EFFECT OF SELECTED TYPES OF COATING ON FATIGUE PROPERTIES OF NITRIDED STEEL

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Abstract

Coating technologies with nanostructured particles belong to advanced promising methods for increasing wear resistance and contact fatigue life of machinery parts and for friction reduction during contact loading of surfaces with slip and consequently reduction of energy losses. One of the application fields are gear wheels, where fatigue loading in gear teeth roots exists besides contact fatigue on teeth sides. Contact fatigue has to be therefore well balanced with pure fatigue resistance. In the paper, research results of fatigue resistance at repeated loading of nitrided steel after application of two types of coating are described: (i) nanostructured C-layer deposited by a modified cathodic arc technique according to Microcoat patent and (ii) Cr-WC:H-DLC layer produced according to Hauzer patent. Fatigue tests were carried out using small samples with 2.1 mm diameter, with nitrided layer of 0.35 mm thickness. Tests were completed with fractographical analyses of initiation areas. Results and analyses showed that coating effects were not unique, but they depended on the specific technology and parameters. The Cr-WC:H-DLC layer affected fatigue limit favourably unlike the Microcoat C-layer, which resulted in reduction of fatigue strength. Some connections between fatigue life, surface layer brittleness and fracture character under static loading were indicated. A significant, unfavourable effect of inclusions in the subsurface layer was demonstrated.

1. INTRODUCTION

Coating is a covering process that is applied to the surface of material or components, usually referred to as substrate. In many cases coatings are applied to improve surface properties of the substrate, such as wear resistance, corrosion resistance, friction coefficient etc. Automotive engine components, which have to sustain high wear resistance and low friction under relatively hostile conditions, are one of the largest area of potential applications. High durability low friction specially tuned coatings for the protection of critical automotive engine components are being developed by numerous manufacturers. Particularly nanostructured based coatings are considered as the most advanced.

Besides automotive components loaded by wear or contact fatigue like tappets, bearing rollers, cams and camshafts, there is another rather complicated component exposed to a complex loading – gears and gear wheels. Surface treatment of gear wheels by microcoating with nano-layers is a perspective and promising technology to increase (i) resistance against damage, both contact and fatigue and (ii) performance of gears reducing friction coefficient. Fatigue, either contact fatigue or bending fatigue, is a dominant damage mechanism in gear wheels. Therefore, both these damage mechanisms are to be investigated and fatigue resistance of surface treated materials is to be tested.

The available literature on the effect of various types of overlay coatings on contact fatigue and fatigue is considerable, but it is generally difficult to synthesize all of the results to obtain a comprehensive understanding of the parameters affecting the fatigue damage processes [1]. Fatigue resistance and failure mechanisms depend on numerous parameters like coating processes, coating materials, substrate materials, coating thickness, residual stress. Surface coatings usually increase surface hardness of treated
components. Despite the good wear resistance of such coatings, fatigue behaviour of the bulk material may be affected, either negatively or positively by changes in the residual stress field and microhardness.

Attempts using FEM models have been performed with the aim of giving the designer a useful tool with which to predict the fatigue behaviour of thin-coated components [2]. A considerable effect of the coating quality and physical properties was pointed out in [3-5]. In [3], a positive effect of thermally sprayed coating on fatigue resistance at elevated temperatures due to the increase of elastic modulus is described and discussed. Deterioration of fatigue resistance of hard metals by CVD coating due to embrittlement of the interface between coating and substrate and due to tensile residual stresses is shown in [4]. Due to the damage by the coating procedure subcritical crack growth into the substrate was made easier. This led to a strong decrease of the life times under cyclic loads. The mechanism degrading the mechanical properties was found in the coating and the adjacent region of the substrate with a very low thickness, just 20 μm. On the other hand, a special combination of PVD-CVD coating applied to hard metals could increase fatigue life due to the increase of resistance against propagation of subcritical cracks [5].

