the surface of the samples is not exactly reproduced by the FE-simulation due to modelling restrictions of near-surface elements. This will be also topics of further investigations.

The results presented in this study indicate a considerable impact on the near-surface residual stress state towards a reduction of residual tensile stresses, which is favourable for further subsequent processing. The insights gained in this paper about the coherence between forming elements and the degree of deformation as well as the deformation direction are to be transferred to the typical wire drawing process at further investigations. On the basis of the research findings, a drawing device for wire drawing was constructed. Using this tool, the results from impact extrusion with the same geometric elements should be transferred to tensile compression forming.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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