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Impact of fracture toughness on surface properties of PVD coated cold work tool steel

B. Podgornik [a,*], M. Sedlaček [a], M. Čekada [b], S. Jacobson [c], B. Zajec [d]

[a] Institute of Metals and Technology, Ljubljana, Slovenia
[b] Institute Jožef Stefan, Ljubljana, Slovenia
[c] Tribomaterials Group, Uppsala University, Uppsala, Sweden
[d] Hidria Rotomatika d.o.o., Spodnja Idrija, Slovenia

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ABSTRACT

Limited load-carrying capacity and impact loading resistance greatly restrict the use of hard coatings in forming applications, making substrate hardness and resistance crack initiation and propagation very important. Therefore, the aim of this research work was to investigate the effect of substrate fracture toughness and hardness on the load carrying capacity and impact wear resistance of coated tool steel, coated by monolayer (TiAlN), multilayer (AlTiN/TiN) and nano-composite ((Ti,Si)N) PVD coatings. By using different combinations and parameters of vacuum heat treatment and deep cryogenic treatment effect of the substrate fracture toughness and hardness on the load-carrying properties was determined under progressively loading dry sliding conditions, while ball-on-plate impact fatigue test was employed to investigate impact wear resistance. Results clearly show, that substrate hardness is the most important property influencing load-carrying capacity and impact wear resistance of the coated surface. However, with increased hardness and brittleness of the coating increase in fracture toughness although on the expense of the reduced hardness becomes beneficial.

1. Introduction

In fine blanking, stamping and punching applications tools are exposed to very demanding contact conditions, including high impact loads, high contact pressures, elevated contact temperatures and wear. Thus tool surface is subjected to complex combination of cyclic mechanical, chemical and tribological loads, which lead to fatigue, chipping and wear of the tool [1,2]. In general, type of tool failure mode and its progression depend on the tool material and heat treatment used, tool shape, design and manufacturing, forming process parameters and work material [3,4]. However, the biggest impact comes from the tool material and its microstructure. Basic material properties that govern the performance of the tool are hardness, toughness and ductility, and although the prevention of tool failure is often related to a critical hardness level, the toughness reveals full potential of the material [5–7]. As the market, especially automotive industry focus toward the use of new light-weight high-strength materials, i.e. high-strength steels (HSS and AHSS), which are more and more difficult to form [8], also requirements on tool properties including hardness, fracture toughness and wear resistance are becoming more demanding [9]. In this case already a small difference in hardness and fracture toughness can be significant when it comes to tool performance and resistance against failure. It also needs to be pointed out, that required tool properties are often not mutually compatible, i.e. high hardness and high toughness, which to some extent can be reduced by use of powder metallurgy (P/M) tool steels with finer and more uniform microstructure [10].

Traditionally, forming tools are vacuum heat treated in order to obtain microstructure of tempered martensite and uniform distribution of carbides, which gives sufficient fracture toughness at working hardness and acceptable wear resistance [11]. Furthermore, by optimizing heat treatment parameters and using additional heat and thermo-chemical processes tool steel properties and its wear resistance can be further enhanced and adjusted for a specific application [12]. Another way of improving tool wear resistance is application of hard wear resistant coatings [13–15], where tribological process is dominated by properties including the coating-to-substrate hardness relationship, the coating thickness, the surface roughness, the state of residual stresses between the coating and the substrate [16]. However, although the huge potential and benefits of hard PVD, CVD and PACVD coatings in improving friction properties and wear resistance of contact surfaces have been demonstrated by many investigations and successful industrial application, the majority of forming tools are still uncoated and cutting elements in stamping and punching made from tungsten carbide. Beside complex shape of forming tools and high tendency of

* Corresponding author.
E-mail address: bojan.podgornik@imt.si (B. Podgornik).

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hard ceramic coatings to galling, limited load-carrying capacity and impact loading resistance greatly restrict the use of hard coatings in forming applications [17,18]. Load-carrying capacity can be simply improved by increasing substrate hardness, which on the other hand also results in reduced fracture toughness. However, under cyclic impact loading, typical for many forming applications, resistance to crack initiation and propagation is equally or even more important than coating wear resistance [14,19]. Formation of surface and subsurface cracks may lead to coating spallation, flaking or delamination and thus to failure of a very expensive tool.

Thermo-chemical processes including vacuum heat treatment, plasma nitriding and deep cryogenic treatment all alter tool steel microstructure and thus influence on its performance [12,20]. Over the past tremendous research efforts and funds were devoted to study the effect of different thermo-chemical treatments and parameters on the properties and wear resistance of cold-work tool steels and high-speed steels. Through proper selection of austenitizing and tempering temperature vacuum heat treatment results in optimized microstructure with increased fracture toughness at high hardness and thus in improved fatigue and wear resistance of the tool [21]. On the other hand, sub-zero treatment like deep cryogenic treatment in liquid nitrogen at −196 °C was shown to have many benefits in terms of tool steel properties enhancement [12,20,22]. Cryogenic treatment is not, as often mistaken for a substitute for good heat treatment, but supplemental process to vacuum heat treatment before tempering [23]. Complete transformation of retained austenite into martensite, cryogenic aging and carbon clustering, and the precipitation of fine η-carbides into the tempered martensitic matrix improve wear and fatigue resistance, and increase strength and hardness of the material [24]. When combining different vacuum heat treatment parameters and deep cryogenic treatment, residual stress field and hardness vs. fracture toughness ratio of tool steel can be further enhanced [25] and thus optimized depending on the tool requirements. This is especially important if tools are planned to be coated, where beside coating thickness, hardness and surface roughness, properties and surface structure of the substrate have significant effect on the wear behavior, load-carrying capacity and adhesion properties of the coating [26,27]. However, in traditional tool design, material selection and heat treatment is mainly based just on one property, hardness, with fracture toughness gaining importance in recent years.

