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Advanced functionalisation and numerical simulation of the boundary layer by deformation-induced martensite on bearing rings through bulk metal forming

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Abstract. The phase transformation of metastable austenitic steels caused by externally superimposed strains during cold forming increases the material strength in addition to strain hardening. Although numerous research papers have described the basic effects of the phase transformation from metastable austenite to martensite, it is not yet applied in the dimensions of common bulk formed components. Thereby the functionalisation of deformation-induced martensite to increase the material strength specifically at heavily loaded surfaces bears potential. However, the amount of deformation-induced martensite formation within a forming process is limited through the occurring strain hardening. In this paper an approach for an advanced functionalisation of this transformation through an adaption of the process is presented. The setup of a forming process is adapted, forming experiments are carried out at low temperatures and the specimens are investigated through hardness measurements (HV1), magnetic inductive testing (Feritscope MP3C) and microstructure analysis. The results were compared to distributions of plastic strain determined through FE simulations and showed a good correlation. It can be shown, that at cryogenic temperatures a significant increase of martensite formation is achieved.

Introduction

For applications with high mechanical and tribological loads bulk formed components with tailored heat treatments such as hardening or tempering are required because of their superior mechanical properties [1]. However, this does not apply for austenitic stainless steels, since they cannot be hardened conventionally and therefore don’t reach sufficient properties such as hardness or yield strength [2]. As Stainless steels are usually applied in corrosive environments due to their strong resistance to corrosion, increasing their mechanical and tribological properties expands their field of applications. In the context of ball bearings, a suitable approach to enhance the service life is increasing the material strength specifically at heavily loaded surfaces, such as the contact areas of a rolling element to the rings. For example, Coors et al. demonstrated the positive effects of an increased material strength at the bearing surface on the service life through a hybrid material approach [3]. As the most common stainless steels are austenitic and have a metastable austenitic state at room temperature, they allow deformation-induced martensite transformation [4]. The functionalisation of this deformation-induced martensite transformation at heavily loaded surfaces bears considerable potential.

In principle, a crystal structure can be described through its current specific Gibbs free energy, whereby a low amount of free energy is strived for. In a so-called metastable state, the amount of free energy is higher, until additional energy is brought in, a threshold is surpassed and the structure can transform into a more stable state with less free energy. For austenitic stainless steels, the austenitic structure is metastable and can transform to the stable martensitic structure. For this transformation, a specific minimum amount of energy, shown as ΔG in Fig. 1a, has to be brought into the microstructure. This can be achieved when the required amount of energy ΔG is brought in thermally through strong cooling as ΔG_{chem}, mechanically, through induced deformation as ΔG_{mech}, or through a combination of both. The transformation can occur thermally for every amount of deformation if the so-called martensite start temperature M_s is reached, but not at all, if the temperature rises above a critical threshold T_0, as shown schematically in Fig. 1b. The specific values of these limit temperatures depend on the alloy elements in the investigated material [5].

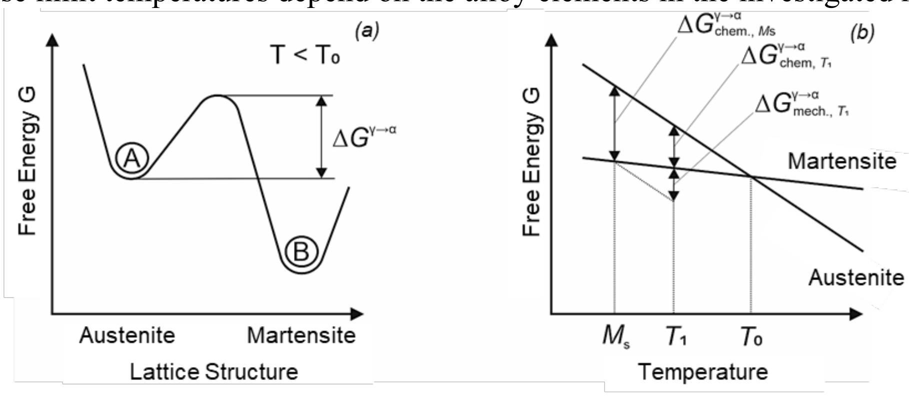

Figure 1: The metastable and stable states (a) and the thermodynamical description of the martensite transformation (b) according to [2]

