EFFECT OF SELECTED TYPES OF COATINGS ON FATIGUE STRENGTH OF NITRIDED STEEL WITH SMOOTH SURFACE AND STRESS CONCENTRATOR

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Abstract
The work was aimed at research of effects of nitriding and selected types of coatings with nanostructured layers on fatigue resistance of nitriding steel with stress concentrator modelling characteristic situation at roots of gear teeth. Small testing samples with notches were designed. Stress concentration of the notch was calculated to model real conditions at roots of gear teeth. The experiments were performed on nitriding steel heat treated to relatively high strength and $R_p0.2$ (yield stress), on nitrided smaples and samples coated using method patented by Microcoat company – with nanostructured C layer deposited with modified cathodic arc technique. Fatigue loading was of repeated type, i.e. with load asymmetry $R = 0$.

It was shown that in the case of notched specimens, potential unfavourable effects of nitriding and coating with the specific method were under repeated loading even more significant. Results of fatigue tests were compared with previous test results obtained on smooth specimens. Fatigue experiments were completed with fractographical analyses of fracture surfaces, with the aim to explain mechanisms of cracks initiation. Some residual stress measurements also were carried out. They indicated, together with the fractographical analyses that premature fatigue failures were caused by brittle fracture of surface nitrided and coated layers, respectively, and were affected by residual stresses.

Keywords: Nitrided steel, coatings, fatigue strength, stress concentrator

1. INTRODUCTION
Thermo-chemical treatment methods and recently particularly duplex surface treatment methods like nitriding in combination with coatings or advanced nanostructured coatings are being developed and used for improving mechanical surface properties of specific machinery parts exposed to combined contact fatigue, wear, and fatigue loading in operation. Gear wheels are probably one of the most typical examples. In operation, gear teeth are loaded by contact fatigue on the side surface, whilst in their root, fatigue bending load is dominant. Numerous cases where failure of gear wheels were caused by fatigue damage as a dominant mechanism and not by contact fatigue were shown [1]. Therefore, both failure mechanisms have to be studied independently, if complex effects of surface treatments of gears are to be determined.

It may be useful to point out that recently developed advanced coating methods can have a number of benefits, which can be summarised as follows [2]:

- Through tribological gear box optimisation, it could be possible to reduce friction force and consequently reduce fuel consumption up to 10 - 13%.
- Sophisticated coating methods are able to improve wear resistance of gears to pitting, scuffing and adhesion wear and by this way to increase component lifetime by 50% or more.
- Coating can potentially increase transmittable power at equal or smaller gear box mass by up to 30%.
- Surface coating of gears can reduce noise by approximately 15%, which is a considerable and important step particularly considering recent general trends in reducing environmental impacts of transport vehicles, where noise is an important issue.
Coating methods represent environment friendly replacement of galvanic surface treatments.

A brief, limited literature survey of coating methods and their effects on fatigue resistance was provided in [3]. It was concluded that effect of coating can be either positive, but also negative, depending on numerous parameters affecting the surface and subsurface layers, where initiation of fatigue cracks usually occurs. Unfortunately, technologies resulting in excellent tribological and wear properties do not generally improve fatigue resistance, they can have detrimental effects. New publications confirm that big effort is being put to optimise detail parameters of coating methods, because achievements can be of a breakthrough character. As an example, in the study of rolling-sliding, scuffing and tribocorrosion behaviour of PVD multilayer coatings for gears application [4], the PVD coating improved wear in almost 90% compared to nitrided substrate, presenting a similar behaviour to this one under extreme pressure conditions. CrN/ZrCN coating also improved substrate wear and especially good behaviour for this coating was observed under extreme pressure conditions. Cr/CrN coating strongly decreased micropitting and scuffing effect under rolling-sliding configuration. Under micro-pitting conditions, coating protected the substrate and reduced fatigue of uncoated discs. New papers also show that vacuum-plasma PVD coatings are potentially able to increase considerably fatigue strength, even of non-ferrous materials like Ti [5]. Contrarily to other works, the most significant improvement of fatigue strength was achieved in [5] in case of formation of ultra-thin coatings, but under well defined conditions of their deposition.

Some effects of two different types of coatings, studied on smooth surface, were discussed in [3]. One of them affected fatigue limit more or less positively, the second one negatively. In this contribution, effects of these coatings on fatigue strength in another case, more characteristic for fatigue of gear teeth roots, namely specimens with stress concentrators are described and discussed. In the previous work, some doubts arose in connection with quite small fatigue specimens used, namely specimens of just 2 mm diameter. The most important question was, weather the fatigue strength reduction was not caused by too small amount of bulk material [6]. Therefore, some additional fatigue experiments using alternative specimens with a larger cross section were carried out and are described, too.

2. EXPERIMENTAL PROCEDURE

Fig. 1. Notched fatigue specimen

To study effects of the duplex surface treatment with nitriding and subsequent coating in case of stress concentration, fatigue specimens were designed and manufactured, simulating actual stress concentrators occurring typically in roots of gear teeth. In general, the same type of specimens like in [3] and [6] was used. In the centre of specimen gauge length of 2.65 mm diameter, a single circular notch of 1.5 mm radius and 0.55 mm depth was made by turning. The notch was not ground, just machined, simulating similar manufacturing methods used for gears. Theoretical stress concentration factor of the notch corresponded to 1.7. Actual effective factor evaluated from the reduction of fatigue strength of basic, non-treated material (will be shown later) corresponded approximately to 1.3, which represents similar conditions in roots of gear teeth. The notched specimen (after fatigue break) is shown in Fig. 1.

