DEFORMATION-INDUCED STRENGTH INCREASE IN A FUNCTIONAL SURFACE OF ANGULAR BALL BEARING RINGS MADE OF X5CRNI18-10 (AISI 304)

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https://doi.org/10.37904/metal.2023.4634

Abstract

By cold forming metastable austenitic steels below 0 °C, the strength is increased significantly through martensite phase transformation in addition to strain hardening. This deformation-induced effect enables the use of corrosion-resistant materials for highly loaded applications such as bearings under oxidative atmospheres, where the use of conventional corrosion-prone steels is unsuitable. In this context, components made of austenitic steel could enable an economic application through a sustainable manufacturing process. The aim of this study is the modification of the functional surface layer of angular ball bearing rings made of X5CrNi18-10 (AISI 304) through bulk forming to increase their service life. Forming parameters and tool settings are determined numerically to obtain the material flow and prevent tool cracking, since tool steels show a lower resistance to high mechanical loads at process temperatures below 0 °C. After forming, local martensite formation in the surface layer of the angular ball bearing rings is detected through metallographic analyses. The resulting increase in martensite content and dislocations is correlated to the achieved surface hardness and to the simulated true plastic strain. It can be shown that by adapting the forming process, a significant increase in hardness is achieved in the running surface of the angular ball bearing ring.

Keywords: Austenitic steel, cryogenic forming, martensite formation, bearing rings

1. INTRODUCTION

In food processing machinery, bearings are subject to tribological and mechanical stresses while the material has to fulfill the requirements for compliance with hygiene standards [1]. Therefore, heat-treatable steels with poor corrosion resistance must be protected against corrosion by oils, which are not compatible due to the risk of contamination. For this steel type, the increase in strength and hardness is achieved by rapid cooling below the martensite start temperature M_s after austenitizing, during which a spontaneous phase transformation from austenite to martensite occurs. Stainless steels like X5CrNi18-10 (AISI 304) do not require any additional corrosion protection, but cannot be conventionally hardened to reach a sufficient mechanical strength. In case of austenitic steels, the M_s temperature is below 0 °C. By cooling austenitic steel, the effect of strain-induced martensite formation can be utilized to improve the mechanical properties, in addition to strain hardening. Below the martensite finish temperature M_f no further phase transition from austenite to martensite occurs, with a maximum martensite content of about 85 % [2]. A higher martensite content is not possible due to the elastic stresses caused by the volume change of the phase transformation [3]. The required energies for martensitic phase transformation are shown in **Figure 1** (left). To transform the austenitic to martensitic phases, the minimum formation energy $\Delta G_{\min}^{\gamma\rightarrow\alpha'}$ must be exceeded. This is achievable by cooling to the martensite start temperature M_S. At higher temperatures, the missing chemical formation energy ΔG_{chem} is compensated with mechanical energy $\Delta G_{mech.}$ to exceed the formation energy $G_{\gamma'}$. Above the martensite deformation temperature M_d, the phase transformation cannot take place, regardless of the true plastic strain [4]. At temperature T_0, the austenitic energy G_γ and martensitic energy $G_{\alpha'}$ are in thermodynamic balance. The temperature is too high for a formation of martensite, because ΔG is zero and the mechanical energy is insufficient.

By cooling AISI 304 to -188 °C, a high martensite content can be achieved with a low true plastic strain, see **Figure 1** (right). With increasing true plastic strain φ, the maximum martensite content can be achieved by introducing mechanical energy while forming up to a temperature of -30 °C. From there, the maximum martensite content decreases even at high true plastic strain. At forming temperatures of 50 °C and higher, phase transformation is almost completely suppressed [5].

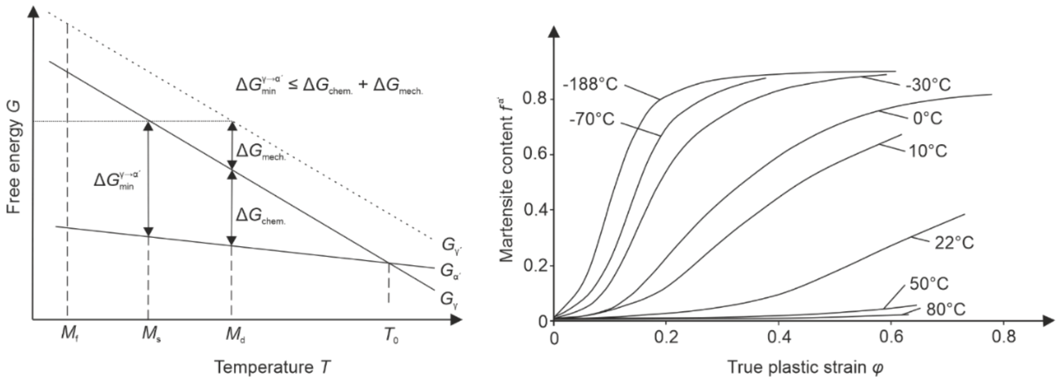

Figure 1 Free energy versus temperature diagram for martensitic transformation, according to [3] (left) and martensitic content versus forming degree and forming temperature of AISI 304 according to [5] (right)