Martensite formation from γ-austenite can occur in different forms. As shown in Fig. 2, the austenite can either transform directly to α-martensite or to ε-martensite, which then can also transform into α-martensite. For the direct transformation from austenite to α-martensite the volume increases by 2.1 % and the material strength is enhanced. The volume decreases by 0.8 % for the transformation to ε-martensite which results in a slight increase of the strength but a strong increase of ductility. Although the transformation from austenite first to ε-martensite and then to α-martensite leads to the same volume behaviour, the material strength is increased less than for the direct transformation [2]. As the different transformations lead to different mechanical properties, the resulting properties are a result of the totality of the occurred transformations. These three transformations all take place simultaneously, whereby their specific distribution depends on the forming parameters such as the temperature, the strain rate and the resulting stress. In general, lower temperatures, slower forming rates and tensile stresses (rather than compressive) lead to higher amounts of α- martensite [7].

In the context of sheet metal forming, Behrens et al. researched the effects of deformation induced martensite transformation and developed a material model for FE simulations to determine the resulting amount of martensite as well as consider the change of flow stress. For bulk forming the material model was transferred and applied to simplified forming processes such as uniaxial compression tests [8]. Behrens et al. also presented a first functionalisation of the deformation induced martensite for bulk forming, whereby two forming processes were numerically designed and carried out [9]. The following research [10] showed increased hardness values and microstructures images, which indicated deformation induced martensite transformation.

This paper is dedicated to the advanced functionalisation for bulk forming. The forming processes of Behrens et al. [10] are revisited, the martensite contents of the specimens are determined and compared to numerically determined distributions of plastic strain, as well as to previous results of hardness measurements and microstructure analysis. Additionally, to enable a stronger martensite formation as in the previous studies, the process with the higher degree of plastic strain was carried out at cryogenic temperatures of -196 °C. The formed specimens were analysed and compared to the results of forming at -17 °C.

