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Investigation of wear resistance of dry and cryogenic turned metastable austenitic steel shafts and dry turned and ground carburized steel shafts in the radial shaft seal ring system

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ABSTRACT

The state of the art industrial manufacturing process to produce shafts as counter surfaces for radial shaft seal rings is plunge grinding. This process consists of three major steps. The blank is turned to a slight diameter-oversize followed by the heat treatment and the hard-finishing by plunge grinding. The geometric surface structures of the resulting shafts in general exhibit a stochastic distribution. These surface characteristics contribute to a reliable and stable sealing functionality. And the surface and subsurface hardness generally leads to a higher wear resistance of the shaft.

Motivated by economic benefits and in order to achieve a compact production process for at least ten years, turning is investigated as an alternative manufacturing process. However due to the resulting lead structure on the shaft surface and the associated risk of leakage it has not become prevalent yet. In this paper turned shafts of the metastable austenitic steel AISI 347 (1.4550, X6CrNiNb1810) are investigated as alternative material for counter surfaces of radial shaft seal rings and compared to turned shafts of carburized AISI 5115 (1.7131, 16MnCr5). In addition to surfaces dry turned at room-temperature, cryogenic turned AISI 347 counter surfaces are analyzed. By applying cryogenic cooling, the formation of deformation-induced α'-martensite in the surface layer is possible during the turning process. Endurance tests in radial shaft seal ring test rigs are performed and complemented with detailed investigations of microstructure, micro-hardness and surface topography. The results are compared to results of state of the art ground AISI 5115 shafts.

1. State of the art

For functional surfaces such as shaft counter surfaces for radial shaft seals in sealing systems a hardened surface layer is often required to improve the wear resistance of the component. This can be achieved by several methods which allow a controlled alteration of the surface and material properties [1]. The most common method is a separate heat treatment of the blank like carburization. The hardening effect is obtained by a thermally induced martensitic transformation which occurs by quenching below the martensite start temperature (M_s) after austenitizing the shaft [2]. With this process a significant increase in hardness as well as a high hardness penetration depth up to several millimeters dependent on the workpiece material is possible. On the other hand this process is very energy and time consuming [3]. Due to the heat treatment and storage between machining processes and workpiece finishing the process chain is significantly enlarged. As a possible alternative to thermal hardening there is a possibility of strain hardening. In this process the manufacturing parameters are chosen in order to generate high mechanical loads in the surface layer. The resulting deformation leads to a formation of nanograins and twins and also to an increase of the dislocation density which result in strain hardening without any phase transformation [4,5]. Proven manufacturing processes that incorporate strain hardening are for example deep rolling, abrasive ball blasting or hammering [6]. The advantage of strain hardening processes is the easy integration into the process chain. As a consequence, those are

