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Optimization of pre-conditioned cold work hardening of steel alloys for friction and wear reductions under slip-rolling contact

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ABSTRACT

The goal of reducing CO_2 emissions in the automobile industry has led to the development of increasingly efficient lightweight material solutions that yield enhanced performance. In light of this goal, this current work involves the optimization of the pre-conditioning of novel, high toughness steel bearings without thermo-chemical treatments, with the aim of transferring the running-in phase into the final step of the mechanical finishing process. A case-hardened gear steel and two novel non-case-hardened steels were evaluated. Pre-conditioning was carried out by running cylindrical sample disks against tungsten carbide rollers on a twin-disk test rig to generate cold work hardening in the contact zone of the cylindrical disks. Subsequent analyses of the pre-conditioned samples indicated strong increases in localized hardness and stable compressive residual stresses. Cold work hardened sample disks were then run against untreated spherical counterbodies of identical alloy in slip-rolling endurance testing to evaluate changes in friction behavior and wear performance as a result of pre-conditioning. Initially, the non-case-hardened alternative alloys experienced premature critical material failure in endurance testing, which indicated that an optimization of pre-conditioning parameters would be necessary. Consequently, new tungsten carbide rollers with more gradual radius of curvature were implemented. Additionally, lubricant temperature and rotational speed were increased to optimize the material residual stress profiles. Endurance testing of optimally pre-conditioned samples showed that the optimization ultimately yielded strong reductions in both friction and wear: coefficient of friction values of under 0.04 were reached, rivaling alloy-equivalent DLC vs. DLC contacts, and wear coefficients of less than 1/10 of those for the untreated alloy pairings were achieved.

1. Introduction

The reduction of emissions from automobiles is primarily achieved through weight reductions and increased power efficiency. In this regard, the weight of the powertrain is a particularly important area of focus. Component downsizing, which seeks to generate higher torques while reducing weight, can result in increases in Hertzian contact stresses and loads to the roots of gear teeth. Therefore novel material and material conditioning strategies must be implemented in order to avoid deteriorations in frictional profile and reductions in fatigue life. An increasingly common solution is to apply adamantine carbon-based coatings and high-alloyed steels. Unfortunately these applications are often associated with high production costs and energy expenditures, as well as many technical difficulties. Therefore it is prudent to consider alternative solutions.

It is known that tribological “running-in” results in the development of protective boundary layers that reduce wear on contact surfaces. These layers may be accompanied by the introduction of compressive residual stresses via work hardening processes when sufficient contact pressure is present. Residual stresses can occur as a result of manufacturing processes like grinding and polishing, surface hardness modification procedures such as shot peening, etc., as well as a result of regular component operation. It has been observed in the literature that residual material stresses are able to influence the load carrying capacity of that material [1–3]. Furthermore, it was observed by Zwirlein and Schlicht that compressive residual stresses can be generated by cyclic stresses when a sufficiently high load is applied [4]. This methodology is a fundamental cornerstone of modern material surface treatment techniques.

It was reported by Böhmer that component lifetime can be optimally improved through control of the magnitude of introduced compressive residual stresses [5]. It was within this context that he evaluated the evolution of rolling contact induced residual

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stresses. Development of a compressive residual stress maximum of approximately −150 MPa was observed at approximately 270 μm from the raceway surface after an applied contact pressure of $P_0 = 2410$ MPa. As the applied contact pressure was increased up to $P_0 = 3060$ MPa, the residual stress maximum shifts to approximately −600 MPa. Furthermore, this new maximum is observed at approximately 400 μm from the raceway surface, indicating that increased loads can drive structural transformations deeper into the material core. Slip rates were also stated to have significant influence on the residual stress profile of a loaded material. It was observed that implementation of strong slip and low to moderate loads will result in minimal variation of the material residual stress profile compared to the heat-treated state. As previously indicated, increased contact pressures will lead to an increase in compressive residual stresses, and the development of a clear residual stress maximum. At both high contact pressures and strong slip conditions, the depth of the compressive residual stress maximum below the contact surface appears to decrease, though the magnitude of the maximum remains relatively constant.

With residual stresses originating from induced structural transformations, it is unsurprising that other mechanical properties are influenced by variations in contact pressure, as well as cycling time. Hardness and strength increases are often the result of increased contact pressure and/or cycling time. Regardless of directional changes in hardness, residual stresses have been shown to vary both tangentially and normally. Most importantly, tangential residual stresses, i.e. from shearing, are suggested to be a propagating force of the growth of microcracks, a leading cause of critical material failure [6]. Therefore it is of great importance to material longevity to neutralize such shear stresses that appear during normal operation as thoroughly as possible. One way to accomplish this is through the utilization of work hardening processes.

