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Effect of the crystallinity of diamond coatings on cemented carbide inserts on their cutting performance in milling

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ABSTRACT

Micro-crystalline diamond (MCD) coatings were deposited on cemented carbide inserts at different temperatures using hot filament chemical vapor deposition technique. For investigating the effect of the developed diamond crystallinity on the fatigue strength and wear behaviour of the prepared MCD coated inserts, inclined impact tests and milling investigations were conducted correspondingly. Raman spectra were recorded for capturing the crystalline phases after the film deposition and their potential changes after the impact and milling experiments induced by the mechanical and thermal loads. Thus, the explanation of the cutting performance of the employed diamond coated inserts with various crystalline phases was enabled.

1. Introduction

Micro-crystalline diamond coatings deposited on cemented carbide substrates can be effectively applied in machining of non-ferrous materials such as of aluminium alloys, carbon fibre reinforced plastics etc. [1–4]. Due to the superior adhesion characteristics of MCD coatings and to improved tribological properties of nano-crystalline diamond ones, various micro- and nano-crystalline layer coating systems on cemented carbide substrates are manufactured and used effectively in machining procedures [5–7]. The applied parameters during the hot filament chemical vapour deposition process such as of substrate temperature, total pressure etc. affect significantly the film growth and structure and in this way their properties [8].

This paper aims at investigating, for the first time, the effect of the resulting crystallinity of diamond coatings due to the applied deposition parameters on their fatigue strength at ambient and elevated temperature and wear behaviour in milling. In this context, two groups of micro-crystalline coatings were deposited on same cemented carbide substrates by varying the substrate temperature. Raman spectra were used to check the crystallinity of the deposited diamond coatings. For evaluating the fatigue strength of the produced coatings, inclined impact tests at 25 °C and 300 °C were carried out [9,10]. The prepared coated inserts were used in milling aluminium foam for assessing their cutting performance. Raman spectroscopy was also conducted on the remaining worn coating in the impact crater and on the tool rake within the chip contact area after milling. Via the detected crystallinity changes, it was possible to explain the different wear evolutions during the impact test and milling when using micro-crystalline coatings at various substrate temperatures deposited.

2. Experimental details

The applied cemented carbide inserts specifications are illustrated at the bottom of Fig. 1. These were coated with micro-crystalline diamond coatings via the hot filament method using a CC800/9Dia CEMECON coating machine. Hereupon, two insert's batches were manufactured at various substrate temperatures during the deposition process. In the first insert batch named as T1, the substrate temperature was adjusted at 900 °C. For preparing the second batch (T2), this temperature was slightly increased. The filament temperature amounted to approximately 2000 °C and the total pressure to 30 mbar. At a carbon to hydrogen ratio of 1%, and a gas flow of 2 l/min, the coating growth rate was around 0.5 μm/h. For the coating thickness of about 5 μm, the overall process time was equal to roughly 19 h.

The inclined impact test at various loads and temperatures up to 300 °C was used to check the fatigue strength of the prepared micro-crystalline diamond coatings. The applied device in the conducted investigations was constructed by the Laboratory for Machine Tools and Manufacturing Engineering of the Aristotle University of Thessaloniki in conjunction with CemeCon AG [9,10] (see Fig. 1a). High pressure air at a temperature equal to the test

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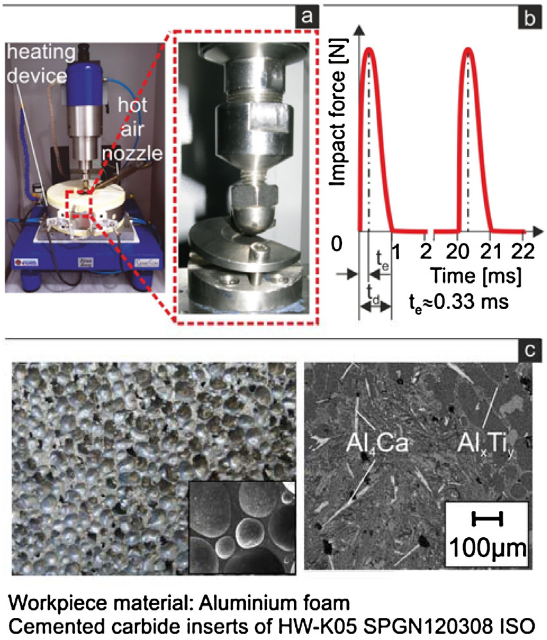

