Influences of die shape and calibration strokes on surface near residual stresses of rotary swaged steel tubes

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Abstract. Forming processes offer a great potential to make production more sustainable by including both the shaping of the geometry and the improvement of the material properties. Through a better understanding of the decisive influencing factors on the resulting material properties of the part, this potential can be particularly exploited and leads to the chance of shortening process chains by e.g. saving heat treatment steps. The part properties during rotary swaging can be improved by strain-induced residual stresses. Thereby, compressive residual stresses can increase the resistance to fatigue fracture, to crack propagation and to corrosion. However, rotary swaging of tubes can lead to undesirable residual tensile stresses at the surface with high fluctuations. Therefore, a better understanding of the rotary swaging process and the actual material flow is necessary. The aim is to realize compressive residual stresses with low fluctuations. Thereby, it is of interest to be able to set residual stresses independently of the desired workpiece geometry. In this paper, rotary swaging of E355 steel tubes (Ø20 mm x 3 mm) was carried out with two different process adaptions. These two adaptions are the number of calibration strokes and the die geometry. They show different influences on surface near residual stresses.

Introduction

Rotary swaging is an incremental cold forming process that is used industrially to reduce and profile the cross-section of parts that are subject to high mechanical loads, such as axle shafts and steering spindles [1]. Furthermore, it has gained importance as a manufacturing process for aerospace industries [2]. In particular, the advantage of producing complex geometries within tight tolerances enables a cost-efficient production of lightweight components. The rotary swaging machine consists of a swaging head, a lubricant supply, a clamping device and a feeding system, Fig. 1a.

In the process, the forming dies - as part of the pressure column together with the cylinder roller, base jaw and spacer within the outer ring - rotate around the workpiece and simultaneously strike with a stroke frequency of approximately 35 Hz towards the centerline of the swaging head. During this, the workpiece is axially fed into the swaging head and retracted after the forming process, Fig. 1b. Here, the die amplitude results from rolling of the cylinder roller over the cam.

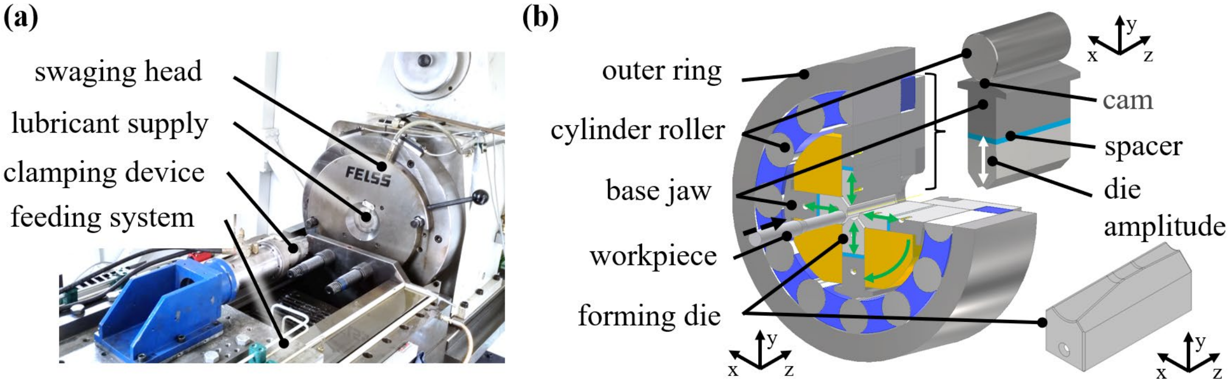


Figure 1: Rotary swaging machine: (a) picture of the rotary swaging machine, (b) schematic drawing of the machine parts, pressure column (top right) and forming die (bottom right)

Due to the incremental character of the process, the desired workpiece properties and geometry arise through the interaction of die shape and circumferential and lateral feed. As an example, the influence of die shape was numerically investigated in [3, 4] showing the effect of changes of die geometry in the reduction zone.

In detail, rotary swaging induces a locally distributed material flow which is related to the described geometric change that as well causes a change of material properties by e.g. work hardening [5] and residual stresses [6]. These changes build up gradually with each forming stroke. In previous studies, the final residual stress fields on the surface of steel tubes and bars were investigated and found to be sensitive to different process parameters like spacer height [7] or forming sequence [8] in the sense of homogenizing and reducing fluctuations. Rotary swaging of different workpiece materials was investigated and showed tensile as well as compressive stresses at the surface [9, 10]. Investigations of the influence of the die shape showed that swaging with round and flat dies leads to different residual stresses and can produce different geometrical features [7].

