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Functional investigation of zero lead radial shaft seal counter-surfaces turned with a special method

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ABSTRACT

The sealing capabilities of RSS do not only depend on the seal itself but also on the lubricant and the shaft surface. A twist structure on the surface can cause pumping of the fluid during shaft rotation which can result in leakage. In this paper a special, new turning method, which consists of at least two turning steps with feed in reciprocal direction, is presented as an alternative to the conventional manufacturing process. The goal is to create a surface structure with a net pumping rate of zero. Shafts turned with the new proposed method are compared to turned shafts from previous investigations [1]. Criteria for the comparison are the surface pumping rate, leakage and wear behavior of the surface.

1. Introduction

Energy losses in machines and vehicles are a major concern for our environment and of course cost effectiveness in general. Holmberg et al. [2] and [3] have shown that about one-third of the fuel energy in vehicles is dissipated by overcoming friction in the mechanical components of the vehicle (engine, transmission, tires, brakes). Furthermore they attribute about 30% of the engine losses to hydrodynamic losses which -amongst other parts- (bearings, etc.) include the dynamic seals and 5% of the transmission losses to mixed lubrication (including seals, forks, etc.). In conclusion, one can state that -although often disregarded- seals play a non-neglectable role in the fuel consumption of a car. Holmberg et al. [2,3] and Tung [4] identified surface modifications, such as targeted surface structuring as promising measures to reduce the fricition in automobile applications. For shaft counter surfaces for radial shaft seals, the use of surface microstructuring can not only be applied in order to reduce friction, but also to counteract leakage. Functional surfaces such as those shaft counter surfaces have to meet various requirements. For many applications counter surfaces often need a hardened surface layer and a good lubrication effect in the contact region to improve the wear resistance and also lower the friction.

The most common method to achieve a controlled alteration of the material properties in the surface layer is a separate heat treatment. Thereby, the hardening takes place through a heating of the material beyond the austenitizing temperature and a subsequent quenching to create a large martensitic phase fraction in the surface layer [5]. On the one hand the hardness can be increased significantly up to a penetration depth of several millimetres. On the other hand, this process is very energy, time and cost consuming and needs an additional machining process for surface finishing [6]. Hence, the process chain is significantly enlarged. Another possibility to enhance the surface hardness without any heat treatment is strain hardening. Deep rolling, abrasive ball blasting or hammering are common manufacturing process to induce this kind of surface hardening. The strain hardening leads to a formation of nanograins and twins and also to an increase of the dislocation density [7,8]. However, no phase transformation takes place. That is why the maximum hardening increase and the penetration depth is less compared to a thermal hardening [6]. On the contrary, strain hardening processes can easily be integrated into the process chain and are not that energy, time and cost consuming. For metastable austenitic stainless steels there exists another possibility to create a hardened surface layer including a martensitic phase transformation as well as the aforementioned strain hardening effects when turning with cryogenic coolants [5]. This so called deformation induced surface hardening requires: on the one hand, an extensive deformation

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in the surface layer during the material removal process has to take place. On the other hand, the temperature in that deformation zone has not to exceed a critical value (typically around or below room temperature) which depends on specific material properties. To lower the level of heat in the deformation zone during the turning process a powerful cooling system is required. CO_2-snow cooling was proven to sufficiently reduce the temperature and enable a deformation induced surface hardening [5]. To achieve the deformation in the surface layer during the turning process the cutting parameters and the tool have to be selected adequately [5,9].

Another requirement on shaft counter surfaces for radial shaft seals in sealing systems is the surface quality. It has a major influence on the tribological behavior of the sealing system [10]. State of the art in-feed grinding is used for finishing the counter surfaces to achieve a lead-free surface structure and to avoid leakage of the sealing system.

Seewig and Hercke describe lead as ‘all surface occurrences which contribute to a conveying action of the fluid to be sealed in’ and characterize it using a number of distinctive parameters such as the depth D_t, the cross section of the valleys D_f or the lead angle D_γ (see Fig. 1). They distinguish between macro-lead (an axial periodic, circumferential structure) and micro-lead (all structures which are tilted with respect to the shaft axis) [11]. Turning processes usually cause a thread-like lead structure which is characterised as macro-lead. Due to the conveying effect of the lead on the fluid in the sealing contact a pumping mechanism occurs, which can be directed towards the oil side or the air side of the seal depending on the direction of shaft rotation. As long as this pumping effect resulting from the lead (towards the air side) is smaller than the pumping effect towards the oil side caused by the seal (see chapter 1.1 and Fig. 8), the seal is leak tight. As soon as the pumping effect caused by the lead is stronger than that caused by the seal, leakage occurs (depending on the direction of shaft rotation). In former investigations researchers tried to substitute the grinding process by turning to shorten the process chain. A comparison of soft-turned and hard-turned shafts with state of the art ground shafts showed that choosing suitable turning parameters results in reliable counter surfaces that proved leak-tight in long term experiments, regardless of the rotational direction, although there was a small lead on the surface [1]. Investigations on lead-free turned surfaces manufactured by tangential turning [12] or start-stop turning, to apply a zero-lead-structure by means of an discontinuous feed motion [13,14] have been performed as well, but such surfaces are not widely used in industry applications yet.

