Influence of material delivery condition on residual stresses and part properties during forward rod extrusion

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Abstract

During the manufacturing of semi-finished products, the material is subjected to various forming steps to achieve the final geometry. In order to reduce the work hardening introduced and to ensure a good formability, it is annealed before component manufacturing. Forming technologies like forward rod extrusion are well-established methods for an efficient production of resilient components. In this process however, an inhomogeneous pre-strengthening of the material influences the stress distribution during forming and therefore the mechanical properties and the residual stresses in the component. Since they affect the parts operating behaviour, knowledge of the influence of the delivery condition of the material is necessary. The aim in this paper is to derive dependencies between material properties and the resulting residual stresses and work hardening in the component. Due to the increasing application, ferritic stainless steel *X6Cr17* in the skin passed (+LC) and soft annealed (+A) states is used. Residual stresses, microstructure and microhardness distribution of both material states are compared regarding the rods and extruded parts. The effects of the delivery condition are evaluated by comparing process and component properties.

Keywords Forward Extrusion, Material Condition, Stainless Steel, Residual Stress, Work Hardening

1 Introduction

Cold extrusion is an established process for the fabrication of components in large series. It offers high material and energy efficiency and the production of dimensionally accurate components, which exhibit high strength due to process-related work hardening [1]. However, in the manufactured components, residual stresses are generated due to inhomogeneous forming, which influence the parts' operating behaviour. Tensile residual stresses generally have negative effects as they inhibit crack initiation and propagation and thus reduce fatigue strength [2]. To ensure a long part service life, they must either be relieved by energy-intensive annealing after component manufacturing or taken into account when designing the part. For the prediction of the component properties after forming, knowledge of influencing variables on the component residual stresses is therefore necessary. So far, only little data is available about the use of pre-strengthened material. Therefore, in this paper, the influences of the material delivery condition on the properties of the forming process and the produced part are researched.

Since ferritic stainless steels are usually used in the annealed condition [3], the soft annealed state serves as a reference. The skin passed state is used to represent an insufficiently annealed material in which single areas still show a strengthening. The objectives pursued and the approach are shown schematically in Fig. 1.

To characterize the initial state, the material parameters of the non-deformed material are identified in the two investigated states "annealed" (+A) and "skin passed" (+LC). The influence of the material condition on the resulting part properties is determined by the comparison of the initial material and the manufactured components. In addition to near-surface residual stresses, microhardness and grain size distributions are investigated, since they influence the cyclic strength [4] and a depth-dependent residual stress measurement is difficult due to the corrosion resistance of the material. The effects of the material delivery condition on the forming process are identified by determination of the process forces necessary for forming and ejection. In order to check for thermal effects on the residual stresses, the temperature in the formed part section is also measured after ejection. By comparing billets and components, correlations between material condition and the resulting process and component properties are determined. On this basis, recommendations for the forming process are derived in order to ensure efficient component production.