However, the aim is to find process-integrated solutions to adjust residual stresses and to generate the workpiece geometry independently. Furthermore, it is preferable that no additional process steps are required to generate the desired workpiece properties. Therefore, two different strategies were followed, a variation of the calibration strokes during retraction and an adjustment of the die geometry.

Materials and Methods

Experimental Setup. In this study, infeed rotary swaging of annealed (700°C, 2h) EN 1.0580 (SAE-AISI 1026) steel tubes (Ø20 mm x 3 mm) from d_0 = 20 mm to a final outer diameter of d_1 = 15 mm was investigated. The experiments were conducted on a swaging machine Felss HU 32V. The workpieces were hydraulically clamped and axially fed by a linear direct drive into the swaging head. In all tests, the infeed speed was set to 1000 mm/min using a spacer height of 5.08 mm. Rotary swaging dies with the similar base geometry in the reduction zone with $\alpha = 10°$, in the calibration zone with l_c = 20 mm and transition radius r_t = 20 mm were used, Fig. 2.

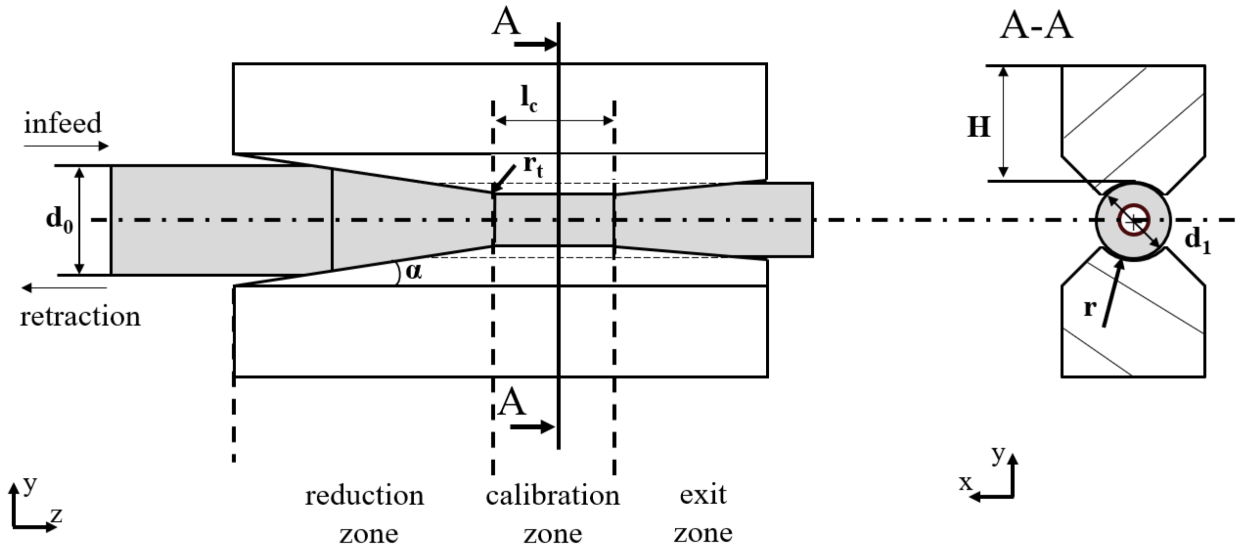
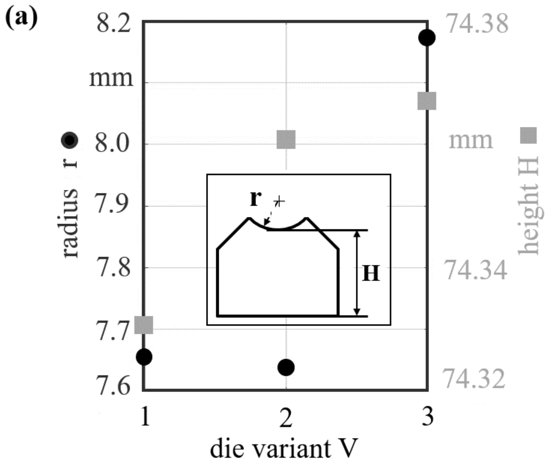


Figure 2: Sketch of dies at bottom dead center (two out of four forming dies are shown)

In the exit zone, the workpiece was gradually unloaded. The dies featured a round shape perpendicular to the infeed direction, whereas the die radius r varied for the dies V1-V3 as given by Fig. 3. Furthermore, due to manufacturing issues the height H slightly varied for the different die variants. The rotary swaging dies V1 were made of ®ASP2013 high-speed steel and tungsten carbide (WC) coated. The rotary swaging dies V2 were made of cold working steel (AISI D2) and provided with a diamond like coating (DLC). The rotary swaging dies V3 were made of cold working steel (AISI D2) and not coated. According to the swaged workpiece diameter d_1, which was given by the set of dies, and the die radius r, the forge value S was calculated with Eq. 1 [1].