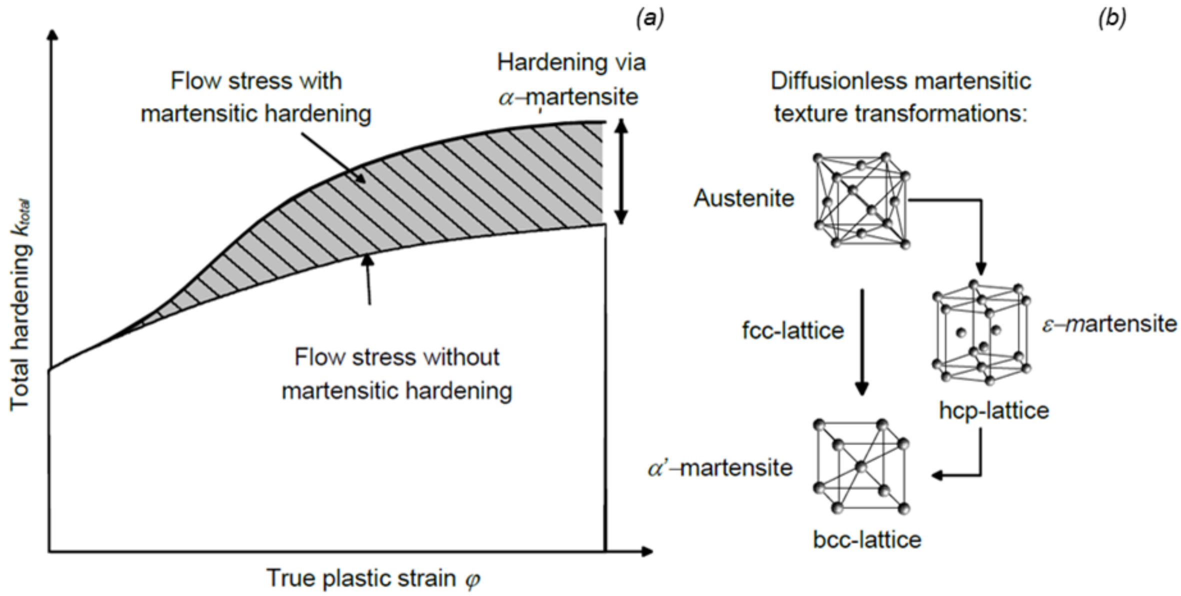

Figure 2: The effects of deformation induced martensite transformation (a) and the possible transformation paths (b) [7]

Material and Methods

As testing material, the stainless steel AISI 304 (EN 1.4301) was chosen. It was already used in previous studies and thereby showed strong hardening through deformation-induced martensite transformation. To recreate the forming processes of ball bearing rings with different diameters, two processes with different material flows were designed. This was an upsetting process for smaller diameters and a full forward extrusion for larger diameters. As shown in Fig. 3 schematically, the forming processes were both carried out with the same set of dies and only the dimensions of the cylindrical semi-finished product were varied. The dimensions were a diameter of 35 mm and a height of 22 mm for the upsetting process and for the full forward extrusion a diameter of 49 mm and a height of 11.7 mm. The lower die was additionally devided into two sections to reduce the stresses in the buttom radius. The die setup is designed as a transportable system with an additional thermal container to reduce the heat exchange with the enviroment. Through this, the complete die system can be cooled as whole and mounted quickly into the press. Before the cooling, all functional surfaces of the die and the specimen are lubricated with molybdenum disulfide and the complete setup is assemlied after the lubricant has dried. The forming tests were carried out on a Schirmer & Plate hydraulic press with an adjustable ram speed. On the one hand, a low ram speed and therefore a low strain rate as well as a longer process time would lead to a stronger heating of the die system (including the specimen) and result in a reduced martensite transformation. On the other hand, a high ram speed and therefore higher strain rate would lead to higher press forces, higher mechanical loads on the dies and also less martensite transformation. Because the work of [9] showed a strong temperature dependency and comparatively low strain rate dependency, in the work of [10] a ram speed of 10 mm/s was chosen as it leads to realtively low strain rates whilst still being in the range of industrial processes. To ensure the comparability of the results to [10], for this study the ram speed of 10 mm/s was kept.

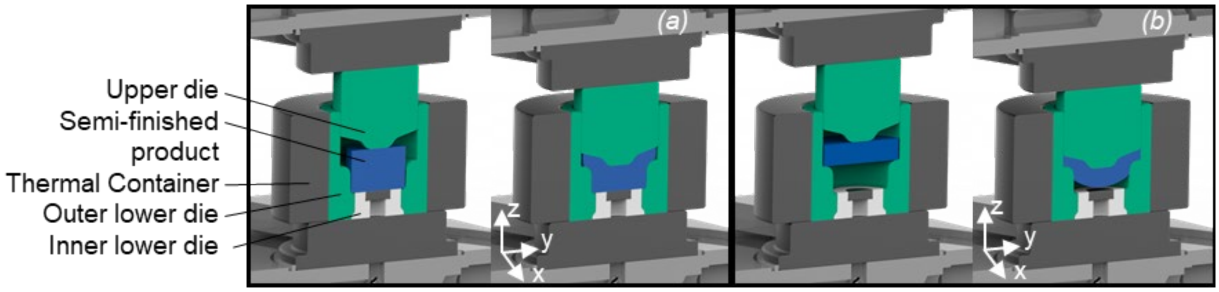

Figure 3: The investigated forming processes: a.) upsetting, b.) full forward extrusion