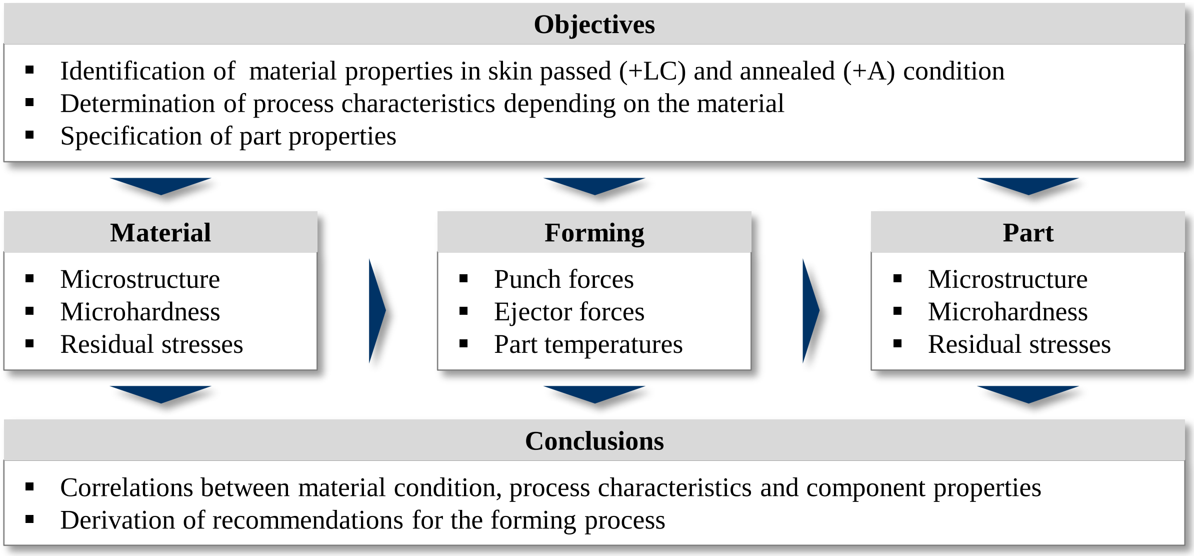

Fig. 1: Objectives and approach

2 State of the Art

During the production of steel rods, various rolling steps are carried out after the casting of the slabs in order to achieve the target geometry of the semi-finished product. This involves either rolling in the hot state in order to keep the process forces low, or in the cold state, which results in a finer structure and a better surface, but a strong hardening. In forward rod extrusion, stainless steels are usually used in the annealed condition to ensure a good formability. Before part production, the semi-finished product is annealed and pickled in order to remove the scale layer [5]. Ferritic stainless steels usually are soft annealed [3], where the respective delivery condition of the semi-finished product is designated as *+A* according to [6]. If a high geometric accuracy of the semi-finished product is required, a final drawing operation with low diameter reduction will be performed. This achieves a high accuracy of the nominal diameter, but also introduces residual stresses and a slight hardening on the surface [7]. This condition is defined as *skin passed* and is abbreviated as *+LC* according to [6].

In forward rod extrusion, the billet is pressed into the die and formed in the die shoulder area. The inhomogeneous deformation results in residual stresses in the component. After forming, tensile residual stresses are present at the surface [8], which are in equilibrium with compressive residual stresses in the core [9]. After achieving the specified geometry, the component is ejected in reverse to the punch direction. In this step, a change of the residual stress state in the formed section may occur due to the elastic springback of the die [10]. For the chosen component material and process configuration, a reduction of the near-surface tensile residual stresses by the ejection step is shown in [11].

For the determination of the residual stresses, several methods exist. One of the most common techniques is the hole-drilling method, where a change of the stress state is measured, while a small hole is being drilled into the part's surface. It allows depth-dependent residual stress profiles to be determined with little effort, but it is destructive, which means that residual stress mapping with smaller point distances is not possible [12]. As a non-destructive method, radiation diffraction is used. X-ray or neutron radiation is emitted onto the material area to be analysed and the angle and intensity of the beam reflected at the material lattice is determined. The measured angle of reflection is used to calculate the lattice spacing, which changes when residual or load stresses are present [13]. In addition to the residual stresses, the full width at half maximum (FWHM) of the recorded intensity curves can be determined and used as an indicator for the deformation introduced [14].

3 Experimental Setup

The single-phase ferritic stainless steel *X6Cr17* (DIN *1.4016*, AISI *430*) is used as the component material. Due to its classification in corrosion protection class I according to [15], it is used for components in food industry and in medical technology. The soft annealed condition (+A) is selected as reference, since it ensures a good formability. The skin passed state (+LC), which is often chosen due to the higher surface quality, is examined as a comparison case. A forward rod extrusion process is used for the forming of the billets. The process for component manufacturing is shown in Fig. 2.

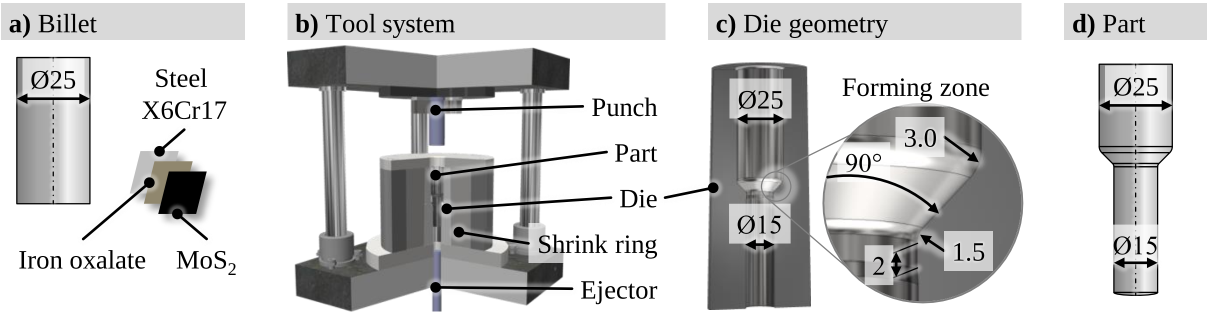

Fig. 2: Experimental setup for part production.