Numerous research papers have described the fundamental effects of phase transformations in metastable austenitic steels, but their application to bulk forming has not been described [6]. The formed martensite consists of ferritic α'-martensite with a tetragonally distorted body-centered cubic (bcc) lattice structure and unstable ε-martensite with a hexagonal close-packed (hcp) structure [7].

2. MATERIALS AND METHODS

The objective of this study was to design, manufacture and test a tool system for the single-stage forming of angular contact ball inner bearing rings which can be cooled with the semi-finished products inside, see **Figure 2**. Furthermore, the tool was designed as a mobile system to be removed manually from the cooling unit and quickly be installed in the press [8]. The tool serves as a thermal container to apply isothermal forming conditions, maintaining a constant temperature of the contact surface. Two different semi-finished product geometries can be formed with the tool, while the material flow is fundamentally different. One cylindrical semi-finished product has a diameter of d = 35 mm and a height of h = 22.8 mm, resembling a flange upsetting process. The other formable semi-finished product has a diameter of d = 49 mm and a height of h = 11.7 mm, representing a full forward extrusion. For the forming tests, AISI 304 was used, which shows a significant hardening compared to other stainless steels.

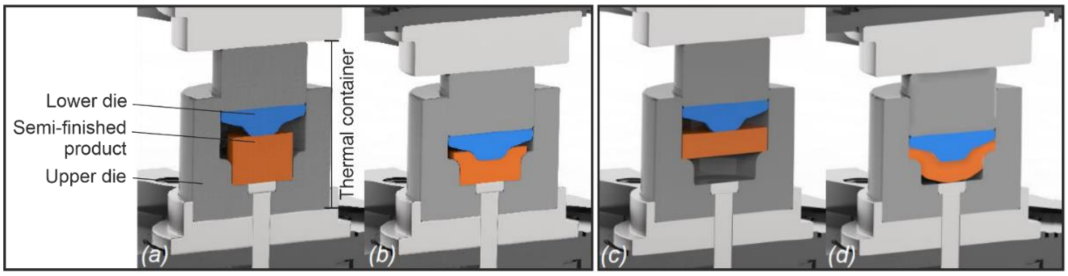

Figure 2 Developed tool system for upsetting (a-b) and full forward extrusion (c-d) of a angular contact ball bearing inner ring

First, numerical simulations were carried out to quantify the resulting local true plastic strain distribution within the formed component and determine the optimal forming conditions for both forming processes. A 2D model was created in the commercial FE system SimufactForming 16.0 using previously determined material data and friction coefficients [8].

Later, forming tests were carried out on a Schirmer & Plate hydraulic press with the developed and manufactured tool system. Forming speed and forming distance are adjustable on this press. A low forming speed of 10 $mm \cdot s^{-1}$ was chosen since previous cylinder upset tests showed higher hardness with lower forming speed. In addition, mechanical loads that can damage the tools were minimized. All sides of the specimen, the punch on the contact surface, and the lower punch were lubricated with molybdenum disulfide. After the lubricant layer dried, the tool system was assembled with the specimen inside. After forming at -17 °C, the components were machined to final dimensions by turning and grinding. Microscopic analyses were carried out on cross-sections and hardness-depth curves were recorded.

3. RESULTS

The numerical results of the upset and the extruded bearing inner rings show different true plastic strain distributions in the area of the bearing running surface (**Figure 3**). The upset geometry reaches a true plastic strain of φ = 1.5 in the shoulder area. However, in the bearing raceway, only a true plastic strain of φ = 0.7 can be achieved and thus the potential cannot be fully exploited. Using full forward extrusion, the area of highest deformation is exactly in the bearing raceway and a maximum true plastic strain of up to φ = 2.2 is achieved.