Work hardening occurs as a result of plastic deformation, which is particularly prevalent in ductile materials, that leads to phase transformations and, ultimately, internal structural volume changes. Reversible elastic deformation is observed in a material up to its elastic limit, or yield point. Beyond this point, irreversible plastic deformation occurs as a result of the breaking of interatomic bonds. This is especially relevant for metals with significant austenitic composition.

As is the case with targeted heat treatment and rapid quenching, martensitic phase transitions can be yielded by mechanical means as well. If sufficient stress (and at rapid enough intervals) is applied to such an austenite-containing metal, the resulting volume increase from the transformation of austenite to martensite will generate compressive residual stresses in subsurface regions, i.e. below the contacted (stressed) surface. Evidence of work hardening in materials is typically observed through changes to residual stress profiles, as well as hardness profiles where an increase in material hardness is observed. The plastic deformation of a material leads to the movement of dislocations that are already present, and the creation of new ones. The greater overall prevalence of dislocations in the material with increasing plastic deformation results in greater resistance of such dislocations to further motion, which essentially means that less and less material is able to migrate under stress, giving the material greater strength [7]. In materials with low austenite content, such work hardening may also be generated through grain-boundary strengthening. Grain boundaries impede the movement of dislocations, so by reducing grain size, and thereby increasing grain-boundary presence, dislocations become less mobile when later introduced to external stresses.

The deformation of metals by a spherical indenter, resulting in work hardening, has been described by Tabor [8]. It was stated that an increase in yield stress will occur where material is displaced around the indentation, but that the elastic limit is not constant at all points around the indentation because of variations in deformation strain. Ultimately, he was able to derive an expression to relate the ultimate nominal stress, σ_u, to the Vicker's hardness, H, and the strain hardening coefficient, n. This expression was later simplified by Cahoon, yielding a clear and direct proportionality between σ_u and n [9]. It becomes clear from the simplified expression that an increase in the strain hardening coefficient leads to an increase in the ultimate tensile strength per hardness. This was verified by comparison of calculated values to those from the original expression from Tabor. Only at larger strain hardening coefficient values does deviation between the two expressions become apparent. Most importantly, strong agreement with previous experimental values (also from earlier work by O'neill [10]) was observed.

Work hardening processes in steel alloys have undergone extensive study. For example, Hirano et al. demonstrated in 1966 that the most effective material combinations for the reduction gears of marine turbines were those that showed the greatest work hardening tendencies [11]. Modern applications of such rolling elements have been developed by Nissan Motor Co., Ltd. (Yokohama, Japan) [12]. Furthermore, Lambda Technologies (Cincinnati, Ohio, U.S.A.), also developed a related technique known as Low Plasticity Burnishing (LPB), which was first applied to metal improvement in 1996 [13]. LPB is able to produce compression ranges from a few thousandths of a centimeter (comparable to shot peening) to over 1 cm in the case of nuclear weld applications. Such methodology has been applied for some time to the improvement of wear performance of P/M manufactured steels. A more recent investigation by Jandeska et al. into the effects surface densification on the rolling contact fatigue of a P/M alloy exemplifies this well [14].

Work hardening can occur during the regular operation of components, i.e. uncontrolled work hardening. This study seeks to utilize work hardening by generating it during a pre-conditioning in a controlled way to yield more predictable material performance benefits. As will be shown, this has been achieved by controlling experimental parameters such as contact pressure, disk rotation speed and lubrication regime. Moreover, it was crucial to implement materials that display a propensity for work hardening.

2. Experimental procedure

2.1. Applied materials

In continuation of prior research, three different steels were applied in this study: the case-hardened gear steel 20MnCr5 (1.7147, SAE 4820/SAE 5120), the hot working tool steel 9966 Super C from Buderus (36NiCrMoV1-5-7) and the silicon alloyed spring steel V300 from Aubert & Duval (45SiCrMo6, 1.8062). 20MnCr5 has been used for decades as a “classical” case-hardening gear steel, and serves as a well-established reference material in this study. Both 36NiCrMoV1-5-7 and 45SiCrMo6 are industrially available materials, as their trade names suggest, and were not case-hardened. Detailed descriptions of the applied heat treatment regimes and elemental analyses, as well as characterization of material microstructures and residual stresses in the heat-treated and finished state, have been previously provided for all testing materials [15]. Some important mechanical properties of the chosen alloys are provided in Table 1. In essence, a comparison of operational performance is sought between the case-hardened reference steel and the non-case-hardened steels, and furthermore, how this operational performance is impacted by the generation of cold work hardening through targeted pre-conditioning.