First, the flow curves at -17 °C from previous work of the authors of [9] were applied to the processes of [10] to determine the distribution of plastic strain numerically through a 2D simulation with the Finite Element (FE) software Simufact Forming v16.0. The dies were assumed as rigid and for the discretisation the element type “quads” was used with an element size of 0.2 mm. Additionally, the martensite contents of the specimens of the former forming experiments at -17 °C were measured. The martensite contents and the numerically determined plastic strain distributions were compared to the results of [10]. As fundamental research, such as Olson [5] and Angel [11], showed the potential of an increased martensite transformation at even lower temperatures, additionally a cryogenic temperature was investigated experimentally. For this, the experimental forming process with higher degrees of plastic strain and therefore a higher potential for martensite transformation was carried out at -196 °C. The specimens were analysed through magnetic inductive testing (Feritscope MP3C), microstructure analysis and hardness measurements (HV1) as shown in Fig. 4.

The content of α-martensite was determined through magnetic inductive analysis for each formed specimen. Thereby, the α-martensite content f^{α} was calculated through the approach of the work of Talonen [7] from the mass percentage of ferrite f^{F}, as shown in Eq. 1. The ferrite percentage was measured at the surface at six separate locations, as schematically shown in Fig. 4b, at the surface of the contact area to the bearing ball.

$$f^{\alpha}=0.261 + 1.714\cdot f^{F} \quad (1)$$

The hardness measurements were taken out on cross-sections of the formed bearings in two directions as shown schematically in Fig. 4a. Along the radius, the hardness was measured every 0.2 mm and perpendicular to the surface at the middle of the contact area, it was tested up to a depth of 5 mm into the specimen. The measurements were carried out with a Qness Q10 A+ micro hardness testing device.

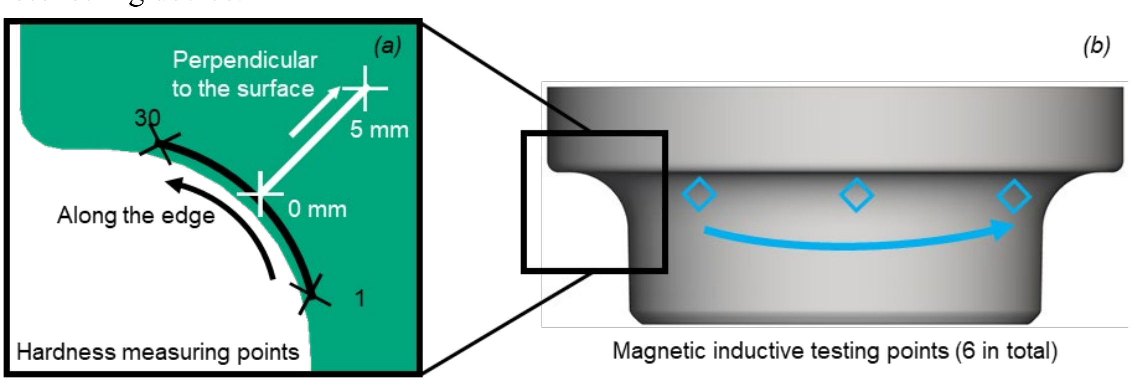

Figure 4: Measuring points for hardness(a) and martensite content(b)

To analyse the microstructure, cross sections of the formed specimens were taken from the area where the contact to the bearing ball shall be. Therefore, cross-sections were cut out of the specimen and cold embedded. Afterwards the samples were grinded, polished, etched with Beraha I and metallographic images were taken.

Results and Discussion

As shown in Fig. 5, the hardness along the radius shows a nearly linear increase for the upsetting and a decrease for the full forward extrusion at -17 °C. This is consistent to the simulations where a similar increase and decrease of plastic strain along the radius can be observed. The hardness values at the beginning of the radius were higher for the full forward extrusion than the upsetting, which changed around the measuring point 20. From there on, higher values were measured for the upsetting process. These hardness profiles are in accordance to the calculated distributions of plastic strain from the simulations. The measurements perpendicular to the radius show a linear decrease in depth for both processes. Thereby, for both processes comparable hardness values as well as similar decreases can be seen. The decrease itself is consistent to the numerically determined distributions of plastic strain, but the low difference between the both processes does not fit to the high differences of plastic strain that could be observed in the simulations.