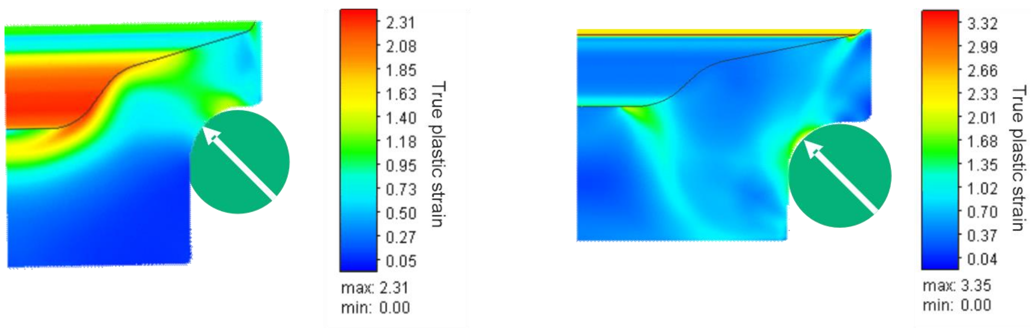

Figure 3 Simulation of true plastic strain by upsetting (left) and full forward extrusion (right) with the developed toolsystem

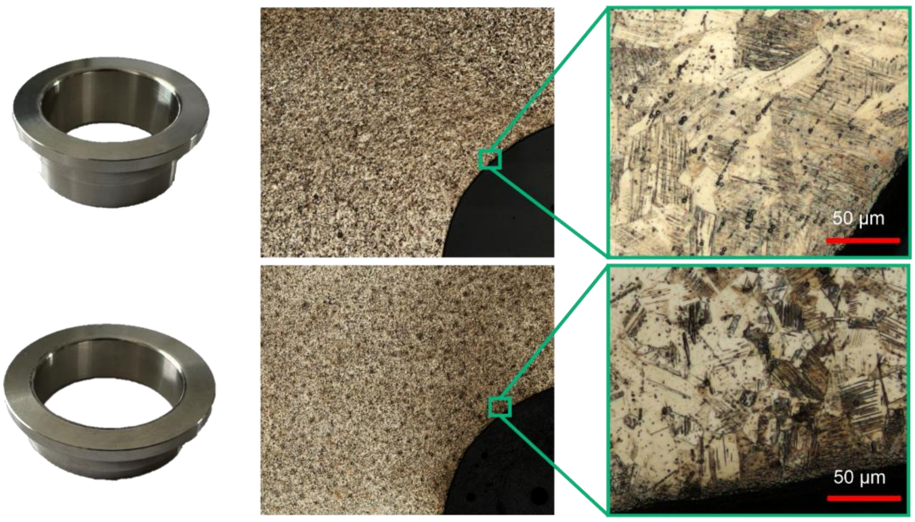

Figure 4 Metallographic images of the running surface area of upset (top) and extruded (bottom) angular contact ball bearing inner rings and their final geometries

Figure 4 shows the specimens formed by the two processes and their cross-sections. A clear grain pattern can be seen with fined grain in the area of the rolling element running surface. The grain pattern shows close correlation with the simulated local true plastic strain for both forming processes. The upset specimen has a homogeneous fine-grained microstructure. The line formation within the grain indicates twin planes and thus an implied lattice defect due to forming. The inhomogeneous microstructure of the extruded specimen shows an increase in twin planes in the area of the contact surface. In addition, a finer-grained microstructure can be seen compared to the upset specimen. Furthermore, a higher number of grains with line formation can be seen. The appearance of the dark areas is consistent with the areas of high true plastic strain from the simulation, which confirms the assumption of deformation-induced grain refinement. In addition, a martensitic content concentrated in the highly formed area can be detected by magnetic induction measurements. Due to the high local variations in true plastic strain, this content cannot be quantified precisely.

In **Figure 5**, the measured hardness in cross-section of the angular contact ball bearing inner ring is shown schematically. Measurements were taken along the radius in 0.2 mm steps and orthogonal to the running surface extending 5 mm into the component. The trend line along the radius shows a hardness decrease for the extruded sample and an increase for the full forward extruded sample. This can be explained by the forming process and the resulting non-uniform true plastic strain along the edge. The maximum of the upset specimen is at the point of highest true plastic strain in the edge at 425 HV. For the extruded specimen, the hardness is even higher, at 457 HV. Furthermore, the hardness of both components decreases with depth, with a minimum at the deepest measuring point at 5 mm. During upsetting, a more uniform material flow has been generated, which is reflected by a lower hardness gradient. In the solution-annealed condition, AISI 304 has a hardness of only 220 HV, which can be significantly increased by forming at -17 °C.