As mentioned above, additional alternative specimens were manufactured to verify, weather some partially unfavourable effects of nitriding on fatigue strength were not caused by the small dimensions of the circular specimens. Additional specimens were of a completely different type – square cross section 8x8 mm, to be loaded by plane bending fatigue.
Both the notched circular specimens and bending square specimens were manufactured from a single, i.e. identical piece of material, from which smooth specimens used in [3] and [6] were manufactured. The original piece of material, namely nitriding ČSN 15530 steel (30CrMoV9), was heat treated to nominal strength of $R_m = 1147$ MPa, yield stress $R_{p0.2} = 1043$ MPa. Before coating, the circular and square specimens were pulsed ion nitrided to depth $0.10 - 0.15$ mm and approximately $0.25$ mm, respectively.

Four groups of circular notched 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.

All the heat treatment processes were performed with the same methods and parameters like in [3]: 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 $2 \mu m$. Nitriding of the square specimens was performed with the same parameters like those used for the circular specimens with the exception that nitriding time was extended to obtain a more thick nitriding layer.

Metallographical analysis of the substrate material after nitriding was carried out. Microhardness measurement of the surface layers before and after coating was performed.

Fatigue tests were performed in tension with load asymmetry $R = 0$ (circular specimens) and in bending with $R = 0.1$ (square nitrided specimens), respectively. Load frequency was approximately $40$ Hz.

3. RESULTS AND DISCUSSION

3.1 Metallographical analysis

Metallographical analysis was carried out in cross section of the square specimen to verify quality of the nitried layer and bulk material and to check, weather microstructure is similar to that of circular specimens analysed before [3,6]. Microstructure of the nitried layer was of a good quality, homogeneous – Fig. 2. Somewhat fairly highlighted grain boundaries were connected with extended time of the nitriding process in comparison with nitriding of the small circular specimens. The same concerns microstructure of bulk material represented by tempered martensite – Fig. 3, the degree of tempering being slightly higher in comparison with that of the small circular specimens.

Fig. 2. Characteristic good quality microstructure of nitried layer, magnification 200x

Fig. 3. Homogeneous microstructure of bulk material, tempered martensite, magnification 200x
Thickness and quality of the nitrided and coated layers also were analysed using microhardness measurement HV 0.04. Results, shown in Fig. 4, are quite consistent with microstructural analysis. It may be worthy to point out some details of the microhardness measurement:

- Microhardness in the very near surface layer of the small circular specimens was high, between HV 0.04 1100-1200, considerably higher in comparison with the larger square specimens.
- Thickness of nitrided layer in the square specimen was significantly bigger in comparison with the circular ones, almost twice.
- Microhardness of the coated specimen in the surfaced layer was, as expected, considerably higher than in specimens only nitrided, more than HV 0.04 1400. Therefore, considerably different fatigue resistance could be expected.
- What particularly should be pointed out is microhardness of the notched nitrided specimen, measured in the notch area. The values are almost reaching HV 0.04 1400, i.e. very similar values characteristic for the smooth specimen coated by Micro-C layer. This point will be discussed with results of fatigue tests.

### 3.2 Fatigue tests

Results of fatigue tests are summarised in the two following diagrams in Figs. 5 and 6. In the diagrams, BM means basic, i.e. just heat treated material (not nitrided), 3PB means three point bend specimens. Fig. 5 concerns comparison of S-N curves of smooth specimens of the two different types – small circular specimens loaded in tension and larger square ones loaded in bending.
Results in Fig. 5 are rather surprising, because they do not confirm anticipated unfavourable effect of the small amount of bulk material in the circular specimens on premature break at increased load amplitudes. Fatigue limit of bending specimens is, as expected, by about 10% higher than that of tension specimens. The effect of nitriding is practically the same in both types of specimens: Some small increase of fatigue limit, but premature failure, if the critical load range is exceeded. These results indicate that the small circular specimens can be considered as quite suitable for studies of the surface treatment methods.
The most important results following from the diagram in Fig. 6 are summarised in Conclusions.

4. CONCLUSIONS

- Results of comparative fatigue tests of heat treated and nitrided material, carried out using alternative larger, bending specimens of square cross section 8x8 mm, indicated that the small circular specimens of approximate 2 mm diameter were suitable for evaluation of effects of the surface treatment methods studied in the work and had no misrepresenting consequences.
- Nitriding and Hauzer type coating (H1) in combination with nitriding had a favourable effect on fatigue limit just of smooth specimens. In case of notched specimens, nitriding considerably reduced not only fatigue strength in the region of limited life, but also in the fatigue limit area. This phenomenon can be related with the very high microhardness in the notch area of the nitried notched specimens.
- Deterioration effect of Micro-C coating (M1) on fatigue resistance of smooth specimens, mentioned in [3], was even significantly stronger in case of notched specimens.
- No unfavourable effect of the Hauzer type of coating (Cr+W:C:H+DLC layer) on fatigue resistance of smooth specimens can be considered as a great success considering its excellent tribological and wear properties described elsewhere. This does not concern, however, notched specimens and so much the more Micro-C coating. Further development works were needed if the two coating methods, though promising from the viewpoint of contact fatigue and wear, could be considered for applications in gears.

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REFERENCES