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not that energy and time intensive compared to heat treatments. However in terms of resulting hardness and penetration depth the mechanical hardening is not as effective as heat treatments [3]. For metastable austenitic stainless steels a third hardening method, which combines the positive effects of both aforementioned hardening methods, exists. In this deformation-induced hardening process a phase transformation from austenite to martensite occurs additionally to the strain hardening effects in the workpiece surface layer due to high mechanical loads at low temperatures (typically around or below room temperature). This kind of hardening can be activated by forming processes like deep rolling or abrasive ball blasting [3,6] as well as machining processes like turning [2,7] which are easy to integrate into the process chain. The central challenge is to reduce the temperature level during the material removal. In cutting processes a large fraction of the total energy generated is converted into thermal energy due to friction and elastic and plastic deformation processes. When turning steel shafts, temperatures of several hundred degrees Celsius near the material separation zone are common and as a result temperatures are too high to enable a deformation-induced hardening. Conventional lubricants like oil or emulsion do not have the performance to cool down the cutting process to the required low temperatures for deformation-induced surface hardening. Cryogenic coolants like carbon-dioxide-(CO_2-)snow or liquid nitrogen (LN_2) are a frequently discussed option to reduce the temperature level. In manufacturing processes a large part of the recent scientific research is dealing with that topic. Cryogenic coolants are used to reduce cutting force [8] and cutting temperature [9,10] as well as tool wear [10,11] and burr formation [12,13]. The use of CO_2-snow or LN_2 as process coolant can improve the chip breakage [14] as well as the surface quality [10,15] and integrity [16,17]. In previous works, the capability of the deformation-induced surface hardening of the metastable austenitic stainless steel AISI 347 during the final turning cut applying cryogenic cooling [2,7] is shown. This leads to a significant reduction of the process chain and thus an increase in economic efficiency. Therefore, new fields of application for these materials can be opened up; for example in a corrosive environment where high chemical resistance and a hardened surface layer are required such as bearings, medical equipment or seal rings. When substituting grinding as a manufacturing process of seal ring counter surfaces by turning, the relation between manufacturing parameters and shaft surface needs to be closely investigated, as the shaft surface contains a closed lead structure that has a major influence on the tribological behavior of the seal system. Investigations of hard turned crank-shafts for the automotive industry conducted at the Daimler-Chrysler AG since 2004 [18] reveal, that the surface roughness parameters R_z and R_{max} that are traditionally used for the description of the geometric surface structures of ground counter surfaces are no longer sufficient. An enhanced characterization of the surface lead is essential in order to take the pumping action due to the lead structure into account. The comparison of soft-turned CK45 (1.0503) shafts and hard-turned 20MnCr5 (1.7147) shafts with state of the art ground shafts in [19] reveals that the choice of proper turning parameters results in reliable counter surfaces that proved leak–tight in long term experiments, regardless of the rotational direction. When comparing the wear of soft-turned shafts and hard-turned shafts in endurance tests the wear of the soft-turned shafts is found to exceed the wear of the hard-turned surfaces [20]. The friction torque in the seal system for shafts manufactured by turning is presented in [21] and compared to state of the art ground shafts. It is found to be strongly dependent on the surface profile in circumferential direction. Shaft surfaces with a rough structure provide a bigger number of reservoirs for the lubricant and by trend result in smaller friction torques. Plateau-like surface structures in contrast show a higher friction torque. In [22] the wear of soft-turned 42CrMo4 shafts in a sealing system is found to be significantly higher when dust particles are carried into the sealing interface. For applications where the sealing interface is exposed to dust or where carbon black is present in the oil, the use of hardened steel shafts is thus necessary. In [23] hard turned 100Cr6 shafts are analyzed in radial shaft seal systems with grease lubrication. The results show that sealing of grease can be accomplished reliably with hard turned surfaces regardless of the rotational direction. The wear on smooth shaft surfaces is found to exceed the wear on rough surfaces. The overview of research in the field of turned surfaces in radial shaft seal applications shows two alternative approaches. In one approach the hardening process is waived altogether in order to achieve an economically beneficial manufacturing process suitable only for applications without dust or carbon black contamination of the seal system. In the second approach shaft surfaces are turned after a separate hardening process. Compared to the traditional grinding process, the process chain cannot be reduced significantly with the second approach.

With the investigation of deformation-induced hardening of turned AISI 347 shafts, this paper contributes to a very compact production process of counter surfaces for radial shaft seal rings. Following a description of the investigated materials and the presentation of the manufacturing process of the shaft samples, the results of seal ring endurance tests are presented. Microstructure and micro-hardness results are discussed and related to the performance of the shafts.

2. Experimental setup and material

2.1. Investigated materials

In this paper specimens of the solution-annealed metastable austenitic steel AISI 347 (1.4550, X6CrNiNb1810) and specimens of the low carbon steel AISI 5115 in carburized state (1.7131, 16MnCr5) are investigated in the following surface conditions: ground carburized AISI 5115 (I), turned carburized AISI 5115 (II), dry turned AISI 347 (III) and cryogenic turned AISI 347 (IV). The steel AISI 347 is annealed at 1050 °C for 35 min and quenched in helium atmosphere. The core microstructure in the solution annealed state is characterized by pure face-centered cubic (fcc) γ-austenitic grains with annealing twins and an average grain size of 21 μm included twins (see Fig. 1a). Carburizing of AISI 5115 is performed in propane gas at 900 °C for 180 min. Afterwards it is cooled down to 850 °C and kept for 15 min, quenched in oil at 100 °C. Finally it is annealed at 200 °C for 120 min. The resulting content of carbon in the near surface area is generally controlled at 0.8 wt% to optimize the mechanical properties [24,25]. The bulk microstructure in the carburized state is characterized by retained austenitic grains in tempered α′-martensite (see Fig. 1b).

The chemical composition (see Table 1) and the heat treatment of the investigated materials significantly influence their microstructure, hardness/micro-hardness (see Fig. 9), corrosion resistance, mechanical properties as well as the producible morphology of the martensite in case of different surface conditions [7,26–31]. Depending on the content of interstitial atoms, e.g. carbon and nitrogen or the presence of substitutional atoms in iron based alloys the basic crystallographic structure of the body-centered cubic (bcc) α′-martensite can be changed into a body-centered tetragonal (bct) or highly distorted α′-martensite, which both yield increased hardness compared to bcc α′-martensite, mainly due to a higher degree of supersaturation [32–34].

From a thermodynamic point of view, the critical free energy change $\Delta G^{min}_{\gamma\rightarrow\alpha'}$ has to be achieved to initiate a phase transformation from paramagnetic γ-austenite into ferromagnetic α′-martensite. This thermally induced phase transformation starts at the so called martensite start temperature M_s (see Fig. 2). At temperatures above the equilibrium temperature T_0 the austenite is the stable phase due to smaller chemical free energy of paramagnetic