An importance of the coating thickness in connection with residual stresses is discussed in [6,7] showing the fact that the coating thickness has to be well optimised. Low thickness has no significant effect on fatigue properties whilst a too thick layer deteriorates them. The generation of residual stresses is not only dependent upon the coating process but also on the coating thickness and substrate geometry [7].

The literature examples show that effects of various coatings on fatigue life can be either negative or positive, depending on many parameters and such effects can be hardly predicted. In this contribution, results of an evaluation of fatigue resistance and damage mechanisms of a nitriding steel, used for manufacture of gear wheels, affected by two types of nanostructured coatings are presented and discussed.

2. EXPERIMENTS

In this work, bending fatigue loading occurring at tooth root were experimentally modelled by tension-tension fatigue tests of small laboratory specimens. Investigations were performed on a nitriding ČSN 15530 steel (30CrMoV9), typical material for manufacture of gear wheels. The specimens were of circular cross section of 2.1 mm diameter in gauge section. According to the delivery acceptance certificate, the basic material was heat treated to nominal strength of $R_m = 1147$ MPa, yield stress $R_{p0.2} = 1043$ MPa. Before coating, specimens with polished surface were pulsed ion nitrided to depth 0.15-0.2 mm.

Four groups of specimens were prepared for fatigue tests: (i) specimens made of the steel just heat treated, (ii) nitrided specimens, (iii) specimens nitrided and coated with Micro – C layer by the Italian Microcoat company and (iv) nitrided specimens coated with Hauzer Cr+W-C:H+DLC layer.

The Micro – C layer coating was made using a modified cathodic arc technique. The Hauzer Cr+W-C:H+DLC layer coating was made according to the Hauzer patent using PACVD (plasma assisted chemical vapour deposition) technique. The resulting layer is of a complicated nanostructured type characteristic by an excellent wear resistance and hardness. Both the coating layers were rather thin, the thickness was approximately 2 μm.

Metallographical analysis of the substrate material after nitriding was carried out. Microhardness measurement of the surface layers before and after coating was performed. To complete the basic characterisation, static tensile tests with stress-strain curve records were carried out using standard
specimens of 7 mm in diameter and the small specimens as used for the fatigue tests. Fractographical analysis of fracture surface of selected specimens using scanning electron microscopy (SEM) was carried out, too.

Fatigue tests were performed with load asymmetry $R = 0$ and load frequency 40 Hz.

3. RESULTS AND DISCUSSION

**Fig. 1.** Metallographical analysis: a) Homogeneous microstructure of heat treated substrate and nitrided layer, b) detail of nitrided layer and white layer

**Fig. 2.** Microhardness of different surface layers and bulk heat treated material

Metallographical analysis of the substrate material after nitriding confirmed a good quality of both heat-treated substrate material and nitrided layer, as documented in Fig. 1. Both metallographical analysis and microhardness measurement (Fig. 2) confirmed that the nitrided layer was relatively thin, about 0.15 – 0.20 mm, because the small specimen diameter did not allow to make a deeper nitriding due to a possible superposition of effects of opposite surfaces. Thickness of white layer was up to 4 $\mu$m. The white layer was not removed before fatigue tests or coating, respectively.
The nitriding resulted in a significant increase of surface hardness, approximately 2.5 – times in comparison with the bulk, heat treated material. The coating contributed to further surface hardness increase by approximately 40 % in comparison with the nitrided surface. The thickness of surface layer with higher hardness values affected by the coating corresponded to 12 – 20 μm, which was more than the thickness of the coating layer itself (2 μm only).

