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INFLUENCE OF HEAT TREATMENT AND K_{Ic}/*HRc* RATIO ON THE DYNAMIC WEAR PROPERTIES OF COATED HIGH SPEED STEEL

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The aim of this work was to determine the impact of various heat treatments on the K_{Ic}/*HRc* ratio and subsequently on the wear properties of coated high-speed steel under dynamic impact loading. The results showed that hardness and improvement in the fracture toughness have significant influence on the adhesion and impact wear properties of the coated high-speed steel.

Key words: high-speed steel, TiAlN coating, heat treatment, fracture toughness,wear

INTRODUCTION

The quantity and quality of products depends on many factors such as tool shape, material properties, tools and working materials, operating conditions and in particular tool wear [1, 2]. During the manufacturing process of the product the tool is exposed to high dynamic loads, sliding movement against the work material and the high contact temperatures [3], leading to high friction and wear of the tool [4]. Manufacturing industry increasingly uses P/M steels which have a higher toughness but a lower abrasion resistance. A problem with lower abrasion resistance is usually solved by the use of techniques of surface modification, and to a limited extent also with the application of hard coatings.

Applying hard coating can in some extend solve abrasion resistance, but since hard coatings are normally very thin (a few microns) and brittle, substrate has to carry majority of the contact load and support the hard coating. This can be achieved by using different heat treatment processes and parameters, which have influence on the microstructure of a tool steel and therefore on its mechanical and tribological properties [5]. Especially vacuum heat treatment, deep-cryogenic treatment and pulse plasma nitriding have shown great effect on the performance of high-speed steels [6-10]. If the substrate is not hard enough to carry the load, elastic and plastic deformation will occur in the substrate under the contact, leading to the failure of the coating. Therefore harder the substrate, the higher loading can be applied to the contact without the fear of coating failure due to fracture [11]. However, the fracture toughness and resistance to crack initiation and propagation of the substrate are equally if not more important than the hardness and wear resistance [12-13]. Combining those properties is therefore essential to be able to have good load-carrying capacity and wear resistance of the substrate.

The aim of our work was to investigate the influence of different vacuum heat treatment parameters, combination of deep-cryogenic treatment, and *HR*c/K_{Ic} ratio on the dynamic wear properties of the coated high speed steel.

EXPERIMENTAL

MATERIAL, HEAT TREATMENT AND COATING

In this investigation test specimens were made from powder metallurgy cold work tool steel. The chemical composition is shown in Table 1.

Table 1 **Chemical composition of used powder metallurgy cold work tool steel / wt. %**

C	Si	Mn	Cr	Mo	V	W	Co
0,85	0,55	0,40	4,35	2,80	2,10	2,55	4,50

Vacuum heat treatment parameters were chosen to give three different ratios between hardness (*HR*c) and fracture toughness (K_{Ic}). Maximum hardness of the cold work tool steel substrate (denoted as treatment 1), maximum fracture toughness (denoted as treatment 2) and the maximum fracture toughness obtained at working hardness range (denoted as treatment 3).

Parameters of vacuum heat treatment were chosen according to the existing tempering diagrams. The maximum hardness (treatment 1) was achieved by heating the samples to the austenitizing temperature of 1 130 °C and holding them at this temperature for 6 min, followed by quenching in nitrogen gas at a pressure of 5 bar to a temperature of 80 °C. After quenching, the first group of specimens was triple tempered for 2h, twice at

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520°C, followed by a final 2h stress relieving at 500°C. Samples resulting in maximum fracture toughness (treatment 2) were achieved by lowering the austenitizing temperature to 1 070°C and rising the tempering and stress relieving temperature to 585 °C and 555 °C respectively. Samples with the highest possible fracture toughness at working hardness (treatment 3) were achieved by heating the samples to the austenitizing temperature of 1 100 °C and holding them at this temperature for 20 min. After quenching, test specimens were triple tempered for two hours at 500°C, followed by stress relieving at 470 °C. Additionally all three groups of vacuum heat treatments were combined with deep-cryogenic treatment in such a way that samples were first heated to the austenitizing temperature, quenched in nitrogen gas and followed by immediate controlled submersion of the material in liquid nitrogen at a temperature of - 196 °C for 25 hours. Deep-cryogenic treatment was followed by a single 2h tempering at the same temperature as used for the basic series of vacuum heat treatment. Samples which were deep-cryogenic treated were denoted with the letter U (for example 1U). The parameters of used vacuum heat treatments and combination with deep-cryogenic treatment in liquid nitrogen are shown in Table 2.