The billets a) are manufactured from bar-shaped material by cutting and plane-parallel grinding of the end faces. They are coated with a lubrication system consisting of iron-III-oxalate as a carrier layer and a MoS_2-based lubricant. The forming of the components takes place on a hydraulic press *Lasco TZP 400* with the tool system shown in b). In a one-step process, the components are formed and then ejected in opposite direction to the punch movement. The die c) is designed and manufactured according to usual design guidelines with a shoulder opening angle of $2\alpha = 90°$. The formed part d) consists of a non-deformed area, the transition area, which represents the shoulder geometry, and a deformed shaft. The deformation from diameter 25 mm to 15 mm results in an equivalent plastic strain of $\bar{\varepsilon} = 1.02$.

The influences of the material condition on the component properties are determined by material characterization before and after forming. For this purpose, the near-surface residual stresses in the axial and tangential directions in both the non-deformed and the formed section of the component are determined by X-ray diffractometry. The measurements are performed with the 8-axis *Seifert XRD 3003* X-ray diffractometer. Cr-Kα radiation with a wavelength of $\lambda = 0.2291$ nm is used for the measurement, since it is within the range of the lattice constant of 0.286 nm of unstressed α-iron. The measuring spot diameter is approximately 0.8 mm with a maximum penetration depth of 5.8 µm. The measurement is carried out on the {2 1 1} lattice plane using the χ-method according to [16] with 13 ψ-tilts from -50° to +50°, subdivided for constant $\sin^2\psi$. The reflected beam is detected with a line detector. The angle positions of the recorded intensity curves are determined by fitting with a pseudo-Voigt function. For the evaluation, the $K\alpha_1$ peak is used, which is gained by subtracting the $K\alpha_2$ peak from the measured intensity distributions. The calculation of the present stress state is done by the software *Rayflex Analyze* with the $\sin^2\psi$ method. In addition to the residual stresses, the FWHM values of the recorded peaks are determined, allowing conclusions to be drawn about the induced deformation [17].

The determination of depth-dependent residual stress profiles is difficult due to the corrosion resistance of the material. In order to determine the properties in the interior of the component, the microstructure and the microhardness are therefore investigated in the longitudinal section. The samples are embedded and severed by sawing. The preparation of the surface to be examined is carried out by grinding up to a grit size of 15 µm and final polishing with diamond paste with 6, 3 and 1 µm grain size. The grain structure of the material is made visible by etching with an etchant consisting of water, hydrochloric acid and nitric acid. The aim of the microstructural investigations is to determine changes in the grain structure during the forming process, depending on the condition of the material used.

To quantify the mechanical properties of the material, the indentation hardness in the initial and formed state is measured. For this purpose, microhardness measurements according to [18] are carried out on longitudinal sections. The Vickers hardness is determined with the *Fischerscope HM2000* microhardness tester in an air-conditioned measuring room. During this test, a tungsten carbide pyramid penetrates the material. The time required to apply and relieve the testing force on the component is 20 s. When the test load of 1 N is reached, a creep time of 5 s is maintained. The hardness is determined from the measured penetration depth. To reduce the required measuring time, the spot distances in the component areas are varied. In the non-deformed area, measurements are taken in lines with a distance of approximately 5 mm and a radial spot distance of approximately 0.8 mm. In the area of the shoulder, a spot distance of 0.3 mm in axial and radial direction is used to achieve a high resolution. In the formed shaft and the tip, the point spacings are 0.8 mm radially and 1.2 mm axially.

4 Results and Discussion

In order to determine the influence of the initial material state, material, process and part properties are determined. The results are shown and discussed in the following section. Regarding the process properties, maximum forces and part temperatures are taken into account, since these allow drawing conclusions about the die load. As part properties, residual stresses, microstructure and microhardness distribution are considered, which influence the operational behaviour of the produced component.

4.1 Forming process properties

During extrusion of the components, the process forces required for forming and ejection were determined. Their maxima are shown in Fig. 3. Additionally, the component temperatures - measured after ejection and removal from the tool - are displayed.

