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# Processing and characterisation of cermet/hardmetal laminates with strong interfaces

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ABSTRACT

Cemented carbides and cermets are potential materials for high speed machining tools. However, cemented carbides are not chemically stable at high temperature and cermets present poor fracture toughness. Novel cermet/hardmetal multilayer systems show a huge potential for this intended application. It would be possible to achieve the right balance of the required thermomechanical properties using cermet as temperature protective outer layers and hardmetal as reinforcement layers. In this work, preliminary results on the microstructural and mechanical characterisation of a multilayer $TiC_xN_{1-x}$–Co/WC–Co composite densified by hot pressing are presented, with special attention to the properties of the interface. Microstructural observations revealed the existence of strong bonding interfaces between cermet and hardmetal layers due to chemical interaction during the sintering process. As a consequence, owing to the different coefficient of thermal expansion between cermet and hardmetal, a tensile and compressive biaxial residual stress of $\sigma_{\mathrm{res,Cermet}} \approx +260 \pm 50$ MPa and $\sigma_{\mathrm{res,WC-Co}} \approx -350 \pm 70$ MPa was estimated in the corresponding layers. Microindentation cracks introduced in the cermet layers (the less toughness material) and propagated transversely to the layers were arrested at the interface, showing the combined effect of toughness and compressive stresses on crack shielding.

## 1. Introduction

High speed machining is acquiring a great relevance as it allows not only an improvement of the superficial finishing but also a gain in productivity and a decrease of the associated cost [1]. This type of process imposes work conditions each time more extreme in terms of temperature and induced stresses, and so requires, from the corresponding cutting tools, an excellent thermo-mechanical and tribological behaviour [2]. So, the principal parameter to take into account becomes the wear produced by the high temperature reached in the cutting zone [3]. Indeed, the materials used for cutting tools design must present a set of different properties among which wear resistance, fracture toughness, hardness, mechanical reliability at high temperature, impact behaviour, chemical stability with temperature and friction coefficient can be cited as the more fundamentals ones [4].

Cemented carbides and cermets, which are actually substituting rapid steels in numerous applications, become good candidates for high speed machining tools. Cermets show a good wear and oxidation resistance, but are brittle with relatively low fracture toughness [5]. In this sense, this type of material is only used for high speed finishing but does not work under cyclic and concentrated stresses. On the other hand, cemented carbides or hardmetals have good fracture resistance, but are not chemically stable at high temperature, undergoing significant wear due to diffusion phenomena [6]. The only way to associate cemented carbides and high speed machining seems to be the use of ceramic coatings [7], but rather increasing exponentially the cost of the material.

Developing materials for cutting tools combining the good properties of cermets and cemented carbides remains a challenge. In this context, some authors have proposed the use of mixed Ti(C,N)–WC–Co materials, either developing a more refractory structure in the bulk [8] or providing a graded structure [9]. More encouraging results have been obtained with the so-called functionally graded cemented carbides, characterised by a compositional gradient from the surface to the inside of the material.

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It is possible to obtain materials with a tough WC–Co layer at the surface [10], and also with a hard cermet surface and a tough hardmetal core [11]. In general, these materials exhibit acceptable fracture toughness in the surface (as opposed to cracking during machining) behaving in many cases better than coated cemented carbides. The key to getting the desired graded material is the precise design of the overall chemical composition and the strict control of the metallurgical reactions and the working atmosphere during sintering. However, the complexity of the phase equilibrium diagrams and metallurgical reactions involved in these functionally graded multicomponent systems often makes to achieve the desired properties and specifications difficult.

Layered ceramic materials (also referred to as "laminates") are becoming one of the most promising areas of materials technology [12]. They have been proposed as an alternative for the design of structural ceramics with improved fracture toughness, strength and mechanical reliability [13–25]. Good results have also been obtained in metal–ceramic [26] and metal–intermetallic laminates [27,28]. A key factor in the design, leading to the improvement in mechanical properties, is associated with the presence of compressive residual stresses in the laminate, designed with strong interfaces. Tailoring of compressive stresses and architectural design (e.g. thickness and disposition of layers) has led to an increase in fracture energy, thermal shock resistance and, in some cases, a decrease in the sensitivity of the material strength to the different size of defects, i.e. "flaw tolerant" approach [17,21,25,29–31]. The specific location of the compressive layers, either at the surface or internal, is associated with the attempted design approach, based on either mechanical resistance or damage tolerance, respectively. In the former case, the effect of the compressive residual stresses results in a higher, but single-value, apparent fracture toughness together with enhanced strength (the main goal) and some improved reliability [13,14,32]. In the latter case, the internal compressive layers are designed to act rather as a stopper to any potential crack growing from processing and/or machining flaws, at or near the surface layers such that failure tends to take place under conditions of maximum crack growth resistance [15,17,18,21]. The utilisation of tailored compressive residual stresses acting as physical barriers to crack propagation has succeeded in many ceramic systems, yielding in some cases a so-called "*threshold strength*", i.e. a minimum stress level below which the material does not fail [15,17,21–23,33,34]. In such layered ceramics, the strength variability of the ceramic material due to the flaw size distribution in the component is reduced, leading to an almost constant value of strength. The selection of multilayer systems with tailored compressive stresses either at the surface or in the bulk is based on the end application, and can be determined by the loading scenarios where the material will work.