After heat treatment monolayer TiAlN coating with a hardness of 3 300 HV and 2 μm thickness was deposited using PVD procedure on polished heat treated samples. Details of the coating deposition process are given in [14].

FRACTURE TOUGHNESS AND HARDNESS

Fracture toughness was determined with the use of round circumferentially notched tensile test and a fatigue pre-crack in the root of the notch made in the rotating-bending mode prior to the heat treatment [15]. Fatigue pre-cracks were created under rotating-bending mode with the load of 450 N and a time of 4,5 min.

After tensile test Rockwell hardness measurements using Instron B2000 machine were done on each K_{Ic} test specimen. For each sample up to six measurements were done circumferentially on the widest part of K_{Ic} test specimen.

COATING ADHESION

Adhesion and static load-carrying capacity of coatings applied on the different vacuum heat-treated substrates were determined according to standard VDI 3198, using the Rockwell C indentation test (*HR*c). Depending on the size and density of cracks and eventual delamination of the coating around the indentation adhesion of the coating is assessed by HF 1 to 6. It is estimated that the coating exhibits good (HF 1 and HF 2) or satisfactory adhesion (HF 3 and HF 4). However, in the case when significant delamination of the coating occurs (HF 5 and HF 6), the adhesion of the coating is unacceptable.

IMPACT-DYNAMIC PROPERTIES

In order to evaluate impact of substrate on dynamic impact wear resistance of the coating, ball-on-plate impact wear test was designed. In dynamic impact tests carried out on dynamic testing machine Instron 8802 at room temperature, tungsten carbide ball with a diameter of 32 mm was used as a counterpart. Coated plate was impacting against the stationary ball at a frequency of 30 Hz and 300,000 cycles. Impacting force was changing in sinusoidal wave and reached a peak compressive value of 5,5 kN (3,5 GPa). For each substrate at least three repeated tests were performed. To avoid wear and transfer of tungsten carbide to the coating surface a new ball and lithium grease was used. After the test, wear of the coating was measured.

RESULTS

HARDNESS AND FRACTURE TOUGHNESS

In the case of the treatment No. 1 hardness of 65,8 *HR*c and fracture toughness K_{Ic} = 6.1 MPa·m$^{1/2}$ were achieved. For the second treatment where maximum fracture toughness was expected, fracture toughness K_{Ic} = 12,7 MPa·m$^{1/2}$ and hardness of 59,3 *HR*c were obtained. In the case of the treatment No. 3 where optimal combination of working hardness and fracture toughness was expected, hardness of 63.9 *HR*c and fracture toughness K_{Ic} = 10,1 – 10,2 MPa·m$^{1/2}$ were achieved.

Combining vacuum heat treatment with deep-cryogenic treatment in liquid nitrogen for 25 hours led to an increase in fracture toughness at practically the same hardness. In the case of the first series of samples hardened at austenitizing temperature of 1 130 °C and tempered at 520 °C (1U), at practically the same hardness of 65,0 HR_C, 25 h deep-cryogenic treatment in liquid nitrogen increased fracture toughness from 6,1 to 10,4 MPa·m$^{1/2}$, which represents 67 % improvement in fracture toughness. For the second series of samples (treatment 2), 25 h deep-cryogenic treatment led to approx. 12 % increase in fracture toughness, from 12,7 MPa·m$^{1/2}$ to 14,2 MPa·m$^{1/2}$, at even higher hardness of 59,5 *HR*c. For optimal combination of fracture toughness at working hardness (treatment 3), deep-cryogenic treatment resulted in 16 % improvement in fracture toughness, increasing it from 11,0 to 12,8 MPa·m$^{1/2}$ and in slight increase in hardness.