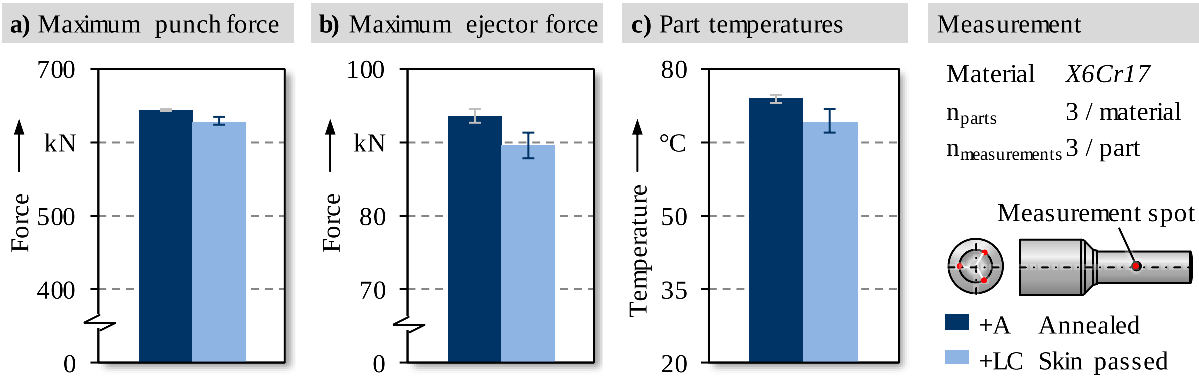

Fig. 3: Process forces and part temperatures

If annealed material (+A) is used, a punch force of 644 ± 2 kN and an ejector force of 94 ± 1 kN are required for the production of the parts. Due to the deformation of the material and friction between the part and the die, the component heats up to a temperature of 74 ±1 °C. Using skin passed (+LC) material, however, slightly lower process forces of 628 ± 5 kN are measured at the punch and 90 ± 2 kN at the ejector. This is also mirrored in the part temperature, where only 69 ± 2 °C is reached. Tribology provides an explanation for these differences. Since the skin passed material has a smoother surface than the annealed one, influences on the resulting friction forces are possible here, which correlates with the resulting component temperatures.

4.2 Residual stresses

To determine the influence of the material condition on the component residual stresses, X-ray stress measurements were performed on the surface of the manufactured components. Since only around 50% of the billet volume is deformed during component manufacture, measurements were carried out both on the non-deformed and on the deformed area of the specimens. In the non-deformed area, an oscillation in the axial direction was necessary during the measurement due to the small measuring point size, resulting in a linear measuring range. In addition to the residual stresses, the FWHM values of the peaks were determined in order to derive qualitative information on the forming history. The results are shown in Fig. 4.