Fig. 1. (a) The mechanical unit of the employed impact tester; (b) characteristic data of the applied force signals; (c) the workpiece material used in milling experiments.

one was employed for removing potentially occurred ball indenter or coating debris. The time course of the applied impact load signal is illustrated in Fig. 1b. The developed impact imprints were evaluated through 3D measurements by the confocal micrscope µSURF of NANOFOCUS AG. The Raman spectroscopy on the untreated as well as treated diamond coatings were carried out using a LabRAM HR spectrometer. The milling investigations were conducted employing a three-axis numerically-controlled milling centre using aluminium foam as workpiece material. This workpiece material consists of various hard phases, as related optical microscopy observations using standard metallographic techniques revealed (see Fig. 1c). Moreover, due to the structure of the workpiece material, intense dynamic loads are developed on the cutting edge of the coated tools during cutting.

3. Characterization of the investigated diamond coatings

3.1. Crystallinity of the diamond coatings

For characterizing the crystallinity of the produced diamond coatings, Raman spectroscopy was performed. The recorded spectra are presented in Fig. 2. Both coated insert batches exhibit a narrow peak at around 1340 cm^{-1} confirming the high diamond crystalline quality of the coatings and the existence of a sp^3-bonded phase [11]. Two more peaks appear pronounced at roughly 1150 cm^{-1} and 1450 cm^{-1} in the Raman spectra of the T2 specimens. These extra features originate from co-existing sp^2-phases, called as trans polyacetylene. The latter is associated with the chemical elements of the applied gases during the film deposition [11]. The trans polyacetylene possesses obviously inferior strength properties compared to the sp^3-bonded phases. Moreover, since the developed maximum cutting temperatures during the conducted milling investigations are roughly equal to 300 °C [3], the prepared coated inserts were annealed at 300 °C for checking a potential effect of such a temperature on their crystallinity. Based on the results presented in Fig. 2, the Raman spectra remain invariable by a temperature increase up to 300 °C, i.e. no effect on the film crystallinity occurs. However, a decomposition of the sp^2-bonded trans polyacetylene phases may take place when repetitive thermal and mechanical loads both leading to elastic film deformations are simultaneously applied. This could happen for example during the impact test at elevated temperatures or a cutting procedure as well.

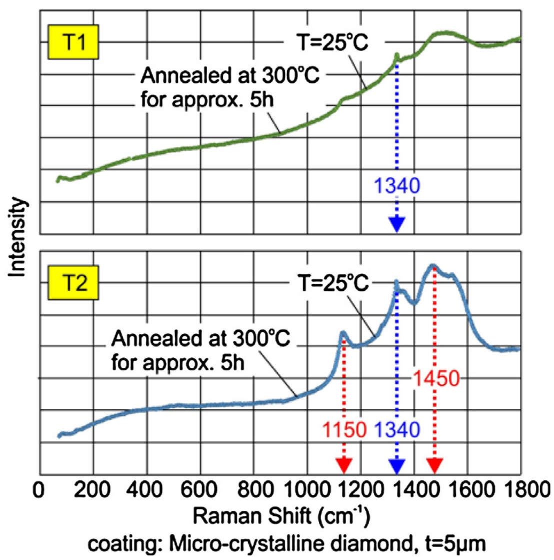

Fig. 2. Raman spectra of the investigated coatings.

3.2. Fatigue strength of the diamond coatings at room and elevated temperatures

The prepared MCD coatings were subjected to repetitive impacts at 25 °C and 300 °C using the inclined impact test. Characteristic imprints after 10^6 impacts generated on T2 coated inserts at 25 °C after various impact loads, are displayed in Fig. 3. These imprints were scanned by white light confocal microscopy and they depict the developed surface topomorphy after one million impacts at the related impact loads. All over the test duration, the impact force, the specimen temperature and further test parameters are recorded and controlled for avoiding a potential drift of the impact spot. In the case of an impact load of 900 N, no film damage can be observed. On the contrary, the impact load growth up to 1050 N leads to a total coating removal and substrate wear. Similar results arise in the case of T1 coated inserts. Consequently, the sp^2-bonded phase of the T2 coated inserts did not affect at ambient temperatures the film fatigue strength. The latter depends in both batch cases only on the impact load.

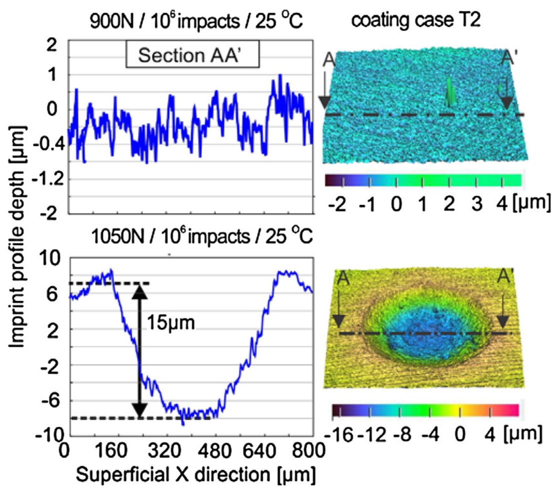

Fig. 3. Inclined impact test results after 10^6 impacts at 25 °C.

Fig. 4 demonstrates further impact craters formed at 300 °C and at an impact load of 150 N, after various numbers of impacts. These imprints were generated at adjacent coated surface locations, since the repositioning of the ball indenter after the conduct of a confocal microscopy scanning cannot be performed at an accuracy of few micrometers. The coating damage evolution versus the number of impacts is more intensive on the coated specimens of the T2 batch. Compared with this, in the case of T1 inserts, the

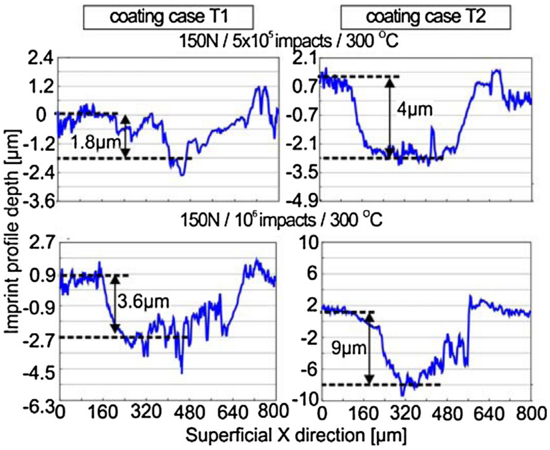

Fig. 4. Inclined impact test results at 300 °C and 150 N after various number of impacts in both investigated coating cases.

diamond coating withstands the repetitive impact loads after one million impacts without a film total removal. On the contrary, an extensive coating failure appears at the same load and number of impacts in the case of T2 coated inserts.

An overview of the developed imprint depths during the impact test at 25 °C and 300 °C is illustrated in Fig. 5. Although both coating batches exhibited the same fatigue strength at ambient temperature, the coating batch T1 shows a superior wear resistance against the repetitive impact loads at 300 °C compared to the T2 batch. Hereupon, the impact load at the 300 °C is significantly lower compared to that one at ambient temperature. Hence, the elevated temperature restricts the film fatigue strength. This restriction is more intensive, if as in the case of the T2 films, trans polyacetylene phases exist in the coating structure.

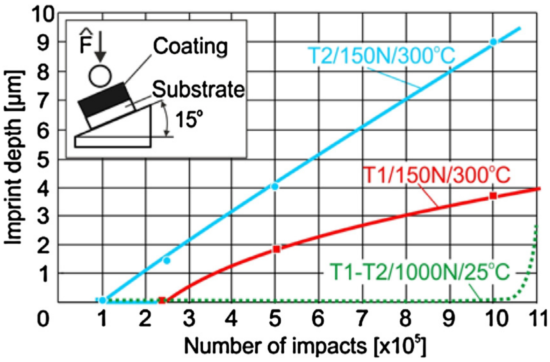

Fig. 5. An overview of the obtained impact test results at 25 °C and 300 °C for both coating cases.

For explaining the latter statement, Raman spectroscopy was conducted on the remaining worn coating in the impact imprint and on an undamaged area outside of the imprint for both film cases (see Fig. 6). On one hand, the Raman spectra of the T1 coated inserts are similar in both measurement positions A and B (see Fig. 6a). On the other hand, in the case of the T2 coating, in the imprint area at the measurement position D (see Fig. 6b), where thermal and impact loads are simultaneously exercised, the spectral peaks are considerably weaker compared to the corresponding ones outside the impact crater at the measurement position C. This fact reveals a decomposition of the sp^2-bonded trans polyacetylene phases indicated by the peaks at around 1150 cm^{-1} and 1450 cm^{-1} as well as of the nano sp^3-bonded phase of high crystallinity at roughly 1340 cm^{-1}. In this way, the film fatigue strength worsens.

4. Cutting performance of the diamond coated inserts in milling and explanation of the obtained results

The cutting performance of the manufactured diamond coated inserts was investigated in milling without coolant or lubricant for

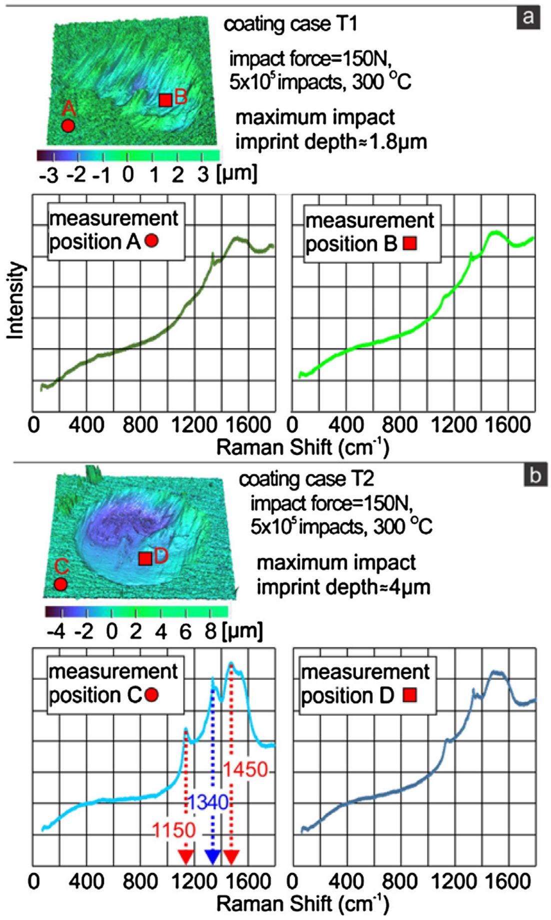

Fig. 6. Raman spectra on the coating in the impact imprint (positions B and D) and outside of it (positions A and C) in both coating cases.

attaining a more intense wear evolution. After a prescribed number of successive cuts, the cutting insert wear was recorded. In the case of the inserts batch T1, after approximately 12,500 cuts, a flank wear width of 0.15 mm ($NC_{0.15}$) developed (see Fig. 7). Compared with this, the wear behaviour of the coated inserts of the

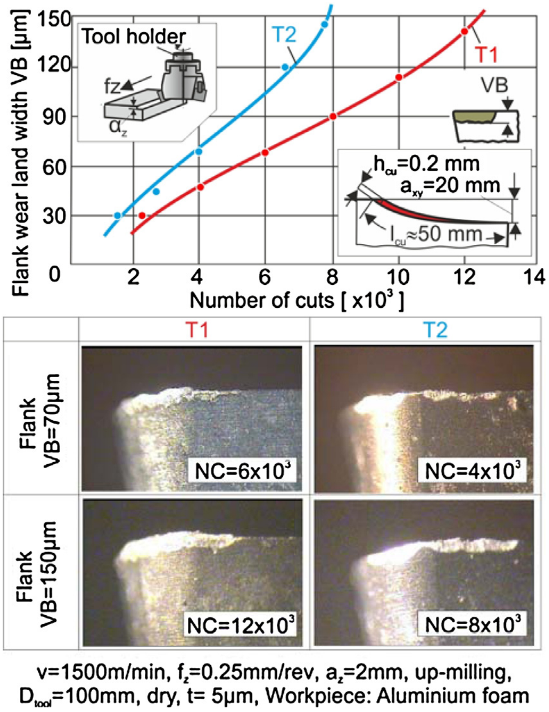

Fig. 7. Flank wear development versus the number of cuts of the investigated diamond coated inserts and their wear status after various number of cuts.

T2 batch deteriorates significantly, as it can be observed in the same figure. The latter coated inserts, up to the same flank wear width, cut only ~8000 times. Hereupon, flank wear widths of 70 μm and 150 μm appeared after the number of cuts, illustrated at the bottom part of Fig. 7. The obtained larger number of cuts when T1 inserts are used exhibit their superior wear resistance compared to the T2 ones.

In order to explain these results, Raman spectroscopy was conducted on the remaining coatings on the tool rake after milling (see Fig. 8). In this way, potential crystallinity changes of the diamond coatings due to the exercised thermal and mechanical loads could be captured. Practically, the same Raman patterns appeared in all examined diamond coated samples of the same batch before and after the impact tests as well as on the tool rake after milling. In the case of T2 coatings, the weaker spectral peaks in the diagram at the middle of Fig. 8 indicate a decomposition of the trans polyacetylene sp^2-bonded phases (peaks at around 1150 cm^{-1}) as well as of the nano sp^3-bonded phase of high crystallinity, when thermal and mechanical loads during milling are simultaneously applied. Consequently, a diamond coating strength weakening arises resulting in a more rapid wear evolution compared to T1 coatings during the cutting processes. Hence, the lack of a trans polyacetylene phase, by adjusting appropriately the deposition temperature, can lead to an improved MCD coated inserts cutting performance.

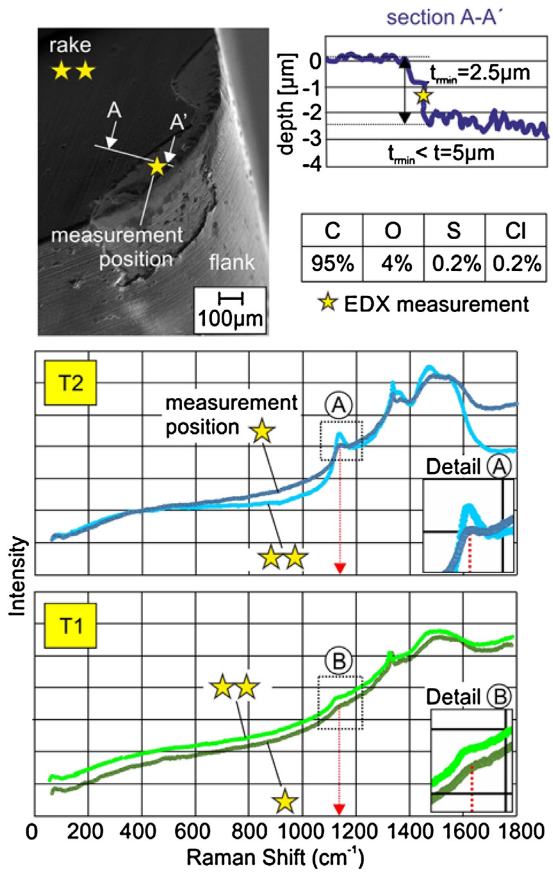

Fig. 8. Raman spectra of the rake and of the remaining coating after milling for both coating cases.

5. Conclusions

In this paper, the effect of the crystallinity of MCD coatings on their fatigue strength and wear behaviour in milling was presented. In this context, MCD coatings were deposited on the same cemented carbide inserts by varying the substrate temperature during the deposition process for attaining different film crystallinities. Based on the attained impact and milling results, when mechanical and thermal loads are simultaneously exercised, the decomposition of a sp^2 bonded trans polyacetylene phases, potentially existing in the diamond coating structure, leads to a more intense wear compared to a trans polyacetylene free MCD film. As a result, the fatigue strength and the cutting performance of the latter diamond coated inserts can be improved.

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