In this work, preliminary results on a new class of materials with a layered design and dedicated to high speed machining tools are presented. Multilayer composites alternating 4 cermet layers and 3 hardmetal layers were fabricated and characterised. The outer layers presented a cermet composition, to obtain good wear resistance and oxidation resistance. The inner layers consisted of a hardmetal to act as a barrier to the propagation of cracks which may develop on the surface of the material during machining processes or in service. The disposition of the hardmetal layers was intended to generate internal compressive stresses, aiming a "flaw-tolerant" approach. The in-plane residual stress in the cermet and hardmetal layers was estimated based on classical laminate theory. The interfaces were thoroughly characterised and their mechanical behaviour was analysed based on microindentation experiments and scratch tests.

## 2. Residual stresses in multilayer systems

In every case where dissimilar materials are sealed together at high temperatures and cooled down to room temperature, they may undergo differential dimensional changes. This can be caused due to different factors: (i) intrinsic such as variations of density or volume, densification, and oxidation at the surface; or (ii) extrinsic such as thermal or thermoplastic strains developed during cooling or by external forces and momentums. Among them, the aspect most commonly referred to is the difference in the coefficients of thermal expansion (CTEs) between adjacent layers. The differences in the CTE ($\alpha_i$), when cooling down from sintering, may promote a differential strain between layers. As a consequence, if the interfaces of the layer materials are strong (i.e. the laminate interface does not spontaneously delaminate), an alternating tensile–compressive residual stress field is generated in the layers.

### 2.1. Analytical solution

For ideal elastic multilayer systems, neglecting the influence of the external surfaces (where stresses may relax) and considering the multilayer as an infinite plate, an analytical solution can be derived to determine the stress distribution in the layers. In an isotropic body at equilibrium under a given stress state, the stresses (i.e. $\sigma_x$, $\sigma_y$, $\sigma_z$) may be considered resolved along three perpendicular directions $x$, $y$ (in-plane) and $z$ (out-of-plane). Thus, the strain in the corresponding directions (i.e. $\varepsilon_x$, $\varepsilon_y$, $\varepsilon_z$) can be given as [35]:

$$\varepsilon_x = \frac{\sigma_x}{E} - \upsilon\frac{\sigma_y}{E} - \upsilon\frac{\sigma_z}{E} \tag{1}$$

$$\varepsilon_y = \frac{\sigma_y}{E} - \upsilon\frac{\sigma_x}{E} - \upsilon\frac{\sigma_z}{E} \tag{2}$$

$$\varepsilon_z = \frac{\sigma_z}{E} - \upsilon\frac{\sigma_x}{E} - \upsilon\frac{\sigma_y}{E} \tag{3}$$

where $E$ is the Young's modulus and $\upsilon$ the Poisson's ratio.

A particular case is that of thin layers superposed in a symmetric way, such that no stress exists in the $z$ direction (direction normal to the layer plane). Thus, $\sigma_z = 0$, and the stresses in the $x$ and $y$ directions will be identical in the bulk, i.e. $\sigma_x = \sigma_y = \sigma$, leading to an equally biaxial stress state. Under these conditions, Eqs. (1)–(3) will reduce to:

$$\varepsilon_x = \varepsilon_y = \varepsilon = \frac{\sigma}{E}(1-\upsilon) \tag{4}$$

and in general, expressed in terms of biaxial (in-plane) stress within each layer,

$$\sigma_i = \frac{E_i}{(1-\upsilon)}\cdot\varepsilon_i = E'_i\cdot\varepsilon_i \tag{5}$$

where $\varepsilon_i$ indicates the elastic strain of the $i$th layer.

For the equilibrium to exist it is required that the sum of the forces (per unit width), $F_i$, equals to zero:

$$\sum_i F_i = 0 = \sum_i \sigma_i\cdot t_i \tag{6}$$

with $t_i$ being the thickness of the $i$th layer.

For a multilayer system composed of $n$ layers of composition A and thickness $t_a$ and $n-1$ layers of composition B and thickness $t_b$, the residual stress magnitude in each layer may be evaluated as follows:

$$\sum_i \sigma_i t_i = \sum_i \varepsilon_i E'_i t_i = \varepsilon_a E'_a n t_a + \varepsilon_b E'_b (n-1) t_b = 0 \tag{7}$$

Defining the mismatch strain $\Delta\varepsilon$ as $\varepsilon_a - \varepsilon_b$, the strain in layers A and B may be rewritten as: