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Progress in high temperature nanomechanical testing of coatings for optimising their performance in high speed machining

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ABSTRACT

Frictional heating results in very high operating temperatures in high speed machining but the nanoindentation tests used to evaluate novel PVD coating systems for improved cutting performance are invariably performed at room temperature. If nanomechanical measurements are to be used reliably in the optimisation of coatings for high speed machining then it is much better that the measurements are performed at the relevant temperature. High temperature nanoindentation data are reviewed for a wide range of nitride-based hard coatings on cemented carbide and design rules suggested for coating optimisation for different machining applications. The importance of high temperature mechanical properties and microstructure on the adaptive and multifunctional behaviour in improving tool life is investigated. The coatings studied show large differences in how their hardness, modulus and H/E vary with increasing temperature which have a significant influence on their behaviour in high temperature mechanical contact applications which have differing requirements in terms of hot hardness and plasticity. In continuous high-speed turning operations the high temperature hardness is paramount and coatings with high hot hardness display longer tool life. In interrupted cutting conditions toughness and plasticity are at least as important, and in end milling of hardened steels for example, high hot hardness should be combined with improved plasticity for longer tool life. Multilayer AlTiCrSiYN/AlTiCrN coatings have shown improved performance compared to the state of the art monolayer coatings. The reasons for this improved performance are discussed. Overall, the high temperature nanoindentation data show excellent correlation to coating life in high speed machining applications.

1. Introduction

Wear-resistant coatings are applied to cutting tool substrates to prolong tool life in machining applications [1,2]. Several trends currently drive the development of improved coatings including (1) cutting faster to increase productivity; (2) "green-machining" — cutting without coolant for environmental reasons; and (3) machining hard-to-cut materials such as advanced Ti alloys or Ni-based superalloys due to their increasing usage in aerospace applications [3,4]. To achieve long tool life under these conditions coatings need to be multifunctional and display several interlinked characteristics to minimise wear and it is usually not sufficient merely to aim to maximise a single property such as hardness or oxidation resistance. A mechanical property approach to minimising wear described by Leyland and Matthews has been effective in general tribological applications such as sliding or abrasion [5,6]. As the severity of the mechanical contact increases, coated components may operate in the region of the elastic limit, and in some cases above it since stresses can be over 3–5 GPa [1,7,8] so plasticity and the ability to dissipate the energy of friction can become increasingly important.

Different cutting conditions require coatings to have a different balance of mechanical properties. As an illustration of this Fig. 1 shows how the relative wear intensity varies in two different contact situations, heavily loaded dry sliding and turning, for three TiN PVD coatings on high speed steel with different hardness and plasticity index [9]. The plasticity index is a non-dimensional parameter which is a measure of the relative proportions of elastic and plastic deformations occurring in an indentation contact. It is defined as

$$\text{plasticity index} = \text{plastic work}/\text{total work}. \qquad (1)$$

The different properties were obtained by altering the nitrogen pressure during deposition. At low nitrogen pressure the TiN hardness was 35 GPa. At high nitrogen pressure the axial texture (111) increased, hardness decreased to 25 GPa and plasticity increased. This higher plasticity index improved the cutting behaviour in turning where adhesive wear dominates, due to the greater ability to dissipate energy. The data in Fig. 1

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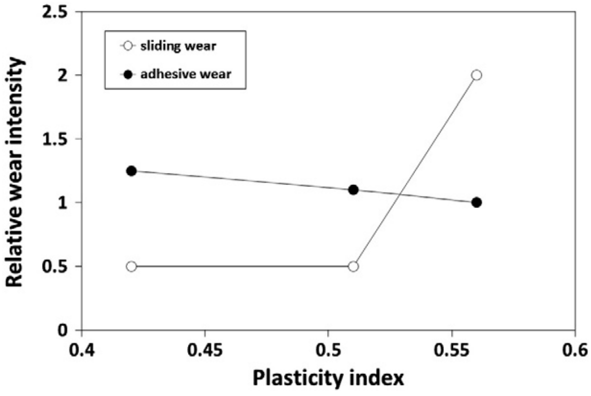

Fig. 1. Influence of the plasticity index of TiN coatings on relative wear intensity in sliding and turning.

clearly show that microstructural design to reduce wear in one situation is not optimum for another. In sliding the requirement for high plasticity is lessened, compared to that for load support, and consequently coatings with higher hardness typically improve wear resistance under these conditions. Plasticity in contact is governed by the roughness and elastoplastic properties of the contacting surfaces. Plasticity is directly correlated with the ratio of hardness (H) and elastic modulus (E) in an indentation contact with a pyramidal indenter through the parameter H/E_r, where E_r is the reduced modulus. The hardness and elastic modulus of coatings are routinely measured by nanoindentation. The load–displacement curve obtained in a nanoindentation test is essentially a mechanical fingerprint for a material. Provided H/E_r is not greater than about 0.1 a good approximation to experimental data is given by Eq. (2) although beyond that there is significant non-linearity.