For forming at -196 °C, an increased hardness can be observed along the radius whilst showing a decrease with a similar gradient as for the forming at -17 °C. In the depth, the hardness is also increased overall, whilst only a low decrease can be seen. In comparison to the hardness of conventional AISI 304 (without strain hardening), which is roughly about 220 HV to 240 HV, both forming processes lead to a strong increase of hardness at -17 °C. This effect is enhanced for forming at -196 °C.

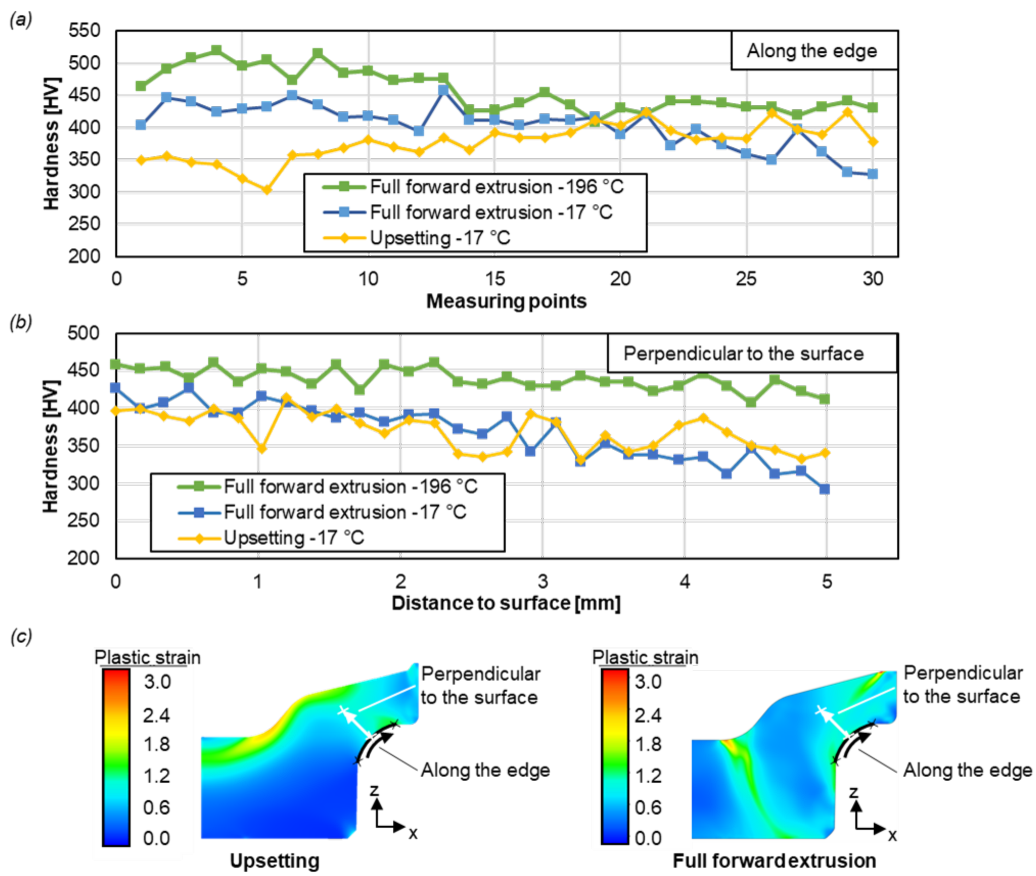

Figure 5: Results of the hardness measurements along the edge (a) and perpendicular to the surface (b) with the numerically determined distributions of plastic strain(c)

The determined martensite contents at the surface of the testing points, as schematically shown in Fig. 4b, are presented in Table 1. As substantial contents of α-martensite could be measured for each specimen, the increase in hardness can be related to deformation induced martensite transformation and not solely to strain hardening. For the full forward extrusion, the martensite content is higher than for the upsetting process, which is in accordance to the numerically calculated higher plastic strain. The low difference in transformed martensite of only 2 Ma.-%, is a possible explanation for the low difference of the hardness values in depth between the two processes (compared to the high differences of calculated plastic strains).