Results of fatigue tests are presented in Fig. 3. The most important characteristics can be summarized as follows:

- The slope of all the S-N curves of the surface treated specimens is similar and quite different from that of the heat treated material without surface treatment. It indicates that fatigue resistance of the surface treated specimens is very sensitive to higher stress amplitudes after exceeding fatigue limit.
- The nitriding process slightly increased fatigue limit, but further increase of stress amplitude drastically reduced fatigue life.
- Microcoat coating with the Micro – C layer resulted in further deterioration of fatigue resistance including fatigue limit reduction, by almost 20 % in comparison with the surface untreated state.
- Fatigue resistance of the Hauzer Cr+W-C:H+DLC coating was comparable with the nitrided surface, i.e. an increase of fatigue limit but reduction of fatigue life at higher stress amplitudes like in [8,9]. Considering the excellent wear and contact fatigue properties including low friction, this is an important result for potential applications to gears. The premature failure – the “exceptional point” will be discussed later.
Fig. 4. Results of static tensile tests performed using the small specimens, a) heat treated specimens, b) coated specimens – first two curves correspond to Micro – C coating, last two curves to Hauzer coating. Horizontal axis is strain (scale 0 – 6 %), vertical axis is stress (scale 0 – 1300 MPa)

Results of static tensile tests performed using the standard specimens were quite uniform and confirmed the values stated in the delivery certificate, the strength being 1163 ± 21 MPa, yield stress 1036 MPa, ductility 16 ± 2% and reduction area 59 ± 4%. Results of the auxiliary static tests performed using the small specimens after different surface treatment to explain the unusual fatigue behaviour are shown in Fig. 4.
The results in Fig. 4 b) are interesting and can help to explain the fatigue properties. Unlike stress-strain curves of the heat treated specimens with smooth and linear parts corresponding to elastic region, the curves of coated specimens in the elastic region are corrugated, indicating instabilities in the region of interface between the coating and substrate layers. The instabilities may be connected with different elastic moduli or subsurface residual stresses or both. In addition, there are differences between the Micro – C and Hauzer coatings, respectively, the former having higher strength, but decreasing saw-like character after reaching the maximum strength. It indicates a strong tendency to brittle cracking of the surface layer. On the contrary, the curves corresponding to the specimens with Hauzer coating have further increasing shape even in the saw-like region. The saw-like character of the curves indicates a kind of surface or near-surface gradual cracking. It is therefore likely that at higher load amplitudes, some brittle microcracks occur in the surface layer initiating rapid fatigue crack growth to failure [10].

As regards the “exceptional point” of premature failure in Fig. 3, fractographical analysis showed that it was caused by large inclusions in the specimen – Fig. 5. The inclusions likely initiated brittle fatigue cracking of the surface layer and quasistatic failure after 600 cycles.

4. CONCLUSIONS

The main results of the investigation of effects of two different types of nanostructured coatings, namely Microcoat Micro – C layer and Hauzer Cr+W-C:H+DLC layer, on fatigue resistance of a nitriding 30CrMoV9 steel can be summarized as follows:

- In comparison with the basic heat treated material, nitriding process without coating slightly increased fatigue limit, but further increase of stress amplitude considerably reduced fatigue life.
- Microcoat coating with the Micro – C layer resulted in further deterioration of fatigue resistance including fatigue limit reduction, by almost 20 % in comparison with the basic heat treated state.
- Fatigue resistance of the Hauzer Cr+W-C:H+DLC coating was almost identical with the nitrided surface. An occurrence of subsurface inclusions resulted in a significantly premature failure.
- The corrugated shape of static stress-strain curves of coated specimens in elastic region indicated that critical damage mechanisms were concentrated in the region of interface between the coating and substrate layers.
- The character of static stress-strain curves confirmed very significant effects of both the coatings, though the thickness of the coating layers only was approximately 2 μm.
- The different character of the static curves of the two coatings in the region of gradual saw-like damaging process, either further strength increase or drop-off, indicated connections with different overall properties of the coatings and affected subsurface layers and connections with very different effects on fatigue behaviour.
ACKNOWLEDGEMENTS

The work was supported by the grant MSM 2579700001 of the Czech Ministry of Education, Youth and Sports.

LITERATURE REFERENCES