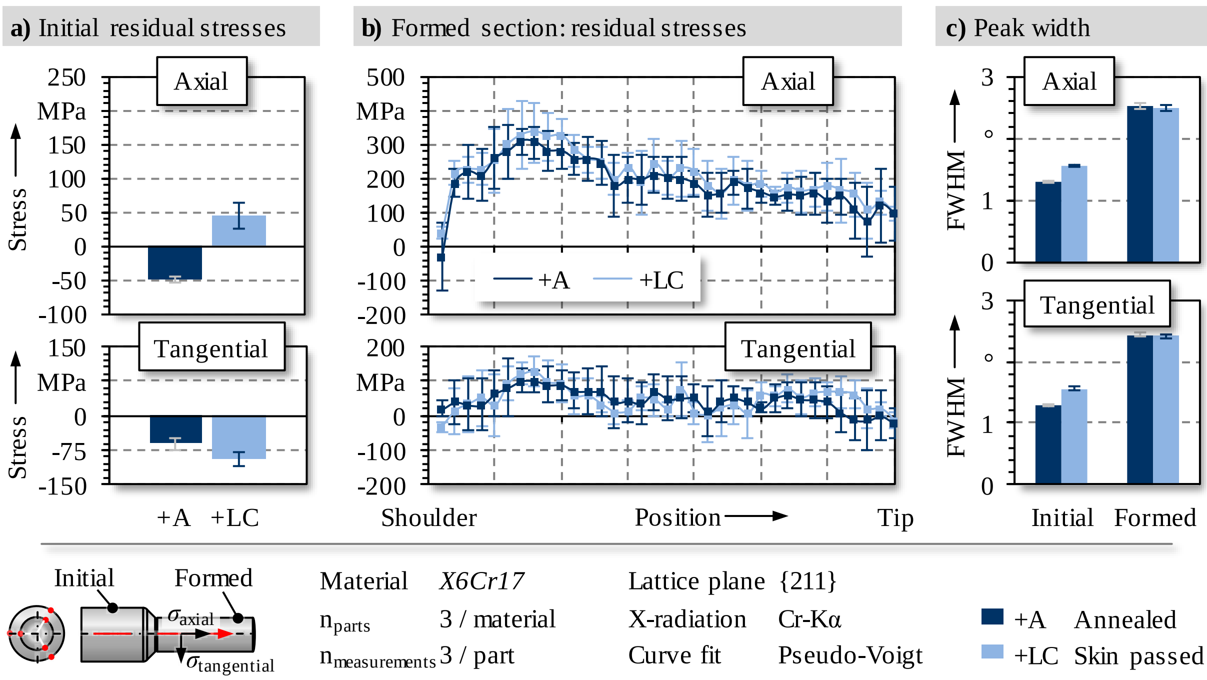

Fig. 4: Residual stresses in formed parts and full width at half maximum (FWHM) values of the measured peaks

In the non-deformed section, the residual stresses shown in Fig. 4 a) are present. The surface of the annealed material (+A) shows compressive residual stresses of -49 ± 5 MPa in the axial and -61 ± 14 MPa in the tangential direction. These stresses result from the cooling of the material after soft annealing, since the core will cool after the surface. Thus, thermal shrinkage induces compressive residual stresses in the surface tensile stresses in the core [19]. In the skin passed material (+LC) there are low tensile residual stresses of +44 ± 18 MPa in the axial direction, which are caused by the cold drawing process [20]. In circumferential direction, compressive stresses with a value of -96 ± 15 MPa are higher than in the annealed material. This residual stress condition is due to the surface load during cold drawing [21].

The residual stresses on the formed shaft of the components are shown in Fig. 4 b). In both main stress directions - axial and tangential - similar curves are present. There are small residual stresses near the shoulder, which change into distinct tensile stresses with increasing distance. Maximum residual stresses are present at a distance of 8 mm from the shoulder with about +310 MPa in axial and about +100 MPa in tangential direction. The residual stresses decrease towards the tip. This stress state can be explained by the inhomogeneous deformation during the flow through the forming zone [9]. It coincides with results from the literature [22]. Despite the different initial conditions, no significant differences can be identified in the formed state between the annealed and the drawn material. One explanation for this is that during the forming of the components, a much higher degree of deformation occurs than during cold drawing of the material. This is backed up by the FWHM values shown in Fig. 4 c). While significant differences can be seen in the initial state due to the different deformation history, the FWHM values in the manufactured components are at the same level.

4.3 Microstructure

However, X-ray diffractometer measurements only map the residual stress state on the component's surface. Since a depth-dependent stress measurement is difficult to perform due to the corrosion resistance, the hardness and the microstructure are investigated to depict the component properties inside the part. In these investigations, the comparison between the original state and the formed material properties is performed on a longitudinal section. Fig. 5 shows the material flow and the microstructure of the manufactured components.