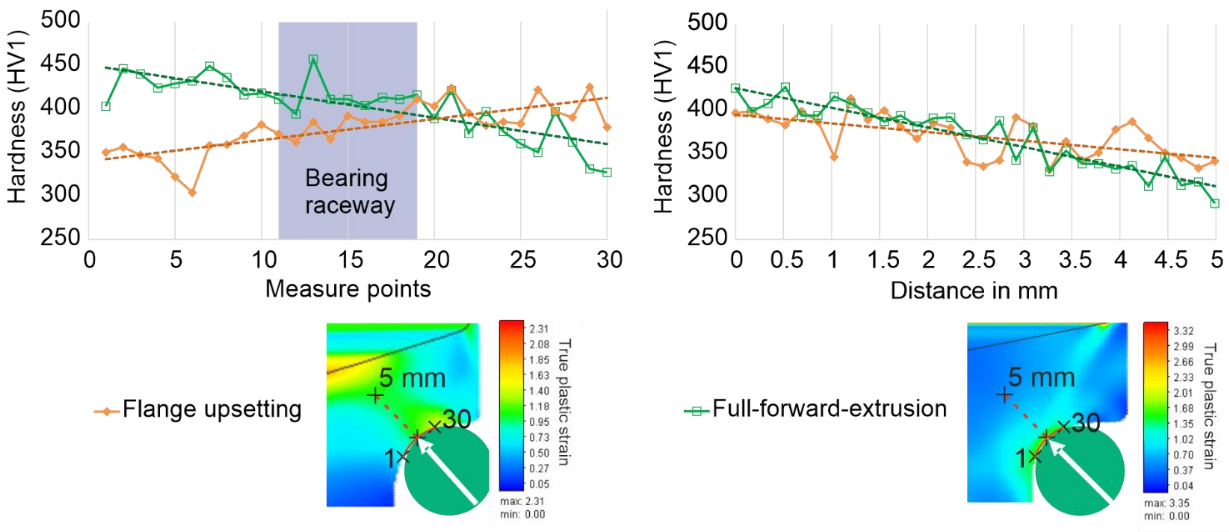

Figure 5 Hardness measurements on the upset and extruded components in the edge region (left) and in depth (right)

4. CONCLUSION

Although high true plastic strain and simultaneously higher hardness can be achieved by upsetting, these are not ideally located in the running surface of the bearing ring. In contrast, full forward extrusion allows significantly higher true plastic strain, which can be placed in the area of the bearing running surface. The metallographic evaluation as well as hardness measurements reflect this result. The extruded specimen shows a significantly better suitability and leads to the expectation of a higher service life.

In following studies, service life tests will be carried out, which will allow conclusions about the application behavior. Furthermore, cooling the specimens with liquid nitrogen to -196 °C will enable a higher chemical formation energy ΔG_{chem}, which should lead to an increase in martensite formation. The service life of the formed angular contact ball bearing inner rings will be investigated on a designed test stand.

ACKNOWLEDGEMENTS

The authors would like to thank the German Research Foundation (DFG) for the financial support of the project (Project-No. 423160066)

REFERENCES

[1] BERNS, H. *Stahlkunde für Ingenieure*. Berlin, Heidelberg. Springer Berlin Heidelberg, 1991.

[2] NEBEL, T. *Verformungsverhalten und Mikrostruktur zyklisch beanspruchter metastabiler austenitischer Stähle. Kaiserslautern*. 2002, Dissertation. Techn. University of Kaiserslautern.

[3] MAYER, P. *Verformungsinduzierte Martensitbildung beim kryogenen Drehen von metastabilem austenitischem Stahl*, Kaiserslautern, 2018, Dissertation. Techn. University of Kaiserslautern.

[4] HÄNSEL, A. *Nichtisothermes Werkstoffmodell für die FE-Simulation von Blechumformprozessen mit metastabilen austenitischen CrNi-Stählen*. Zürich. 1998, Dissertation. ETH Zurich.

[5] ANGEL, T. Formation of Martensite in Austenitic Stainless Steels. *Journal of the Iron and Steel Institute*, 1954, no. 177, p. 165-174.

[6] OLSON, G. B., COHEN, M. Kinetics of strain-induced martensitic nucleation. *Metallurgical Transactions A.* 1975, vol. 6, no. 4, pp. 791-795

[7] BARENBROCK, D. *Influence of deformation-induced martensite transformation on the crack propagation behaviour of austenitic steels*. Dissertation. Leibniz University Hannover. 2002

[8] BEHRENS, B.-A., BRUNOTTE, K., WESTER, H., PEDDINGHAUS, J., TILL, M. Functionalisation of the boundary layer by deformation induced martensite on bearing rings by means of bulk metal forming processes. In: *Metal 2022.* Brno, Czech Republic, 2022.