$$S = \frac{d_1}{2\,r} \tag{1}$$



(b)

V	S	base material and coating
1	≈1	®ASP2013 (AISI M3:2) + WC- layer
2	≈1	1.2379 (AISI D2) + DLC- coating
3	<1	1.2379 (AISI D2) without coating

Figure 3: Rotary swaging die variants and properties: (a) radius r and height H (measured values), (b) forge value S and materials

The influence of additional calibration strokes on residual stresses fluctuations was investigated using a reduced retraction speed with dies V2. Starting with no retraction hence no additional calibration strokes by stopping the swaging machine, the retraction speed – constant within each test – was varied and reduced from v_R = -2000 mm/min to v_R = -100 mm/min. As a consequence, the number of calibration strokes on the surface increased. Previous investigations showed that fluctuations manly appeared at the surface. Hence, in these tests residual stresses were only measured at and near the surface.

The influence of the die radius r on the residual stresses at the surface and below the surface was investigated using different swaging dies V1, V2 and V3. These tests were performed with a retraction speed of - 500 mm/min which was chosen as a compromise between process time and calibration properties. According to manufacturing issues, a difference in the height H of 0.05 mm was measured. Furthermore, due to die material and coating, the friction conditions varied between the used dies whereas the influence on the residual stresses was assumed to be low.

Measurement setup. The diameter d_1 was measured in 60° steps circumferential around the workpiece at two different length positions. Mean values and standard deviations were calculated. The roundness of the workpiece was measured with a Taylor Hobson TalyRond 252 at a distance of 30 mm and 170 mm from the reduction zone as roundness deviation RONt.

X-ray diffraction (XRD) was used for residual stress analysis. Due to its low penetration depth in steel of a few micrometers, this method was applied for surface residual stress measurement as well as by local material removal (etching) to assess depth profiles. For this, the residual stress measurement was performed with a commercial 8-axis diffractometer Type ETA 3003 from GE inspection technologies, equipped with a position sensitive detector. A beam of 1 mm diameter of Vanadium filtered Cr-Kα radiation was used. All residual stresses were determined using the $\sin^2\psi$-method with the {211} diffraction peak of α-iron along 13 χ-angles between -45° and +45° and X-ray elastic constant ½ S2 = 5.81 10-5 MPa-1 [11]. Axial residual stresses were determined. They correlated with tangential residual stresses as showed in previous studies [12]. The residual stresses were measured starting at a distance of 50 mm to the reduction zone.

Results

Geometries measurement. The variation of the retraction speed had no measurable influence on the elongation of the workpiece, i.e. the global axial material flow which manly takes place during infeeding. The diameter was constant with 15.088 mm ± 0.01 mm and the roundness was constant with 12.18 µm ± 0.56 µm for all retraction speeds.

The variation of the die shape had no significant influence on the elongation of the workpiece (±0.01 mm). The diameter of the workpieces slightly varied with die shape due to the difference in height H and the forge value S. Due to the difference in the radial and tangential material flow in each forming increment, as well the roundness changed with the die shape, Fig. 4.

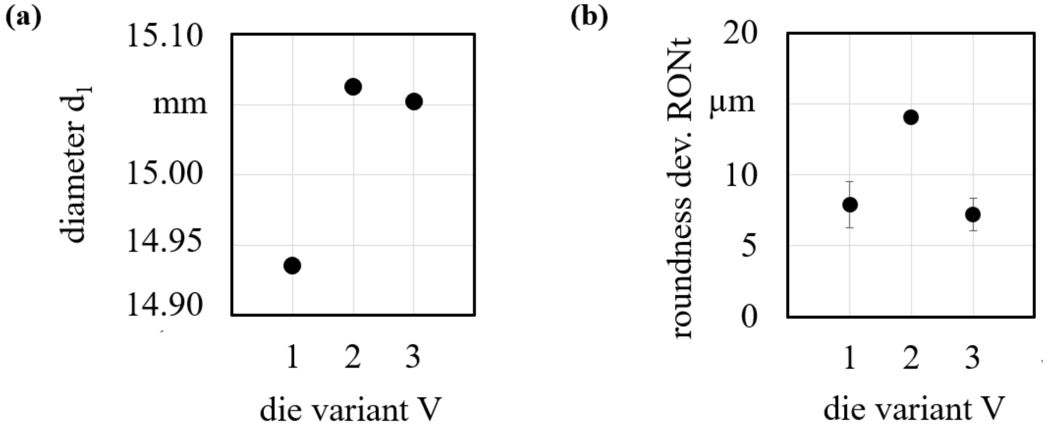


Figure 4: Geometry values of rotary swaged workpieces with different die variants: (a) diameter d_1, (b) roundness deviation RONt

Residual stresses measurement. An exemplary comparison for retraction speeds v_R = - 2000 mm/min and v_R = -100 mm/min is given in Fig. 5. The residual stresses showed a clear sensitivity on the retraction speed.