ADHESION TEST

Comparison of the Rockwell C adhesion test results for monolayer TiAlN coating deposited on six differently vacuum heat treated substrates in general show that all substrates, regardless of the type of vacuum heat treatment used, exhibit good adhesion (HF2 and HF3). None of the samples reached unacceptable damage level, but there are visible differences between the different vacuum heat treatments and deep-cryogenic treatment combinations used.

Measurements show that change in the HRc/K_{Ic} ratio achieved by deep-cryogenic treatment has no significant influence on the diameter of the radial cracks extending around the Rockwell C indent. Measurements also showed that the substrate having hardness lower than 63 *HR*c is not capable of supporting a static load, resulting in distinctive circular cracking of the coating.

DYNAMIC IMPACT-WEAR RESISTANCE

Figure 1 shows the wear depth of a single-layer TiAlN coating deposited on the P/M steel. Figure 1 presents values for three basic vacuum heat treatments (treatments 1, 2 and 3) and heat treatments combined with 25 h deep-cryogenic treatment (1U, 2U and 3U). Minimum wear depth of 0,7 µm, was obtained with the vacuum heat treatment that provided maximum hardness (treatment 1). As the worst case was found the substrate with the maximum fracture toughness but minimum hardness (treatment 2). In this case maximum wear and breakthrough of the coating was recorded. Deep-cryogenic treatment, although providing increased fracture toughness had negative impact on the coating impact wear resistance when combined with vacuum heat treatment that provided maximum hardness (treatment 1) or maximum fracture toughness (treatment 2).

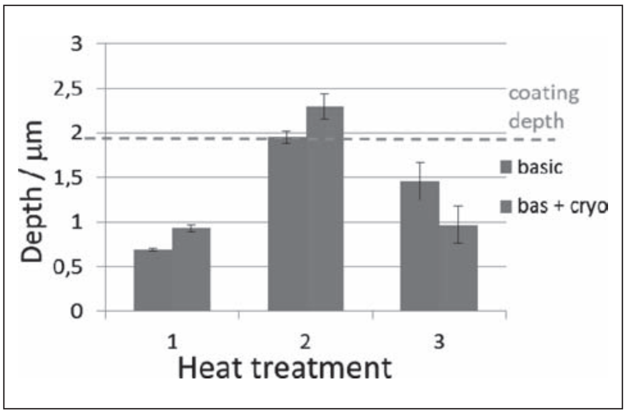

Figure 1 Wear depth of a single layer TiAlN coating for different vacuum heat treated P/M steel substrates

On the other hand, for the vacuum heat treatment 3 which at working hardness of 63 - 64 *HR*c ensures maximum fracture toughness, deep-cryogenic treatment increases both hardness and fracture toughness and thus has a positive impact on the dynamic impact wear resistance of the coatings. By simultaneously increasing hardness and fracture toughness, the wear of the coating decreased for ~ 30 % and became comparable to the case of vacuum heat treatment 1, as shown in Figure 1.

All wear tracks were analysed using scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS), which confirmed that for all cases the main wear mechanism was abrasion. Wear was uniform across the whole wear track without any sharp edges. Additionally, EDS analysis confirmed that even in the middle of the wear track no coating breakthrough occurred for all cases except for treatment 2U.

CONCLUSIONS

- By optimizing vacuum heat treatment maximum hardness of 65,8 *HR*c and fracture toughness of 12,7 MPa·m$^{1/2}$ can be obtained.
- Combination of vacuum heat treatment and deep-cryogenic treatment in liquid nitrogen improvement in fracture toughness from 10 to 67 % can be achieved while maintaining high hardness.
- Regarding the static load carrying-capacity, the most important property of the substrate is its hardness, with the working hardness of 63 - 64 *HR*c already providing excellent static load-carrying capacity of the coated substrate.
- Hardness of the substrate still has the greatest impact. The higher the hardness, greater wear resistance of the coated surface can be expected. Deep-cryogenic treatment and associated increase in fracture toughness has negative effect for cases when substrate has very high hardness and low toughness or high fracture toughness but too low hardness. In the case of hardness of 63 - 64 *HR*c, deep-cryogenic treatment leads to improved impact wear resistance of the coated surface.

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Note: Responsible person for English translation S. Drnovšek, Ljubljana, Slovenia