$$\text{Plasticity index} = 1 - x(H/E_r) \qquad (2)$$

Finite element analysis (FEA) has suggested $x \sim 5$ [10]. Beake and co-workers have reported that with several different Berkovich indenters values around 6–7 were found over a wide load range for coatings and bulk materials such as copper, aluminium, tungsten, bearing steel, stainless steel and WC-Co, whilst only fused silica and K7 glass show lower x values very close to those predicted by the FEA [11]. Choi and co-workers also re-investigated this relationship and reported that $x \sim 5$ for materials which sink-in (glasses) and $x \sim 7$ for materials which exhibit pile-up (metals) [12]. The differences in the proportionality constant x between metals and glasses such as fused silica could also be influenced by differences in radial displacement on unloading which causes the size of the residual indent to be underestimated by calculation of the projected contact area from the contact depth, and other factors such as Poisson ratio and variation in the exponent of the force removal curve [13]. H/E_r is well correlated with how elastic the contact is in other related mechanical contact situations such as scratching/sliding [5,6] or impact/erosion [14]. Higher values result in higher critical loads for the onset of yield (non-elastic deformation) in indentation or scratch testing. In machining of hardened steels a correlation has been established between the plasticity index from room temperature nanoindentation measurements and the tool life [11]. In end milling coatings with relatively high plasticity such as AlCrN, AlTiN and AlTiCrN all showed longer tool life than TiAlN which has higher hardness but low plasticity. In contrast, in continuous turning, TiAlN showed longer tool life than AlTiCrN. Similarly, annealing AlTiN at 700 °C or more decreases its plasticity resulting in longer tool life in continuous turning than as-deposited AlTiN [15]. The different cutting conditions have differing relative requirements in terms of coating hardness (load support) and plasticity (energy dissipation). Plasticity can be considered as an indirect measure of the toughness of the coating, since coatings with higher plasticity can more easily relieve accumulated strain by plastic deformation rather than brittle fracture [16–18]. Despite the encouragement from these correlations, depending on the materials being machined the room temperature plasticity index is not on its own the key factor and elevated temperature properties are more relevant to cutting tool life, since relative rankings can switch with increasing temperatures as will be shown below. Microstructural changes to alter plasticity can potentially be accompanied by other factors during tool operation, such as adhesion, friction, oxidative stability, efficiency of chip formation, elevated temperature mechanical properties and tribo-film formation. It has been highly challenging to determine the relative importance of these factors to tool life.

In this review we describe the requirements for accurate high temperature nanoindentation measurements and review a number of coating machining and evaluation studies where high temperature nanoindentation testing, and its predecessor hot microhardness testing, are improving our understanding of the causes of differences in tool life between coatings. The most common approach to improve our understanding of the relative importance of different factors in tool life has been to perform in-depth studies fully characterising the properties of a small number (typically 2–4) of advanced coatings and investigate the correlation between these properties and tool life under the same cutting conditions. The studies described in this review all concern coatings deposited on cemented carbide substrate which has higher high temperature hardness than high speed steel [3,7] and is more suited to extreme applications (cutting of hard-to-cut material such as hardened tool steels and aerospace materials, especially under dry conditions). We have sought to combine knowledge from these separate studies to move towards possible more generic coating design rules for different cutting applications. The performance of state of the art monolayer and multilayer coatings are contrasted and the reasons for improved behaviour shown by multilayer coatings are discussed. The importance of high temperature mechanical properties and microstructure on the adaptive and multifunctional behaviour in improving tool life is investigated.

2. The role of temperature

For applications involving high temperature contact the mechanical properties at the operating temperature are more relevant than those measured at room temperature. High temperature mechanical properties should be measured by testing at temperature rather than simply retesting thermally annealed samples at 25 °C after cooling which is less effective since it can only provide information on coating stability not on changes to mechanical properties due to enhancement of dislocation movement and creep processes occurring at operating temperatures.

2.1. Hot microhardness testing

High temperature hardness has historically been evaluated by hot micro-hardness testing. Quinto and co-workers investigated the variation in microhardness with temperature of a range of 8–15 μm thick PVD and CVD stoichiometric nitride coatings on cemented carbide, including TiN and HfN [19]. Although the hardness of the PVD coatings was much higher than their CVD counterparts at room temperature it decreased more rapidly so that values of all the coatings were similarly low by 1000 °C. Differences in high temperature mechanical properties between PVD and CVD coatings were correlated with microstructure. The CVD coatings possessed larger, defect free, thermally equilibrated grains whilst the PVD coatings were finer grain size with non-equilibrated microstructure which resulted in a more rapid thermal recovery due to its stored energy (i.e. relaxation of high compressive residual stresses), together with grain boundary sliding [20]. Even though the hardness of PVD and CVD coatings decreases with increasing temperature they nevertheless retain higher hardness than the cemented carbide and can provide improved load support protecting the underlying WC-Co in high temperature contact [8].

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