The friction behavior of shafts strongly depends on their surface structure [15–18]. Turned shaft surfaces with a rough structure in circumferential direction result in smaller friction due to a higher number of reservoirs for the lubricant compared to ground surfaces [19]. Frölich et al. [1] showed that the shaft wear is significantly dependent on the geometric surface structure when comparing ground and turned surfaces. If cutting parameters for turning the surface are

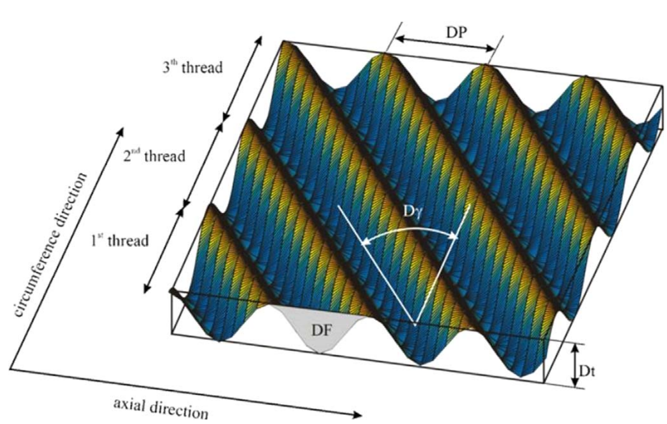

Fig. 1. Lead characteristics according to [11].

properly chosen, turned shafts are leakage free just like state of the art ground shafts. Due to the light lead structure and roughness of turned shafts a fluid film develops in the contact region. Additionally, this geometric surface structure contributes to the separation of the solid body asperities. Other studies on wear of turned shafts show similar results [20,17,21].

Thus, the possibilities of an integrated deformation induced hardening during cryogenic turning and a substitution of the grinding process for finishing the surface, can lead to a more efficient process chain. Especially for metastable austenitic stainless steels new fields of application can be opened. Due to their chemical resistance they show a good performance in corrosive environment or in connection with acidic media.

For a further optimization of the lubrication effect in the contact between seal ring and counter surface, micro-structured surfaces are an appropriate way of improving the tribological behavior [20,17,21–24]. Micro-structures on the shaft surface can provide oil reservoirs and create a higher lubricating film due to hydrodynamic effects. Due to the high material removal rates and the high number of possible geometries micro-cutting processes are suitable methods to microstructure component surfaces [23].

Recent studies have shown, that selective surface microstructuring cannot only improve friction and wear behavior but can as well have a great influence on the pumping rate of the shaft [15,25,16,17]. This allows to counteract any pumping of fluid caused by lead resulting from the shaping process. But those methods use an extra manufacturing step and a separate method to create the desired surface structure after machining the shaft to the right shape. Typical methods are laser technology [18] or lithography processes (LIGA) [16]. The new approach developed for multiple turning goes even further by trying to generate a microstructured surface - with almost no pumping effect - in the same process which is used to give the workpiece the desired shape. The method applies multiple turning steps with feed in opposite direction to create lead structures that counteract each other and are supposed to realize a close-to-pumping-effect microstructured surface (see Fig. 4). By choosing appropriate values of feed, it is to be expected that a zero pumping effect structure (same absolute value of the feed in both directions, symmetric structure [17]) or a desired pumping effect (different absolute values of the feed in each direction) can be generated on the surface. Both cases can be of interest in the application as a seal counter-surface: a zero pumping effect structure (or a structure with close-to-zero pumping effect) is of interest in applications where the shaft can revolve in both directions. In applications where a shaft can only revolve in one direction (e.g. the crankshaft in a combustion engine), a certain (defined) value of pumping effect can be desired if the pumping mechanism caused by this lead-structure counteracts leakage. On the other hand, this pumping effect can cause the sealing contact to “run dry” if it is too strong. In this paper this new manufacturing method, from now on called “multiple turning” is presented. Four different multiple turned shaft surfaces are compared to a surface that has been turned in one step (with feed in only one direction) with similar manufacturing parameters and to surfaces turned with already proven manufacturing parameters for cryogenic turning according to [1]. The focus of the comparison will be the pumping rate and leakage measurements as well as the wear of the RSS determined in a first screening test for the multiple turned surfaces. These results will be compared to existing measurements from previous investigations of the shafts manufactured with parameters according to [1].

1.1. Sealing mechanisms of RSS

To understand the sealing mechanism of a RSS one has not only to investigate the seal itself but the whole sealing system consisting of the seal, the lubricant and the shaft surface in contact with the sealing edge (see Fig. 2).