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Influence of ductile interlayers on mechanical behaviour of hard coatings under depth-sensing indentation: a numerical study on TiAlN

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Abstract In order to determine the influence of interlayers of ductile metals on the overall mechanical properties of the multilayer coatings, three-dimensional numerical simulations of depth-sensing indentation tests of titanium aluminium nitride (TiAlN) hard coatings with copper, silver, aluminium and titanium ductile interlayers were performed. The contribution of ductile interlayers to altering the hardness, the Young's modulus and *H/E* and H^2/E ratios of the multilayer coating with respect to a monolithic TiAlN hard coating was established for the cases of composites with different number and thicknesses of interlayers.

Introduction

Multilayer coatings with nanometer scale layer dimensions are attractive prospects for specific engineering requirements. For example, it is possible to improve the durability of hard films by arranging interlayers of ductile metal, sandwiched between layers of hard film, without causing significant changes in the mechanical properties of the film [1, 2]. In fact, the use of ductile interlayers can enhance the toughness and adhesion of hard coatings, which makes it important to study the mechanical properties of hard coatings with ductile interlayers. Many commonly used multilayer coatings are based on titanium aluminium nitride (TiAlN). These are often used as wear resistant coatings in high-speed machining due to their hardness, outstanding oxidation and corrosion resistance [3–6]. Manufacturing of these coatings with interlayers of low elastic modulus ductile metals, like copper, silver, aluminium or titanium, can improve cutting efficiency.

Micro and nanoindentation techniques are the preferred option for mechanical characterization of bulk, composite and coating materials [7–10]. In case of coatings this occurs for the particular reason that standard mechanical testing methods for bulk materials cannot be readily used on such nano-scaled structures. Various experimental studies [2–4, 11] have been carried out during the last few years, providing data about the deformation mechanisms of multilayer coatings under depth-sensing indentation. The evaluation of the hardness and Young's modulus of multilayer composites is coupled with difficulties induced by the influence of the substrate and constituent layers on the measured properties. In addition, experimental difficulties in the mechanical property evaluation of multilayer composites can arise due to the failure of such multilayer coatings during depth-sensing indentation tests, where strong delamination of the coating can take place [11, 12]. Consequently, the finite element method is an effective way of quantifying the mechanical properties of multilayered materials and providing detailed data for a better description of their mechanical behaviour under depth-sensing indentation. There have been relatively few studies of the numerical simulation of the mechanical behaviour of multilayers under indentation [2, 13–16]. One of these studies [15] considered alternating layers of two ductile metallic materials, with similar or equal thickness. In this

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reference, the alternating layers are modelled as elastically perfect plastic metallic films. A more recent numerical simulation study [16] concerns the modelling of the evolution of Young's modulus of Cr/CrN multilayer coatings where the bilayer thickness is in the range of 1–5 μm. In [13, 14], a numerical finite element analysis was conducted to study the evolution of the elastic modulus and deformation fields in a metal–ceramic (aluminium and silicon carbide) multilayered material, during indentation.

In this context, the aim of this study is to perform three-dimensional numerical simulation of depth-sensing indentation tests of multilayered coatings, alternating layers of hard film with thin ductile metallic interlayers, in order to study the influence of the presence of ductile interlayers on the mechanical properties of the overall coatings. The materials chosen for the multilayer coatings have mechanical properties similar to those of TiAlN (hard layer) with ductile interlayers of copper, silver aluminium and titanium [11].

Theoretical aspects

Depth-sensing indentation numerical simulations were used to determine the hardness and the Young's modulus of the composites. The hardness, H_{IT}, is evaluated by [17]:

$$H_{IT} = \frac{P}{A} \quad (1)$$

where P is the maximum applied load and A is the contact area of the indentation, at the maximum load. The reduced Young's modulus, E_r, is determined from [17, 18]:

$$E_r = \frac{\sqrt{\pi}}{2\beta}\frac{1}{\sqrt{A}}\frac{1}{C} \quad (2)$$

where β is the geometrical correction factor for the indenter geometry (its value was estimated to be 1.05 for Vickers indentation—see previous studies [19, 20]) and C is the compliance. The specimen's Young's modulus, E_s, is obtained using the definition:

$$\frac{1}{E_r} = \frac{1 - v_s^2}{E_s} + \frac{1 - v_i^2}{E_i} \quad (3)$$

where E and v are the Young's modulus and the Poisson's ratio, respectively, of the specimen (s) and of the indenter (i). In this study, the indenter was considered rigid, and so $(1 - v_i^2)/E_i = 0$.

The accuracy of the hardness and Young's modulus results, obtained with Eqs. 1, 2 and 3, depends on the contact area and compliance evaluations. In this study, the contact area, A, was evaluated using the indentation contour. Using this approach, the contact area results are independent of pile-up and sink-in formation [21]. The compliance, C, was evaluated by fitting the unloading part of the load–indentation depth curve, (P–h), using the power law [19]:

$$P = P_0 + T(h - h_0)^m, \quad (4)$$

where T and m are constants, obtained by fitting this equation to the numerical results, and h_0 is the indentation depth which corresponds to a load value P_0, during unloading; h_0 was chosen such that, 70% of the unloading curve was used in the fits [19].

Besides the evaluation of hardness and Young's modulus for the mechanical property characterization of multilayer composites, the H/E and H^2/E ratios were declared by different authors [22–26] to provide close correlation with relative wear resistance. The H/E ratio can be considered as an indicator of the elastic strain to failure, i.e. the degree of elastic deformation before yielding [22, 23]. Also, if a material can absorb impact energy without yielding then its operating life can be longer. This energy, usually called resilience, which is defined as the integral of the tension–strain curve in tensile tests, can in turn be related to the H^2/E ratio [26]. So, both parameters, H/E and H^2/E, are claimed fundamental for the prediction of coating behaviour in wearing.

Numerical simulation and materials

The numerical simulations of the hardness tests were performed using the in-house HAFILM code, which was developed to simulate processes involving large plastic deformations and rotations. This code considers the hardness tests to be a quasistatic process and makes use of a fully implicit algorithm of Newton–Raphson type [27]. Hardness test simulations can be performed using any type of indenter and take into account the friction between the indenter and the deformable body. A detailed description of the HAFILM simulation code has been previously given [19, 28]. Numerical simulations of the hardness tests were performed using a 68° half-angle Vickers indenter, modelled with parametric Bézier surfaces, which allow a fine description of the indenter tip, namely an imperfection (a rectangular planed indenter tip, with one side twice the length of the other, with an area of 0.0032 μm^2) such as the one which occurs in the real geometry [29]. For the ideal indenter geometry, the ratio between the projected area and the square of the indentation depth is 24.5.