In general, the measured martensite contents were considerably lower than contents that fundamental research, such as [11], have reached for the same forming temperatures and degrees of strain. This can be explained through the inhomogeneous and higher strain rates, thereby higher amount of dissipated heat, as well as possible heat exchange with the surrounding environment. The full forward extrusion at -196 °C reached higher martensite contents of approximately 81 % at the contact surface of the ball bearing. Other researchers, such as Angel [11] or Nebel [12], have identified the maximum amount of achievable martensite content at approximately 80 - 90 % for higher temperatures and lower degrees of strain. Therefore, it is likely that the maximum martensite content achievable for the presented forming process in the area of interest, with its comparatively high strain rate, has been reached at the investigated surface and a further increase is not possible.

Table 1: Determined martensite contents for the formed bearing rings

Forming temperature [°C]	Forming process [-]	Martensite content [Ma.-%]	Standard deviation [Ma.-%]
-17 °C	Upsetting	2.66	0.38
	Full forward extrusion	4.55	0.25
-196 °C	Full forward extrusion	81.68	1.87

As presented in Fig. 6, at -17 °C both processes showed inhomogeneous microstructures with noticeable line formations of martensite. These lines indicate twin planes and thereby a deformation induced transformation. The concentration of these lines is higher towards the surface of the contact area than in the depth for both processes. Thereby it is not possible to distinguish clearly between α-martensite and ε-martensite. For the full forward extrusion, the overall concentration is higher than for the upsetting process. Additionally, the microstructures show dark patterns, which are in accordance to the distribution of plastic strain determined through the simulations. This indicates deformation-induced martensite formation and grain refinement. At -196 °C the area of martensite transformation is significantly enlarged and the grain structure is more refined, but it still shows the same schematic pattern as for -17 °C. This pattern is also schematically in agreement to the distribution of plastic strain determined in the simulations. The low decrease of the hardness values in depth as well as the microstructure indicate that martensite was transformed in such a big area of the specimen, and not specifically at the surface. This might be disadvantageous for the mechanical properties of a component in question.