The aim of this research work was to investigate the effect of tool steel fracture toughness and fracture toughness vs. hardness ration on the load carrying capacity and impact wear resistance for different PVD coating types, including monolayer, multilayer and nanocomposite coating. Focus was on which substrate property, hardness or fracture toughness is more important when it comes to coated forming tools.

2. Experimental

2.1. Materials and heat treatment

Material used in this investigation as a substrate material was a commercial high fatigue strength P/M cold work tool steel with the following chemical composition (in wt.%): 0.85% C, 0.55% Si, 0.40% Mn, 4.35% Cr, 2.80% Mo, 2.10% V, 2.55% W and 4.50% Co. After specimens (plates 20 × 20 × 8 mm, cylinders ϕ10 × 100 mm and circumferentially notched tensile bar specimens — CNTB [7]) were machined from soft annealed blocks, they were vacuum heat treated in a horizontal vacuum furnace with uniform high-pressure gas-quenching using nitrogen gas at a pressure of 5 bar. In order to obtain broad range of different hardness and fracture toughness combinations three basic sets of vacuum heat treatment conditions were used and additionally combined with deep cryogenic treatment (Table 1). First group of specimens aimed at obtaining maximum hardness was quenched from 1130 °C and triple tempered for 2 h at 520 °C, with the last stress-relieving tempering performed at 30 °C lower temperature (520/520/490 °C). To obtain higher fracture toughness at working hardness of about 64 HRc austenitizing temperature for the second group of specimens was reduced to 1100 °C and tempering performed at 500 °C (500/500/470 °C). The third group was quenched from 1070 °C and tempering temperature increased to 585 °C, which should result in maximum fracture toughness. When combined with deep cryogenic treatment quenching was followed by a controlled immersion of the test specimens in liquid nitrogen for 25 h and a subsequent 2 h single tempering at 520 °C, 500 or 585 °C (Table 1).

Table 1
Vacuum heat treatment and deep-cryogenic treatment (DCT) parameters.

Group	Austenitizing		DCT treatment		Tempering	
	Temp. [°C]	Soaking time [min]	Temp. [°C]	Immersion time [h]	Temp. [°C]	Time [h]
1	1130	6	–	–	520/520/500	2/2/2
2	1100	20	–	–	500/500/480	2/2/2
3	1070	20	–	–	585/585/565	2/2/2
1P	1130	6	−196	25	520	2
2P	1100	20	−196	25	500	2
3P	1070	20	−196	25	585	2

2.2. Coatings

After heat treatment all plate and cylindrical specimens were surface polished (R_a = 0.05–0.10 μm) sputter cleaned and coated with three different PVD coatings. Coatings included in this investigation were monolayer TiAlN coating with a hardness of 3300 HV, multi-layer AlTiN/TiN coating with AlTiN and TiN lamellas thickness of ~50 nm and ~80 nm, respectively, and final hardness of 3500 HV, and nano-composite (Ti,Si)N coating with a hardness of about 3800 HV. All coatings were deposited at the substrate temperature of ~450 °C with a thickness of ~2 μm using magnetron sputtering process. Details of the coating deposition process are given in [28,29] and fractured cross-sections shown in Fig. 1.

2.3. Fracture toughness and hardness

Quenched and tempered cold-work and high-speed steels have a high notch sensitivity, which makes it very difficult to apply standard fracture toughness measuring methods on these materials. On the other hand, in the case of non-standard CNTB specimens (details given in ref. [7]) fatigue pre-crack can be created before the final heat treatment without detrimental effect on the crack tip blunting and measured fracture toughness results [7]. Therefore, CNTB specimens were used in this investigation to measure cold-work tool steel fracture toughness obtained by different heat treatment conditions (Table 1). In order to obtain statistically relevant data 12 specimens were used for each heat treatment set.

CNTB specimens were first fatigue pre-cracked under rotating-bending loading mode. Using load of 450 N and 5000 cycles, 0.4–0.5 mm deep pre-crack was formed in the notch root. After heat treatment pre-cracked CNTB specimens were subjected to tensile loading using Instron 1255 tensile test machine and cross-head speed of 1.0 mm/min. By recording load at fracture (P), knowing the outside non-notched diameter (D = 10 mm) and measuring the diameter of the brittle fractured area (d), fracture toughness was calculated using Eq. (1) [7].

$$K_{Ic} = \frac{P}{D^{3/2}}\left(-1.27 + 1.72\frac{D}{d}\right) \tag{1}$$

On each CNTB specimen also core hardness was measured using the Rockwell-C Willson-Rockwell B 2000 machine.