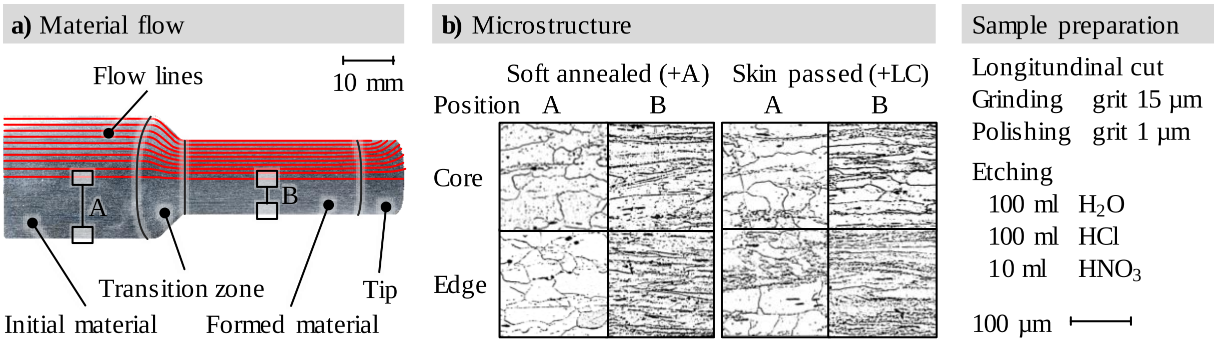

Fig. 5: Material flow and microstructure of formed parts

With regard to the material flow, different areas can be identified in the formed specimens in Fig. 5 a). The material is not deformed during part production in the area of the initial material. Here, the linear structure of the material with parallel lines in the axial direction may be recognized. The forming takes place in the transition zone in the area of the die shoulder. In this region, the material flows to the centre and in the axial direction. This results in a structure with increasingly elongated grains. In the approximately 36 mm long area "formed material" there is a homogeneous structure in axial direction with strongly elongated parallel grains. In the "tip" area, inhomogeneous flow lines can be seen, which end in the edge area, since this is the place, where the end face of the billet and its edge area is located.

A detailed view of the grains in the core and the edge is shown in Fig. 5 b) for the component areas "initial material" and "formed material". The initial material has a linear structure with slightly elongated grains. In the annealed condition (+A), the core and edge areas show a homogeneous grain distribution with grain sizes of about 24 µm in the radial direction. In the skin passed condition (+LC), a similar structure is present in the core. In the edge area, however, slightly narrower and longer grains with grain sizes of 20 µm are present, which can be explained by the forming of the material during cold drawing of the semi-finished product.

In the deformed area, there are strongly elongated grains in both material states. In the edge area, with a size of 9 µm, there are thinner grains than with 12 µm in the core, which can be explained by the deformation when passing the die shoulder. While the core area is only axially stretched, the edge area is stretched in axial direction and additionally compressed in radial direction. There are no significant differences between the annealed and skin passed material. This shows that the deformation during extrusion is so high that the influence on the surface caused by the cold drawing of the bars is negligible.

4.4 Microhardness

To analyse the mechanical properties of the parts, the microhardness is used, as it provides a measure of the work hardening induced to the material. The hardness distribution in the longitudinal section of the extruded components is shown in Fig. 6.

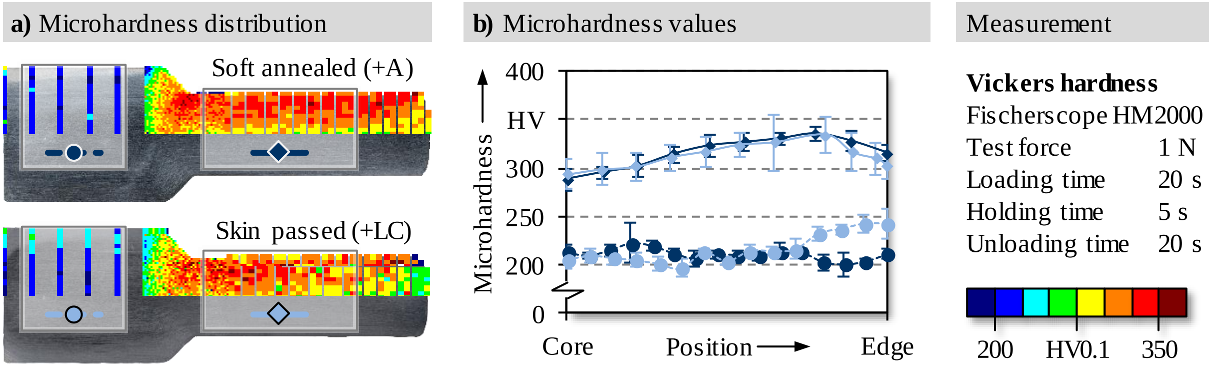

Fig. 6: Microhardness distribution of formed parts

In the initial state, the annealed material (+A) shows a homogeneous hardness distribution in the axial and radial directions with values of about 210 HV0.1. In the forming zone in the shoulder area, the material hardness increases due to work hardening. In the formed area there is a homogeneous hardness distribution in the axial direction. In the radial direction, the lowest hardness values of about 290 HV0.1 are located in the area of the symmetry axis. The hardness increases in the direction of the component surface, with the maximum of 335 HV0.1 being approximately 1.5 mm below the surface. The hardness at the tip of the component is lower due to the lower deformation induced.