The substrate part of the sample used in the numerical simulations has both a radius and thickness of 40 μm, and was discretized with three-linear eight-node isoparametric hexahedrons. For simulation of the multilayer composite material a coating made up of 3/1, 7/3, 11/5 and 15/7 total layers/interlayers was added. In order to facilitate the

Table 1 The coating's total thickness and the respective interlayer total thickness of simulated materials (the total hard layers thickness is always equal to 3.400 μm)

Total coating's thickness (μm)	Total interlayers thickness (μm)
3.425	0.025
3.450	0.050
3.500	0.100
3.600	0.200

comparison of results, the total thickness of the hard layers was kept to 3.400 μm, while the total thickness of the metallic ductile interlayers varied from 0.025 to 0.200 μm. The total coating thickness and the respective interlayer thickness of simulated materials are shown in Table 1. Due to geometrical and material symmetries in the $X = 0$ and $Z = 0$ planes, only a quarter of the sample was used in the numerical simulation. The number of elements composing the finite element meshes used to simulate the multilayer coatings with different amount of layers is summarized in Table 2. Their total thickness and respective interlayer thicknesses, representing the multilayer coating, were selected in such a way as to resemble a multilayer coating commonly manufactured and used in practice [11]. Figure 1 shows the finite element mesh for samples with coatings containing seven interlayers for the particular case where the total coating thickness is 3.500 μm. In all meshes, the finite element size at the surface of the indentation region was about 0.055 μm. This mesh size enables us to obtain a good estimation of the indentation contact area. Due to the fact that the hardness values are almost unaffected by the friction coefficient [19, 20], contact with friction was considered between the indenter and the deformable body, with a Coulomb coefficient of 0.16, which is the most commonly used value.

Full adhesion is taken into account between all components of the numerical samples: the hard and ductile

Table 2 Number of elements of finite element meshes for multilayer composites with different number of layers

Total interlayers thickness (μm)	Number of total layers/number of interlayers	Number of elements of finite element meshes
0.025 and 0.050	3/1	8712
	7/3	12312
	11/5	15912
0.050	15/7	19512
0.100 and 0.200	3/1	9072
	7/3	13392
	11/5	17712
	15/7	22032

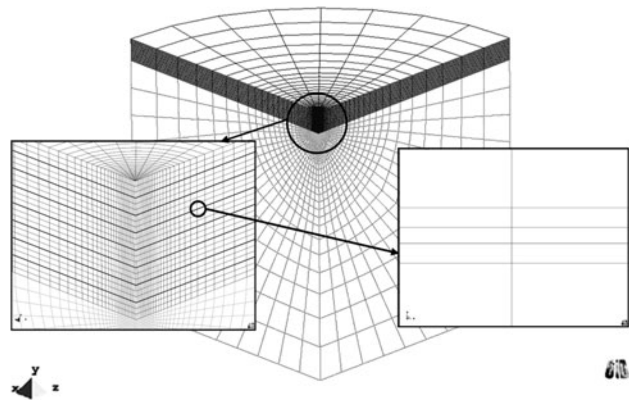

Fig. 1 Examples of finite element mesh for a coated sample with seven interlayers and 3.500 μm total thickness: general view and details of the multilayer coating

interlayers and the substrate. Moreover, the numerical simulations were carried out without considering residual stresses, even though previous works [11, 30–32] have stated that sputtered multilayer coatings (like TiAlN) contain internal stress states, whose magnitude was found to be dependent on the substrate, layer and interlayer materials, layer and interlayer thicknesses and even sputtering conditions and subsequent thermal treatment. In this context, the aim of this paper is to study the influence of the presence of ductile interlayers on mechanical properties, when compared with the hard coating without interlayers, independent of the occurrence of internal stresses.

Three-dimensional numerical simulations of the hardness tests were carried out up to a maximum indentation depth of $h_{max} = 0.4$ μm and, in order to check the influence of the maximum indentation depth value on mechanical behaviour, a few simulations were also performed up to maximum indentation depths $h_{max} = 0.2$ and 0.3 μm; these three values are the maximum indentation depths tested without calibration of the indenter geometry. The plastic behaviour of the material is described by the von Mises yield criterion and the flow stress in tension described by the Swift equation: $\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon}_p)^n$, where $\bar{\sigma}$ and $\bar{\varepsilon}_p$ are the equivalent stress and plastic strain, respectively, and K, ε_0 and n are constants for a particular material [33]. The constant ε_0 was considered to be 0.005 for all simulations [19, 20]. In agreement with the Swift equation, the material yield stress σ_y is given by $\sigma_y = K\varepsilon_0^n$.

The substrate material simulated was a high-speed-steel AISI M2. The mechanical properties chosen for the hard layers were similar to those of TiAlN and for the ductile interlayers similar to copper, silver, aluminium and titanium. The elastic and plastic behaviours of the ductile interlayer were selected in order to take into account different properties in relation to the hard layer: (i) the titanium interlayer's hardness is half the hard layer's hardness;

Table 3 Mechanical properties of hard (TiAlN) and ductile (copper, silver, aluminium and titanium) layers, and substrate (M2 steel)

Material	σ_y (GPa)	n	ν	E (GPa)	H (GPa)
M2	2.57	0.30	0.30	210	6.5
TiAlN	12.05	0.01	0.20	460	27.8
Copper	0.49	0.30	0.33	140	1.8
Silver	0.45	0.30	0.37	76	2.8
Aluminium	0.29	0.30	0.33	70	1.7
Titanium	8.42	0.01	0.33	110	14.5

(ii) the silver interlayer's hardness is about one tenth that of the hard layer and (iii) the copper and aluminium interlayers' hardnesses are relatively low (about one fifteenth of the hard layer's hardness) and have different Young's modulus values (the copper's Young's modulus is twice that of aluminium). The mechanical properties of all materials are summarized in Table 3 and they were selected based on previously reported experimental data [11].

Results and discussion

Load–indentation depth curves

Examples of load–indentation depth curves obtained by numerical simulations for the hard coatings with and without interlayers are shown in Figs. 2 and 3. Figure 2 compares the curves with a different number of copper and titanium interlayers for two cases of interlayer total thicknesses, $d_{interlayer} = 0.025$ and 0.100 µm. The level of the loading part of the indentation curves for coatings containing copper interlayers decreases and the curves tend to converge as the number of the layers increases (Fig. 2a, b). A similar convergence of indentation curves was also observed for coatings containing aluminium or silver interlayer materials. The indentation curves for coatings with titanium interlayers are close to each other whatever the interlayers' total thickness (Fig. 2c, d); nevertheless the relative position between curves is the same as for coatings with copper interlayers.

Figure 3 compares the indentation curves with different total interlayer thicknesses of copper and titanium interlayers, for multilayer coatings composed of 3/1 and of 11/5 total layers/interlayers. The curves for coatings with copper interlayers are lower than the one corresponding to the monolithic coating and the level of the curves decreases with the increase in the total interlayer thickness (Fig. 3a, b). Similar behaviour was also observed for multilayer coatings with silver or aluminium interlayer materials. The load–indentation depth curves for coatings with titanium interlayers are close to the curve for a monolithic coating, revealing an insignificant reduction of the level of the curves with the increase in the total interlayer thickness (Fig. 3c, d).

Hardness

The value of the hardness of the monolithic TiAlN coating deposited on M2 steel was determined independently of the maximum indentation depth values (0.2, 0.3 and 0.4 µm) to be about 28 GPa, which is equal to the hardness value obtained in numerical simulations of TiAlN as bulk material. Thus, the substrate's influence on the hardness results of multilayer composites is assumed hereinafter to be negligible for the maximum penetration depths used ($h_{max} \leq 0.4$ µm). In fact, the analysis of the plastic deformation in the indentation region showed that the substrate does not deform plastically, even for maximum indentation depth values of 0.4 µm, as usually observed when h_{max} is less than approximately 10% of the thickness [34, 35].

In order to check the influence of the maximum indentation depth value on the hardness behaviour of multilayer composites, three-dimensional numerical simulations of hardness tests were carried out up to maximum indentation depths of $h_{max} = 0.2$, 0.3 and 0.4 µm. The results for the coatings with copper interlayers allow us to plot Fig. 4, as an illustration, showing the hardness of the coating as a function of the inverse total interlayer thickness, $d^{-1}_{interlayer}$, for different combinations of the ratio between the numbers of total layers and interlayers. No significant differences in multilayer coating hardness behaviour were observed between the three maximum indentation depths (compare Fig. 4a–c), although the influence of the copper interlayers is slightly lower, for $h_{max} = 0.2$ µm. Whatever the maximum indentation depth, the hardness of the coating containing only one copper interlayer is slightly lower than the hardness of the monolithic coating and does not significantly vary with a decrease in interlayer total thickness (Fig. 4). Increasing the number of interlayers causes the hardness of the coating to decrease, although this is attenuated for low values of interlayer total thickness.

So, it can be concluded that the maximum indentation depth value, between 0.2 and 0.4 µm, does not significantly influence the hardness behaviour of multilayer composites. For this reason, only the hardness results for the case of the maximum indentation depth value of 0.4 µm are discussed.

The hardness results of the coatings with interlayers of copper, silver, aluminium and titanium, for a maximum indentation depth of 0.4 µm, are represented in Fig. 5. The presence of ductile interlayers contributes to a decrease of the coatings' hardness. Moreover, the hardness of the coating decreases gradually with an increase in the number

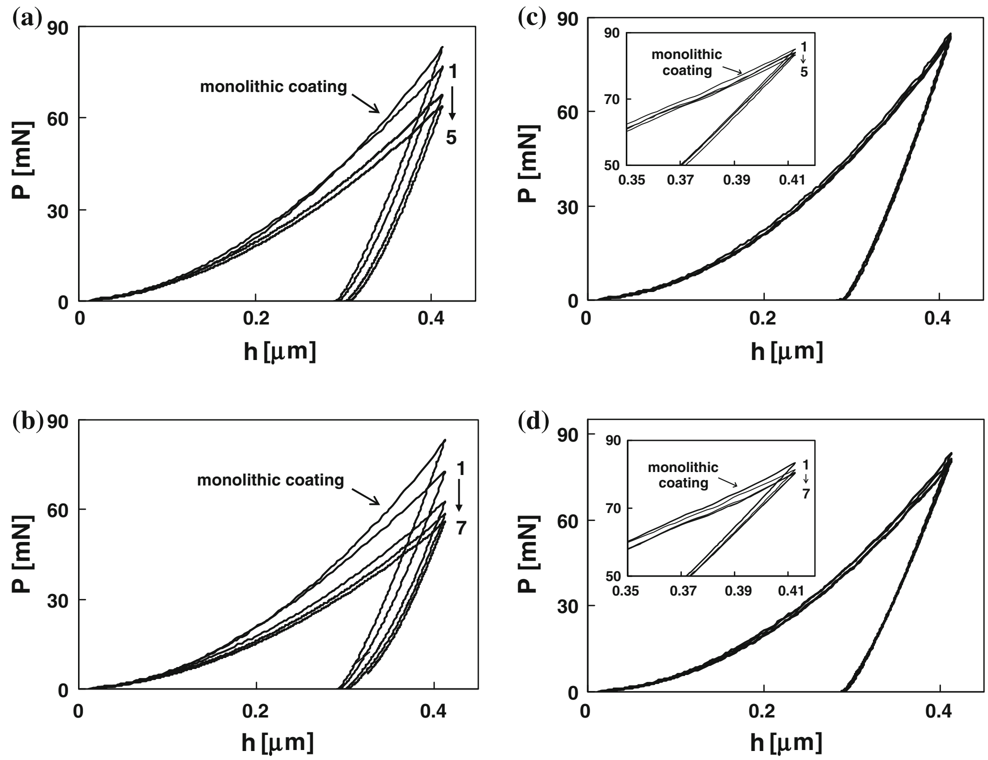

Fig. 2 Load–indentation curves for TiAlN composite with different number of interlayers (number plotted on the figures), for the cases of copper: **a** $d_{\text{interlayer}} = 0.025$ μm; **b** $d_{\text{interlayer}} = 0.100$ μm; and titanium: **c** $d_{\text{interlayer}} = 0.025$ μm; **d** $d_{\text{interlayer}} = 0.100$ μm. These curves were plotted taking into account the offset correction, using the area function of the indenter [28]

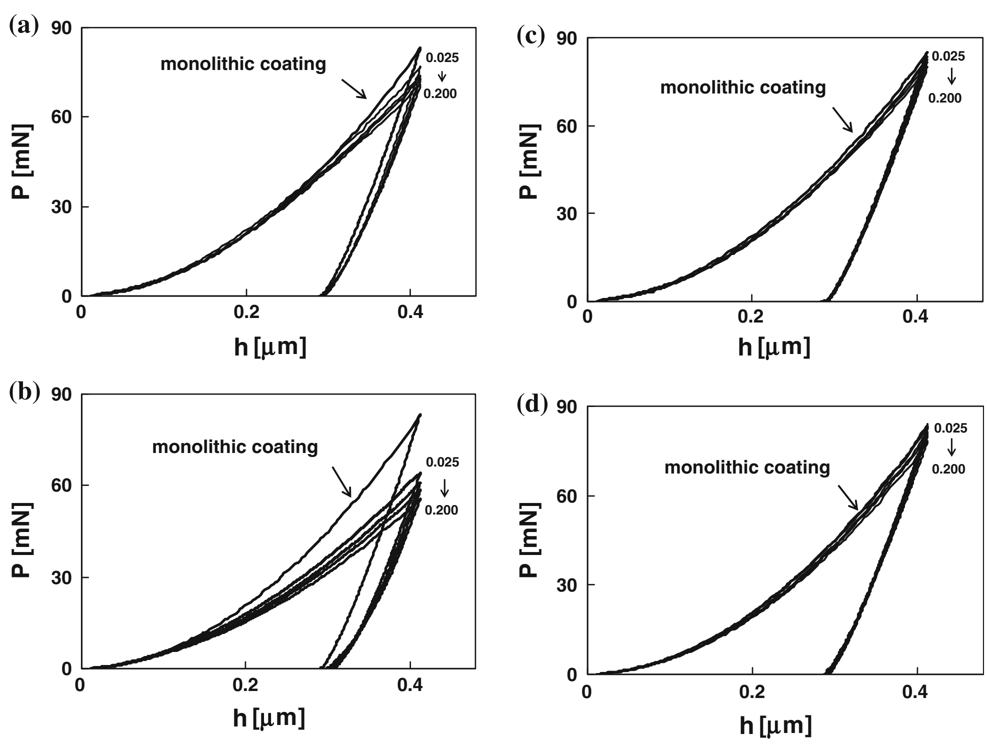

Fig. 3 Load–indentation depth curves for TiAlN composite with different total interlayer thicknesses (these values are plotted on the figures), for the cases of copper: **a** 3/1 layers/interlayers; **b** 11/5 layers/interlayers; and titanium: **c** 3/1 layers/interlayers and **d** 11/5 layers/interlayers. These curves were plotted taking into account the offset correction, using the area function of the indenter [28]

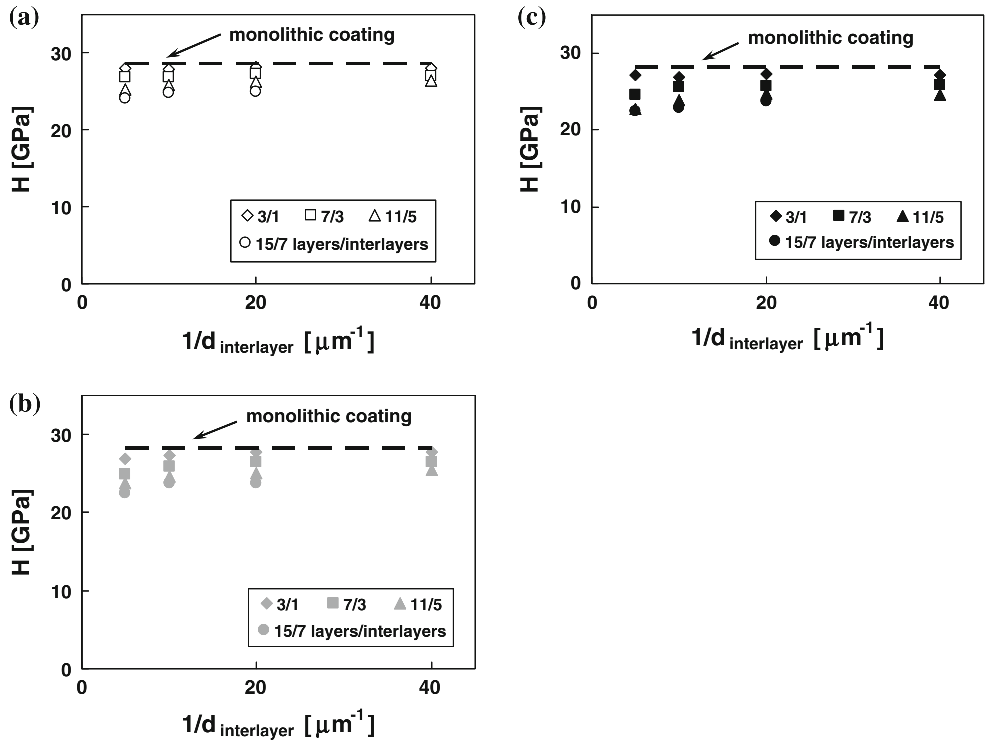

Fig. 4 Hardness of multilayer coating with copper interlayers as a function of the inverse of the interlayer total thickness, for maximum indentation depths equal to: **a** *open diamond* $h_{max} = 0.2$ µm; **b** *gray-shaded diamond* $h_{max} = 0.3$ µm; **c** *filled diamond* $h_{max} = 0.4$ µm

of ductile interlayers, for a given interlayer total thickness. For all cases of interlayer total thicknesses given in Table 1, the presence of a single copper interlayer produces a decrease in the coating's hardness of less than 2%. This reduction is even less for silver and aluminium single interlayers, for which the hardness decreases by about 0.9 and 0.7%, respectively. The hardness value of the coating with a single titanium interlayer does not differ from the one obtained for the monolithic coating. Further introduction of interlayers causes a linear decrease in the hardness in case of aluminium, copper (both show 17% hardness decrease for coatings with seven ductile interlayers) and silver (13% hardness decrease for coatings with seven ductile interlayers). Increasing the number of titanium interlayers in the multilayer coating leads to a relatively insignificant decrease in the hardness values (4% hardness decrease for coatings with seven ductile interlayers).

As consequence of having metallic interlayers, the hardness behaviour of the hard TiAlN coatings is identical, as observed in experimental studies [11]. In fact, the numerical hardness behaviour observed in our study is qualitatively similar to that experimentally observed for a total interlayer thickness of 0.080 µm [11]. Experimental observation showed that for titanium the hardness values varied insignificantly with the number of layers. However, for copper and aluminium, hardness values decreased as the number of interlayers increased. Interestingly, this measured reduction in hardness is higher than our numerical simulation study and can attain about 40% for coatings with seven aluminium interlayers, for example. The reason for these quantitative differences between experimental and numerical hardness results is probably related to the existence of residual stresses, failure, delamination and adhesion troubles sometimes observed in the coatings, which modify the experimental conditions for measuring hardness, in contrast to the numerical study, for which full adhesion is considered in the model. This enhances the importance of the present numerical studies, which can expurgate such technical hitches from the hardness and Young's modulus depth-sensing indentation results.

The high yield stress and hardness values of titanium make the overall hardness of the multilayer coatings almost insensitive to the presence of titanium interlayers, which is not the case with the three other interlayer materials (see Table 3). Among these three cases, the multilayered coatings with silver interlayers show the best performance, which is related to the relatively higher hardness of this interlayer material.

The decrease in the hardness with the increasing number of interlayers is related to the characteristics of the plastic strain distribution in the hard and ductile layers. Figures 6 and 7 show examples of the equivalent plastic strain distribution in coatings with silver and titanium interlayers. The features of the equivalent plastic strain distribution for

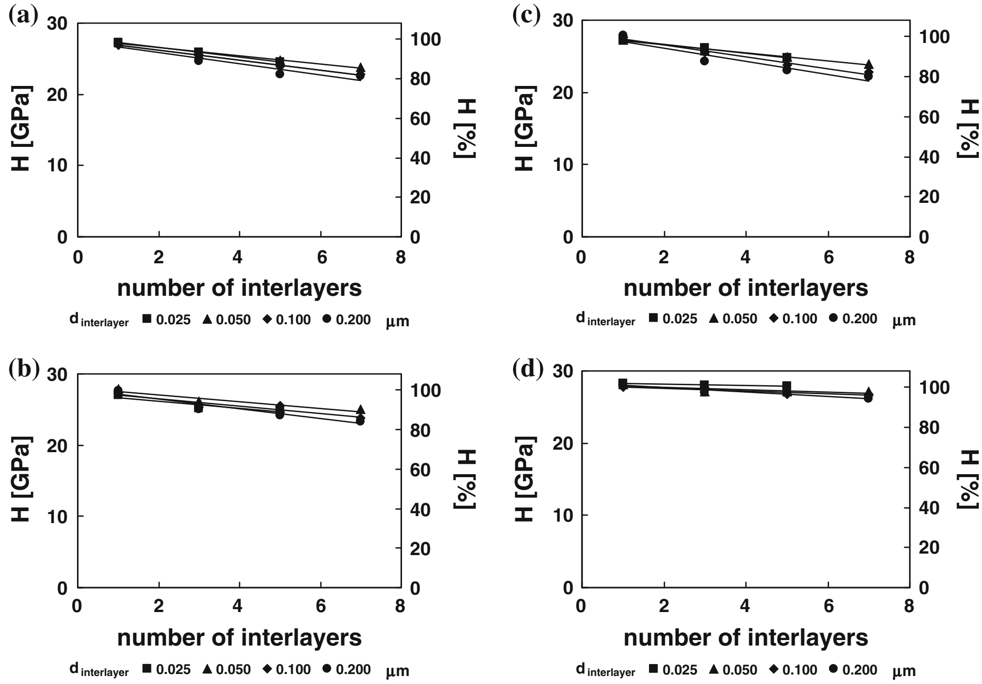

Fig. 5 Hardness of multilayer coating with copper interlayers as a function of the inverse of the interlayer total thickness (maximum indentation depth equal to 0.4 μm), for coating with interlayers of: **a** copper; **b** silver; **c** aluminium and **d** titanium *open diamond* hardness value of the monolithic TiAlN hard coating

the coatings change with the number of interlayers. The

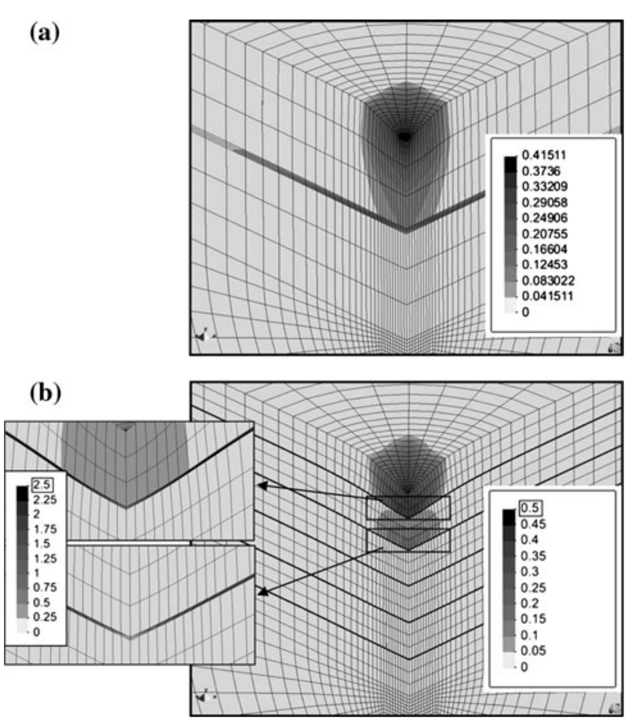

Fig. 6 The equivalent plastic strain distribution in TiAlN multilayer coatings with silver interlayers: **a** 3/1 layers/interlayers, **b** 11/5 layers/interlayers; $d_{\mathrm{interlayer}} = 0.100$ μm

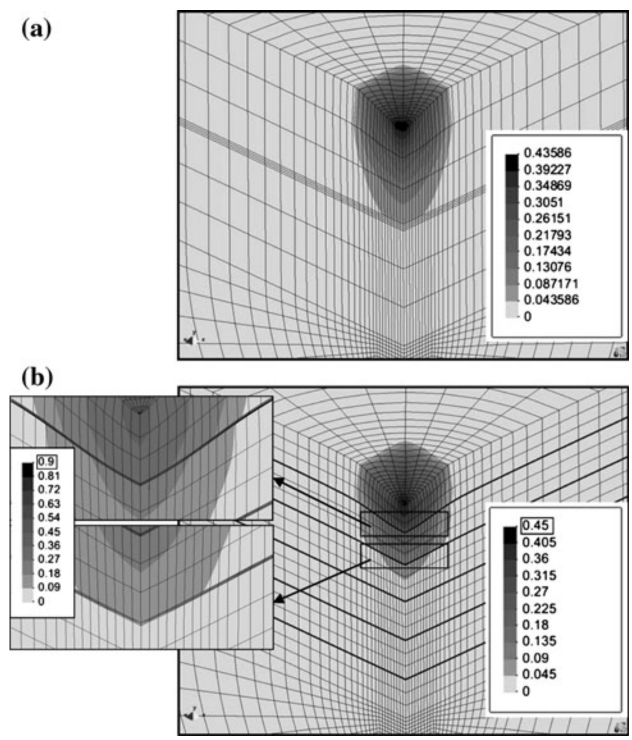

Fig. 7 The equivalent plastic strain distribution in TiAlN multilayer coatings with titanium interlayers: **a** 3/1 layers/interlayers; **b** 11/5 layers/interlayers, $d_{\mathrm{interlayer}} = 0.100$ μm

maximum plastic strain value of multilayer coatings increases when the number of ductile interlayers increases (see Figs. 6, 7 a, b). Moreover, for three or more interlayers, the maximum value of plastic strain appears in regions sited within the ductile interlayers and this value is reduced for deeper interlayer positions (Figs. 6b, 7b). Plastic deformation within the hard layers is always extended up to at least the first ductile interlayer and the maximum strain value is quite similar, independent of the number of interlayers. However, the size of the region of the hard layers plastically deformed across the thickness depends on the number of interlayers (Figs. 6, 7a, b). For example, in the case of one silver ductile interlayer (3/1—layers/interlayers), the plastically deformed region is limited by the only interlayer (Fig. 6a); in the case of the same interlayer material with seven ductile interlayers (11/5—layers/interlayers), the plastically deformed region is limited by the second interlayer (Fig. 6b), but the size of the deformed region within the hard layers is smaller than in case of just one ductile interlayer. This means that the increase in the number of ductile interlayers attenuated the propagation of the plastically deformed region to deeper hard layers. Consequently, the contribution of the hard layers, to the hardness of the composite, decreases when the number of ductile interlayers increases, which justifies the observed decrease in the hardness value of the composite with the number of interlayers (compare Fig. 6a with b for silver interlayers and Fig. 7a with b for titanium interlayers).

No plastic deformation was undertaken during unloading, as has recently been observed in the analysis of two-dimensional numerical simulations of the indentation tests of multilayer coatings [13, 14]. In fact, these authors mentioned that certain regions of the ductile interlayer, near the surface, can undertake relatively high values of plastic deformation even during unloading. This unexpected result was associated with the increase in the magnitude of shear stress during unloading, due to internal constraint promoted by the elastic action of the hard layers adjacent to the ductile interlayer. In the current three-dimensional numerical simulation, no such plastic deformation was observed during unloading. The reason for these dissimilar results is certainly related to different architectures of the multilayer coatings, which causes different internal constraints. Tang et al. [13] used a total of 41 very thin (50 nm) layers (hard plus ductile layers). The thickness ratio between hard and ductile layers is always 1.0. In the present study, the number of total layers is between 3 and 15 and the hard layer is always thicker than the ductile layer: for the case of 3-layers the thickness ratio between hard and ductile layers is always higher than 8.5, and for the case of 15-layers this ratio is always higher than 14.9.

For the same number of interlayers, the influence of the interlayer total thickness on the hardness of the composite depends on the number of interlayers. In case of just one interlayer, the hardness does not depend on the interlayer thickness (see Fig. 5). A perceptible but small influence of the interlayer total thickness on the hardness was observed mainly for the cases of copper, silver and aluminium interlayer materials (see Fig. 5). This agrees with the character of the plastic strain distribution in the hard layers, whose size and values are almost independent of the total thickness of the ductile interlayers. For a given number of interlayers, only the plastic deformation within the interlayers increases with reducing thickness (compare Fig. 6a, b with Fig. 8a, b, respectively, for silver interlayers).

In conclusion, the presence of ductile interlayers can contribute to the decrease in the hardness value of the coating, depending on their number and thickness. This is because part of the plastic deformation is absorbed by the ductile interlayers, which act as barriers to prevent the plastic deformation propagating to deeper hard layers.

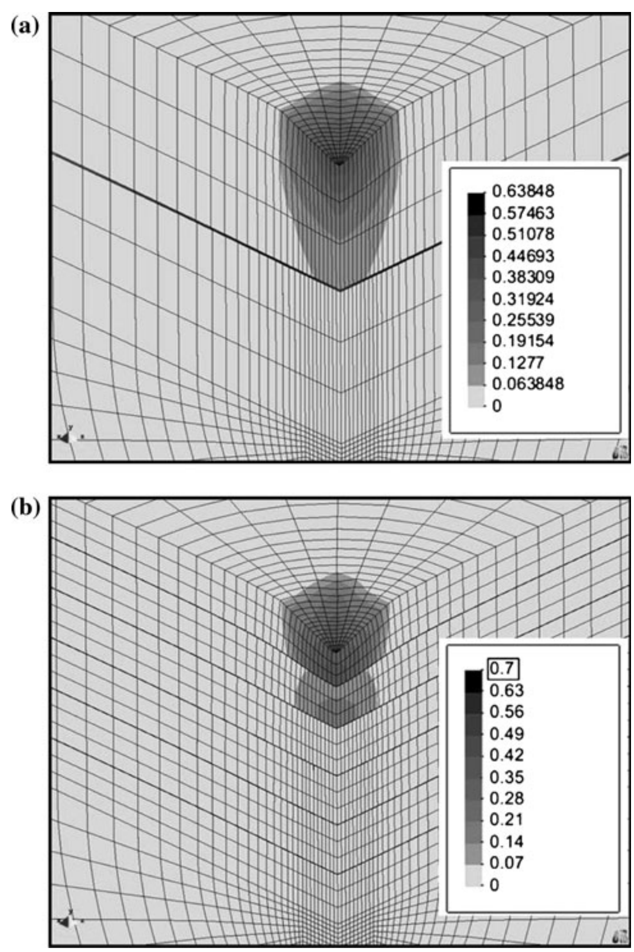

Fig. 8 The equivalent plastic strain distribution in TiAlN multilayer coatings with silver interlayers: **a** 3/1 layers/interlayers, **b** 11/5 layers/interlayers; $d_{\mathrm{interlayer}} = 0.025\ \mu\mathrm{m}$

The efficiency of the ductile interlayers as barriers for the propagation of the plastic deformation to the deeper hard layers increases when the same total interlayer thickness is separated into various interlayers. In other words, the more the ductile interlayers are involved in the plastic deformation process, the more efficient the accommodation of the plastic deformation between adjacent hard layers. The presence of interlayers leads to the reduction in the size of the plastically deformed region in the hard layers, with consequent decreasing hardness. However, it is worth noting that the decrease in hardness is always lower than 17%, even for very high ratios of the hard and ductile interlayer hardnesses such as in case of TiAlN hard layer and copper or aluminium ductile layers ($H_{hard}/H_{ductile} = 16$, for the ratio of number of total layers/ number of ductile interlayers is 15/7).

Young's modulus

The Young's modulus values of the monolithic TiAlN coating deposited on M2 steel are sensitive to the maximum indentation depth (0.2, 0.3 and 0.4 μm). As usual, the Young's modulus results for the monolithic coating were found to be sensitive to the maximum indentation depth, showing a decrease in the values of the Young's modulus with increasing maximum indentation depth. The Young's modulus of TiAlN as bulk material is equal to 460 GPa. For the monolithic coating, the Young's modulus value decreases from 428 GPa for a maximum indentation depth of 0.2 μm to 403 GPa for a maximum indentation depth of 0.3 μm and 390 GPa for a maximum indentation depth of 0.4 μm, which corresponds to reductions of 7, 12 and 15%, respectively. This indicates that in this case there is a substrate influence on the Young's modulus results of the composite, which cannot be assumed to be negligible (as opposed to the hardness behaviour).

In order to check the influence of the maximum indentation depth value on the Young's modulus behaviour for multilayer composites containing interlayers of different total thicknesses, three-dimensional numerical simulations of hardness tests were carried out up to maximum indentation depths, $h_{max} = 0.2$, 0.3 and 0.4 μm. The coatings with copper interlayers are shown as an illustration in Fig. 9. For all cases, the Young's modulus is equal to or lower than the Young's modulus of a monolithic coating at a corresponding indentation depth. For a given maximum indentation depth, the difference between the Young's modulus values of the multilayer and monolithic coatings increases with increasing interlayer total thickness. For the same interlayer total thickness, this difference increases with the increasing number of ductile interlayers, although the mentioned difference is not significant.

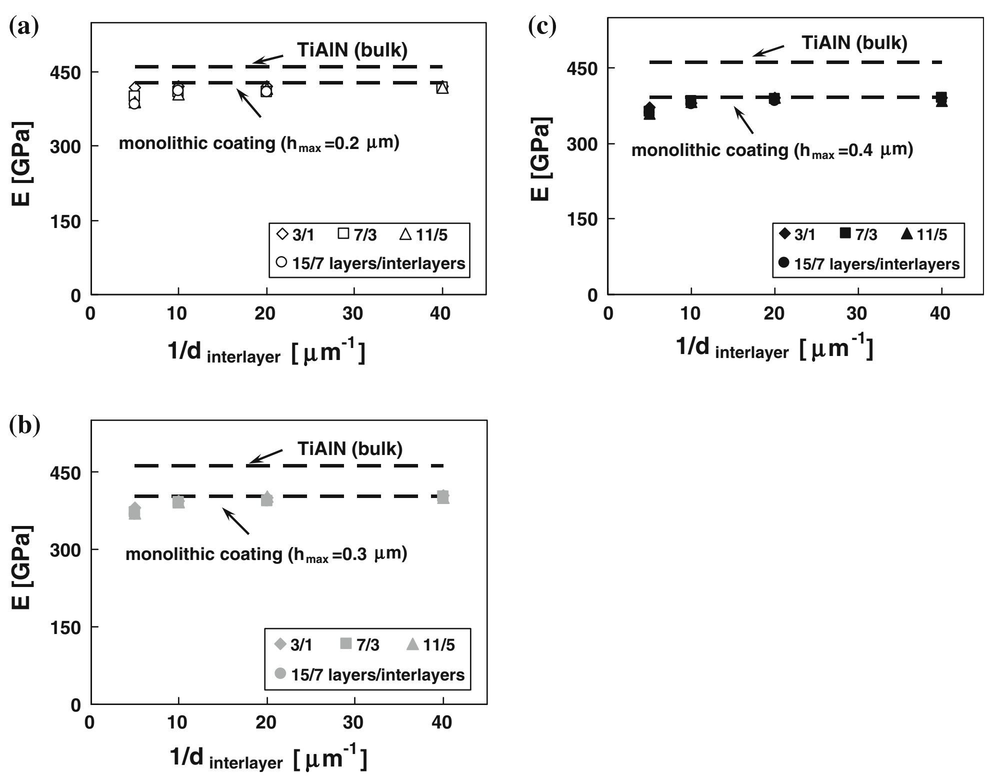

Fig. 9 Young's modulus of multilayer coating with copper interlayers as a function of the inverse of the interlayer total thickness, for maximum indentation depths equal to: **a** $h_{max} = 0.2$ μm; **b** $h_{max} = 0.3$ μm; **c** $h_{max} = 0.4$ μm

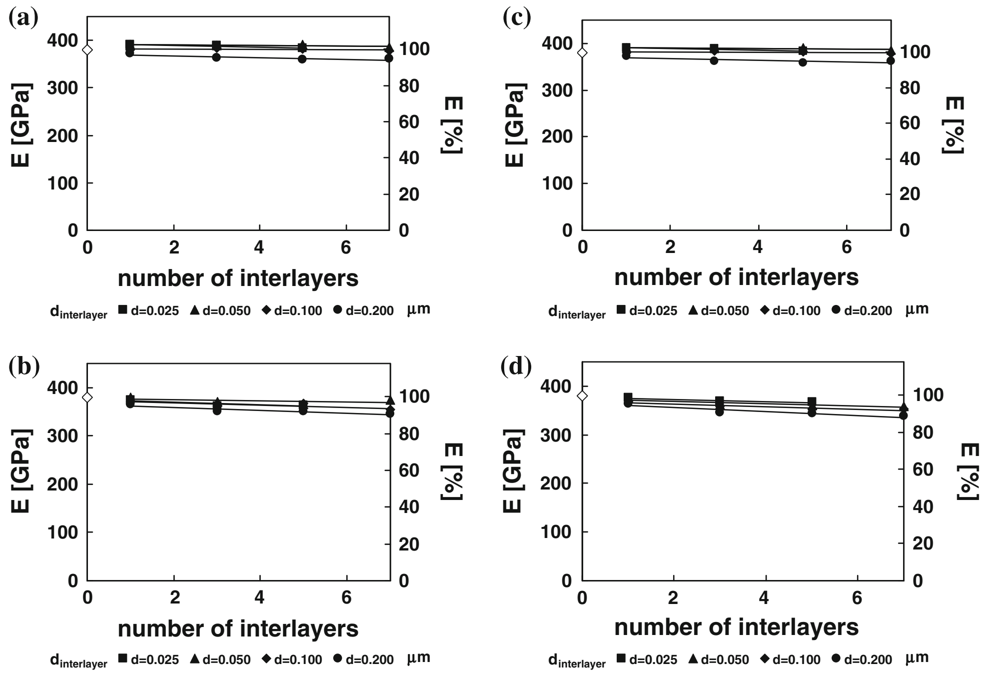

Fig. 10 Young's modulus of multilayer composite versus the number of interlayers for different interlayer total thickness $d_{\text{interlayer}}$ for coating with interlayers of: **a** copper; **b** silver; **c** aluminium and **d** titanium *open diamond* Young's modulus value of the monolithic TiAlN hard coating

Figure 10 shows the Young's modulus evolution with the number of ductile interlayers of the multilayer composites, for the maximum indentation depth value equal to $h_{\max} = 0.4$ µm. For multilayer coatings with silver, aluminium and titanium interlayers, the Young's modulus undergoes a decrease relative to the monolithic coatings, at the same maximum indentation depth, which is more evident for the highest total interlayer thicknesses when the number of interlayers increases (Fig. 10b–d). The introduction of one single interlayer leads to a slight decrease in the Young's modulus (up to 2.5%). The decrease in the Young's modulus attains a value less than 8% in the case of the coating with seven silver, aluminium and titanium interlayers. In case of multilayer coatings containing copper interlayers, the Young's modulus remains almost stable with an increasing number of interlayers and has a value quite close to the Young's modulus of the composite with monolithic TiAlN coating. Only for relatively high interlayer thickness (0.200 µm) does the Young's modulus tend to decrease with the number of interlayers (Fig. 10a), although the Young's modulus reduction is always less than 1.5%. This small difference between copper and the other interlayer materials must be related to the higher value of the copper's Young's modulus. Nevertheless, it can be stated that the presence of interlayers does not significantly influence the Young's modulus value, at least not so much as the hardness, which is certainly related to the relatively low contribution of the elastic deformation in the interlayers to the overall elastic deformation of the sample.

H/*E* and H^2/E ratios

In order to better understand how the above results concerning the hardness, *H*, and Young's modulus, *E*, of the multilayered coatings influence the wear behaviour, the *H*/*E* and H^2/E ratios for multilayer coatings with copper, silver, aluminium and titanium interlayers versus the number of these ductile interlayers are presented in Figs. 11 and 12, respectively. The most visible feature of these figures concerns the fact that the evolution of the *H*/*E* and H^2/E ratios is almost independent of the interlayer total thickness. For the case of coating containing copper, silver and aluminium interlayers, the value of the *H*/*E* and H^2/E ratios decreases as the number of interlayers increases. The maximum decrease in the *H*/*E* ratio is 15, 8 and 11%, for copper, silver and aluminium, respectively. The maximum decrease in the H^2/E ratio is 30, 19 and 27%, for copper, silver and aluminium, respectively. On the contrary, in the case of titanium, the *H*/*E* and H^2/E ratios are equal to the one for the monolithic coating, whatever the number of interlayers. This behaviour is attributed to the fact that the hardness and the Young's modulus of coatings with titanium interlayers are hardly influenced by the presence of these interlayers (the little influence observed shows a similar tendency).

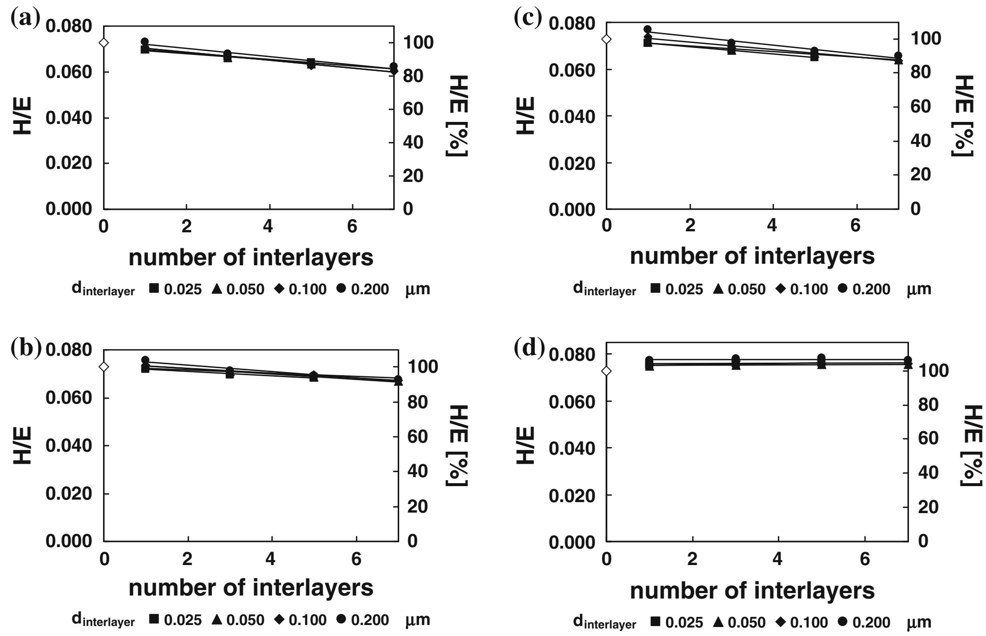

Fig. 11 *H/E* ratio as function of the number of interlayers for multilayer coatings with interlayers of **a** copper **b** silver **c** aluminium and **d** titanium *open diamond* value of the *H/E* ratio for monolithic TiAlN hard coating

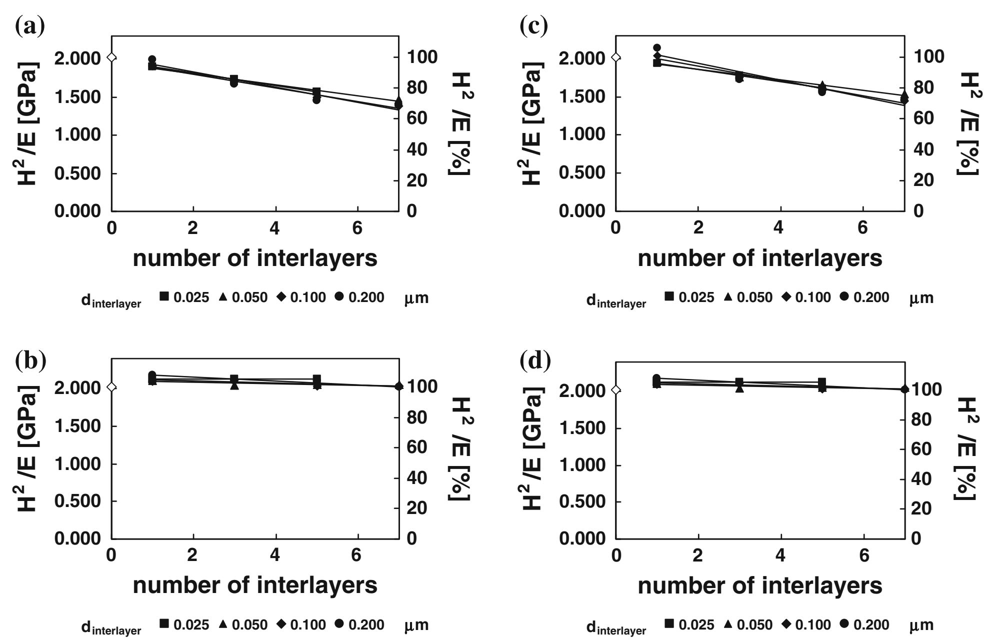

Fig. 12 H^2/E ratio as function of the number of interlayers for multilayer coatings with interlayers of: **a** copper **b** silver **c** aluminium and **d** titanium *open diamond* value of the H^2/E ratio for monolithic TiAlN hard coating

The experimental results do not report any reduction of the *H/E* ratio with the presence of ductile interlayers and show qualitatively similar behaviour concerning the H^2/E ratio [11], although the values are lower than the present numerical ones. The source of these differences was discussed above in the section concerning the hardness results.

Conclusions

The influence of the presence of interlayers of ductile metals on the overall mechanical properties of multilayer coatings of TiAlN hard coatings with copper, silver, aluminium and titanium ductile interlayers was studied, by using three-dimensional numerical simulations of depth-sensing indentation tests. The main conclusions can be summarized as follows:

– The presence of interlayers contributes to the reduction in the hardness of the multilayer coating. It decreases gradually with an increasing number of ductile interlayers, for a given interlayer total thickness. However, in case of titanium interlayers, the reductions in hardness are insignificant when compared to the other cases of ductile interlayers. This is because the hardness of the hard layer is about twice the hardness of the titanium interlayer. The hard layer is about 10 times harder in the case of silver and about 16 in the cases of aluminium and copper. However, even in these last two cases, the maximum reduction in hardness is always less than 17%. This is due to the fact that the plastic deformation is supported by the ductile interlayers, which act as barriers for the propagation of the plastic deformation to the deeper hard layers.
– For multilayer coatings with copper, silver, aluminium and titanium interlayers, the Young's modulus undergoes a decrease relative to the monolithic coatings when the number of interlayers increases. However, the elastic response of the multilayer coatings is much less influenced by the number of interlayers than the hardness.
– The above mentioned behaviour, of the hardness and the Young's modulus of the multilayer composites, determines the evolution of the H/E and H^2/E ratios. The values of these ratios decrease as the number of interlayers increases, for the coatings containing copper, silver and aluminium interlayers. On the contrary, in the case of titanium, the H/E and H^2/E ratios are quite similar to the one for the monolithic coating whatever the number of interlayers.
– The obtained results allow us to suppose that the multilayer coatings with five or less ductile interlayers and a total thickness in the range of 0.025–0.100 μm are quite favourable for wear applications, since they do not considerably reduce multilayer hardness, or other mechanical properties, when compared to a monolithic hard coating.

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