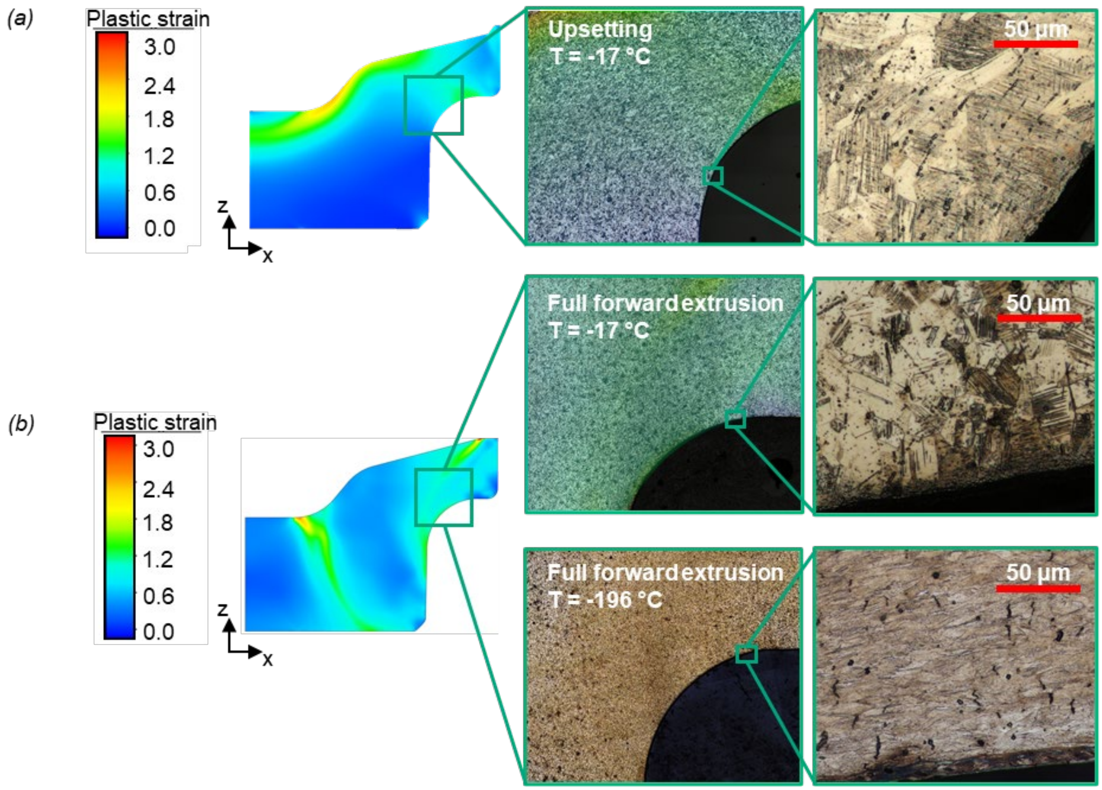

Figure 6: Metallographic images of the formed specimens of the upsetting (a) and full forward extrusion (b) forming process

Conclusion and Outlook

Through a thorough investigation the fundamental knowledge of deformation induced martensite transformation was functionalised for the application in the field of bulk forming. In previous studies two forming processes were numerically designed to show high plastic strains, and thus martensite transformation, at specific surfaces of the workpiece, which are expected to be heavily loaded. In this study specimens formed at -17 °C were investigated through magnetic inductive testing as well as through FE simulations and compared to hardness measurements and microstructure analysis. To study the possibilities of a further increase of hardness through martensite transformation, the full forward extrusion was additionally carried out at -196 °C. At -17 °C both processes showed increased hardness values at the surfaces of interest. The values were in agreement of the microstructure images as well as the magnetic inductive testing which showed an increased martensite content at these surfaces. The full forward extrusion process showed higher contents of martensite and a more refined microstructure. This can be explained through the higher degrees of plastic strain, which were calculated through the simulations. The forming at -196 C led to a further increase in hardness with a more homogeneous distribution. The microstructure showed an expansion of the area of the martensite transformation as well as a greater grain refinement. As a martensite content of approximately 81 % was reached specifically at the heavily loaded surface and fundamental researchers identify the limits of deformation induced martensite transformation at 80 to 90 % for processes with higher temperatures and lower degrees of deformation, it is assumed that this limit was reached for the presented process.

Throughout this series of studies, the numerically determined distribution of plastic strain was in good agreement with the occurring martensite transformation. Therefore, the simulation of the plastic strain can be considered as suitable simplified approach to estimate an approximate distribution of the deformation induced martensite transformation for a preliminary process design. This approach does not require additional models nor extended material data.

In following studies, the resulting residual stresses will be investigated. Although the full forward extrusion showed higher amounts of deformation and therefore reached higher amounts of α-martensite, the resulting residual stresses might have a negative influence on the service life. Also, a high martensite content will weaken the resistance to corrosion. Therefore, service life tests will be carried out for the specimens of this study to evaluate the influence of the martensite content, the hardness distribution and the resulting residual stresses.

As the cooling, as well as the handling of the complete die system was challenging, applying the presented approach industrially would require a high amount of effort and resources per workpiece. The results of the service life tests will allow to evaluate which forming process is more suitable and if the benefits of the functionalisation of deformation-induced martensite transformation are enough to consider an industrial application.

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