In the skin passed (+LC) material, however, there is a hardness gradient in the radial direction in the initial state. With a value of 208 HV0.1, the hardness in the core is similar to that in the annealed material. The surface is strengthened to a depth of approximately 3 mm and has a significantly higher hardness of 230...240 HV0.1. In the transition area, the formed area and the component tip, similar hardness distributions can be found compared to the soft annealed material.

In the formed components, there are comparable microhardness distributions for both material states. Since there is no significant change in the microhardness despite the different levels of pre-hardening in the surface layer, it can be assumed that the low level of deformation during cold drawing of the semi-finished product has no influence on the forming result.

5 Conclusions and Recommendations

A forward rod extrusion process was performed with a ferritic stainless steel in the delivery conditions “soft annealed” (+A) and “skin passed” (+LC). For the determination of the influence of the material delivery condition, the properties of the forming process and the initial and the formed material were identified. With the findings shown in this paper, the following conclusions can be drawn.

- The delivery condition affects the material properties

The cold drawing during the production of skin passed (+LC) material does not only change the appearance of the surface of the material. On the surface, residual stresses are induced. In the near-surface material volume, the microhardness is increased due to work hardening. The microstructure is affected only slightly.

- The material condition slightly affects the process properties

When skin passed material is used, slightly lower maximum forces are required for forming and ejection. This reduces the tool load, which may result in a higher tool life. As a side effect, slightly lower component temperatures are achieved, which improves component handling.

- Skin passing does not affect the parts’ microhardness and residual stresses

During the forming of the material with a comparatively high degree of deformation carried out within the scope of this article, no influences of the material condition on the target variables "residual stresses", "grain size" and „work hardening" are detectable. The induced residual stresses and the hardening of the material due to the skin pass process do not cause any significant difference in the target values in the formed component.

For this reason, the following recommendations for process design are derived. The use of skin passed material is recommended if a high accuracy of the billet diameter is required in the process. Furthermore, it is recommended when cost-intensive forming dies are used, as the lower maximum process forces can be expected to increase the tool life. However, if there is, for example due to previous process steps, a certain hardening in the material, which is comparable to the "skin passed" state, it can be tolerated, if the deformation during component production is much higher. In this case, it is advisable from an economic and ecological point of view to avoid heat treatment, as this eliminates the need for a cost-intensive and energy-intensive annealing step. In addition, there is no necessity for pickling with hazardous acids to remove scale after annealing.

6 Summary and Outlook

Semi-finished products for cold extrusion are produced by various rolling, annealing and drawing operations. At the end of this process chain, ferritic stainless steels are soft annealed with final pickling to remove scale and an optional drawing step to achieve a small diameter tolerance. The aim of the paper was to investigate the influence of the material condition on the resulting process properties and component residual stresses and material properties for forward rod extrusion. To determine the process properties, billets made of ferritic stainless steel *X6Cr17* (DIN *1.4016*, AISI *430*) in the soft annealed (+A) and skin passed (+LC) condition were extruded and maximum process forces and part temperatures were determined. The residual stresses were determined both in the initial and in the formed state on manufactured components. To analyse the material properties inside the component, grain sizes and microhardness distribution in longitudinal section were identified. The results showed that slightly lower process forces are required for forming and ejection when using skin passed material. Due to the lower part temperatures, tribological influences were identified as the cause. Despite different residual stresses in the initial material, a similar near-surface residual stress condition was measured in the formed components. Differences in grain size and microhardness distribution in the initial material also did not cause any significant change in the formed components. This was attributed to the comparatively large deformation during forming compared to the cold drawing (skin pass) during the manufacturing of semi-finished products. These results led to the conclusion that a low pre-strengthening in the material does not cause any changes in the process and component properties, if the deformation in the forming process is comparatively high. The recommendation was derived from this, that soft annealing can be omitted for semi-finished products with low hardening if a significantly larger forming operation is carried out in the main forming operation.

These findings form the basis for further investigations to ensure reliable handling of residual stresses during cold extrusion. Due to increasing demands on corrosion resistance, the applicability of the findings to materials with a more complex structure, such as duplex steels, will have to be investigated. In order to include the residual stresses in the calculation of the component operating behaviour, the stability of the residual stresses under typical operating loads is to be researched.

7 Acknowledgement

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