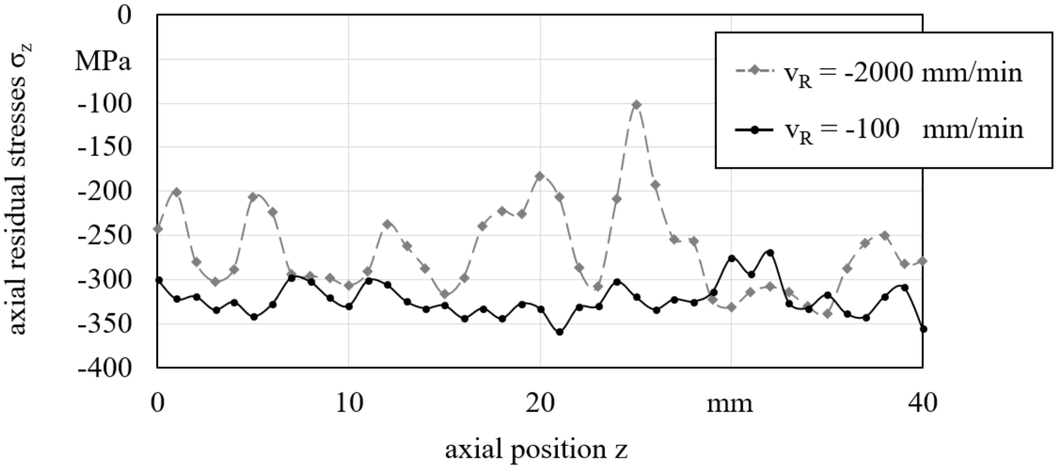


Figure 5: Exemplary axial residual stresses σ_z along the axial position z for retraction speed -2000 mm/min and -100 mm/min

Mean values and standard deviation values of these profiles were plotted in Fig. 6 as a function of the total number of calibration strokes per workpiece according to the retraction speed. It can be observed that by an increased number of strokes the mean value slightly decreased by 15% from around -350 MPa to -300 MPa. However, the deviation respectively the residual stresses fluctuations were reduced by 300% from about ±100 MPa to about ±25 MPa.

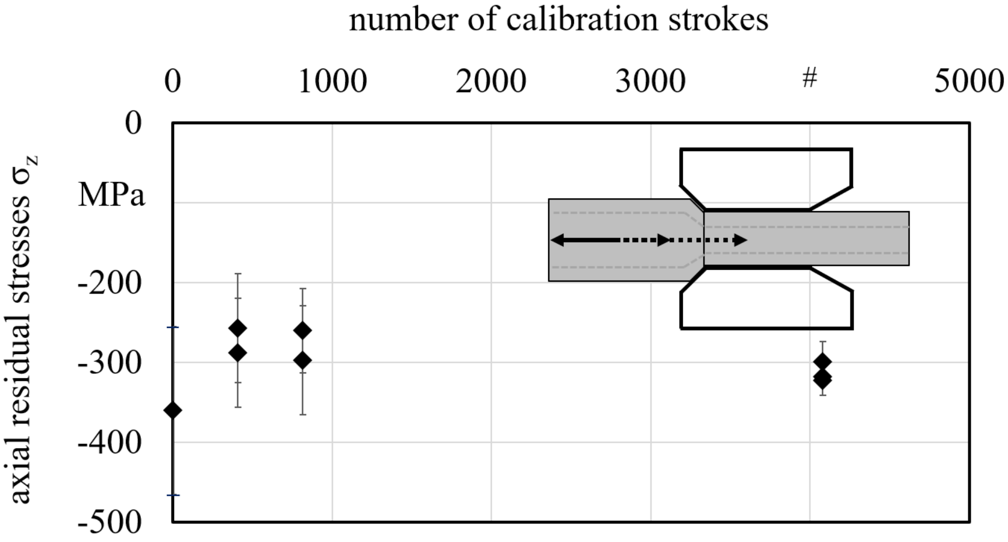


Figure 6: Mean value and deviation of axial residual stresses σ_z depending on the number of calibration strokes during retraction, cp. [12]

After rotary swaging with different die shapes (V1-V3), the workpieces showed different residual stresses on the surface and below the surface, Fig. 7. Using dies V1 and V2, the workpieces showed compressive residual stresses of around -400 MPa on the surface and as well in the compressive range up to 100 µm below the surface. Using rotary swaging dies V3 resulted in residual stresses close to zero at the surface. Below the surface the residual stresses on the workpieces which were rotary swaged with the dies V1 and V2 changed to low tensile range in the depth below 100 µm. However, for die V3 the residual stresses stayed close to zero slightly shifting into the compressive range.

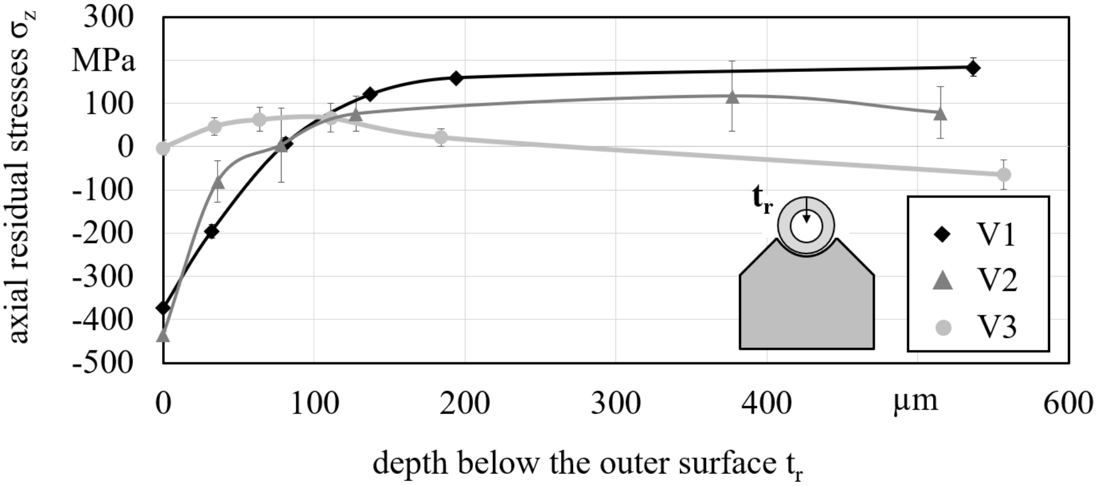


Figure 7: Axial residual stresses σ_z depth profile for different die variants V1-V3, cp. [12]

Discussion

The depth profile of residual stresses can be significantly changed by the die geometry. The forging value S was the most influencing parameter in this study. With a value $S < 1$, the radius of the die (perpendicular to the infeed direction) is larger than the resulting outer radius of the part. Only tiny residual stresses were built at and near the surface. In contrast, with a forge value of $S \approx 1$ beneficial compressive residual stresses were produced at the surface that decreased in the depth and changed to tensile stresses below a depth of 80 µm. Other parameters like height of the die H and coating dependent friction conditions showed minor influence. Additionally, theses residual stresses at the surface could be homogenized by increasing the number of calibration strokes during retraction of the workpiece with reduced velocity.

Conclusion and Summary

The results introduce two different approaches of adjusting residual stresses in rotary swaging of EN 1.0580 (SAE-AISI 1026) steel tubes. The following observations can be summarized:

- Process-integrated solution was found for residual stresses calibration by reduced retraction speed.
- Calibration strokes contributed to more homogeneously distributed compressive residual stresses at the surface with less fluctuations.
- Forging value S had a significant influence on the residual stresses at the surface and in the depth of the workpiece.
- Residual stresses close to zero as well as in the high compressive range were generatable by rotary swaging with different die shapes without additional annealing steps.

The results enable both the manufacturing process and the resulting components becoming more sustainable. Thereby, the approaches influence the residual stresses in a process-integrated manner with constant workpiece geometry.

Future Work

The method of changing the number of calibration strokes by a changed retraction speed was based on the idea of a uniform distribution of calibration strokes on the surface. Here, it is needed to find a constant process kinematic to evenly distribute the strokes on the surface. As the rotation of the workpiece was not measured or controlled, it was only assumed to be nearly constant during the retraction for an homogenic distribution of strokes. As a consequence, a measurement device was applied to the machine to measure the rotation angle in future work. A reduced retraction speed increased the process time. As a result, for a future use of the approach a compromise between the fluctuation remaining and the process time has to be considered in the subsequent process design.

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