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Adhesive bonding and brazing of nanocrystalline diamond foil onto different substrate materials

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ABSTRACT

Diamond coatings are used in heavily stressed industrial applications to reduce friction and wear. Hot-filament chemical vapour deposition (HFCVD) is the favourable coating method, as it allows a coating of large surface areas with high homogeneity. Due to the high temperatures occurring in this CVD-process, the selection of substrate materials is limited. With the desire to coat light materials, steels and polymers a new approach has been developed. First, by using temperature-stable templates in the HFCVD and stripping off the diamond layer afterwards, a flexible, up to 150 μm thick and free standing nanocrystalline diamond foil (NCDF) can be produced. Afterwards, these NCDF can be applied on technical components through bonding and brazing, allowing any material as substrate. This two-step process offers the possibility to join a diamond layer on any desired surface. With a modified scratch test and Rockwell indentation testing the adhesion strength of NCDF on aluminium and steel is analysed. The results show that sufficient adhesion strength is reached both on steel and aluminium. The thermal stress in the substrates is very low and if failure occurs, cracks grow undercritically. Adhesion strength is even higher for the brazed samples, but here crack growth is critical, delaminating the diamond layer to some extent. In comparison to a sample directly coated with diamond, using a high-temperature CVD interlayer, the brazed as well as the adhesively bonded samples show very good performance, proving their competitiveness. A high support of the bonding layer could be identified as crucial, though in some cases a lower stiffness of the latter might be acceptable considering the possibility to completely avoid thermal stresses which occur during joining at higher temperatures.

1. Introduction

Due to the extreme hardness of crystalline diamond it is suitable for the use on tools for machining high strength materials, prolonging tool lifetime [1]. Furthermore thin diamond layers are used in industrial applications to reduce wear and friction, e.g. on sliding rings. The high temperatures of more than 700 °C, which occur during the hot-filament chemical vapour deposition (HFCVD) of diamond, limit the selection of substrate materials for diamond coating. Only ceramics like SiC or selected metals which are able to form stable carbides are suitable as substrate materials. Nevertheless there is a desire to coat light materials, steels or polymers with diamond to broaden the spectrum of diamond applications. By using temperature-stable templates in the HFCVD process and stripping-off the diamond layer afterwards, free standing diamond foil can be produced (Fig. 1). These flexible, up to 150 μm thick, self-supporting nanocrystalline diamond foils (NCDF) have high hardness of more than 80 GPa and outstanding mechanical strength [2]. These novel NCDF must not be confused with freestanding microcrystalline diamond films grown by Microwave Plasma CVD for application as e.g. optical windows [3]. In contrast to single- or polycrystalline diamond NCDF shows low thermal conductivity of less than 10 W/m K [4] due to a high degree of phonon scattering at the numerous grain boundaries. By applying NCDF on technical components by common joining techniques, any material becomes coatable with diamond. In this paper adhesive bonding and brazing are tested in terms of adhesion strength. For testing the bonded or brazed samples, a modified scratch test and the Rockwell indentation test is used.

2. Methods for testing adhesion strength

2.1. Rockwell indentation test

The Rockwell indentation method for testing the adhesion strength equates to the Rockwell hardness test, which is described in DIN EN ISO 6508-1 [5]. A diamond cone indenter penetrates the testing material under a known load. By measuring the depth of penetration, hardness can be calculated. In case of using a coated substrate the indentation damages the coating in the immediate

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Fig. 1. Photograph of self-supporting nanocrystalline diamond foil building a "house of cards".

vicinity. The defect pattern in form of cracks, delamination and a combination of both is classified via six different adhesion strength classes ("HF classes") [6]. An overview of the classification is presented in Fig. 2. The delaminated areas, which occur in HF classes 3–6 only, are the starting point for further failure. Only indentations which can be classified as HF 1 or HF 2 are acceptable for adhesive bonding or brazing NCDF on substrates. The results of the Rockwell indentation test must be considered critically and differences between the acceptable classes must be additionally analysed by other test methods like scratch testing – which also allows a quantification of adhesion strength. The testing method is very well suited for a first evaluation of the bonding quality, for quantification other test methods have to be used.

2.2. Scratch test

A widely used method for testing the adhesion of coatings is the scratch test, which is standardized after DIN EN 1071 part 3 [7]. As the common use of a diamond tip leads to heavy wear on the latter, a modified scratch test has been used in this work to determine the bonding strength of the NCDF–substrate-composites [8]. As shown in Fig. 3, 100Cr6 bearing balls are used as indenter. They are replaced after each scratch to guarantee constant geometrical relations. The scratch test is performed by moving the sample underneath the indenter with a constant speed while the normal

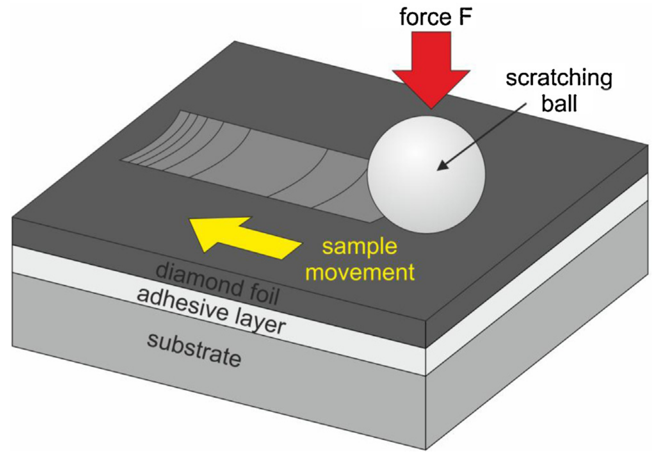

Fig. 3. Modified scratch test using a ball indenter with increasing force F on a composite out of NCDF, adhesive and substrate [7].

force F is increased constantly. After reaching the maximum load, the scratch track is analysed with a light microscope. From the distance between the first occurring crack to the starting point, the critical load F_c can be derived. The diameter of the indenting ball determines the level of stress in the sample. According to Hertzian Laws, a smaller ball induces a higher stress [9]. Nevertheless a finer resolution of the critical force is possible with a bigger ball, as the slope of stress increase is smaller. Hence two different sized balls were used here. The bigger ball with a diameter of 3.969 mm was used for samples with low adhesion strength. The smaller ball with a diameter of 2.778 mm was used in cases where the maximum critical load of the testing machine (200 N) was too low for sample failure with the bigger ball.

Obviously, critical load cannot be compared directly when two different sized balls are used. Therefore a normalized utility value is introduced to describe the adhesion strength. It is defined by the critical load and the ball diameter, delivering a critical stress σ_c according to Hertzian Laws (see Eq. (1), where E^* equals the reduced elastic modulus of the system and R the ball radius).

$$\sigma_c = \frac{0.62}{\pi} \cdot \sqrt[3]{\frac{6F_cE^{*2}}{R^2}} \quad (1)$$

We are well aware that we apply a theory, which is based on several assumptions, we cannot fulfil in this case. First, in our case a 3-component system (substrate–joining layer–NCDF) rather than a Hertzian two component system is investigated. Furthermore we have not performed a detailed analysis of stress distribution in the system and do not consider friction and plastic deformation. Nevertheless results show, that the critical stresses, which are derived from scratch tests with two different sized balls on one sample are well in accordance (deviation below 5%). In addition we normalize

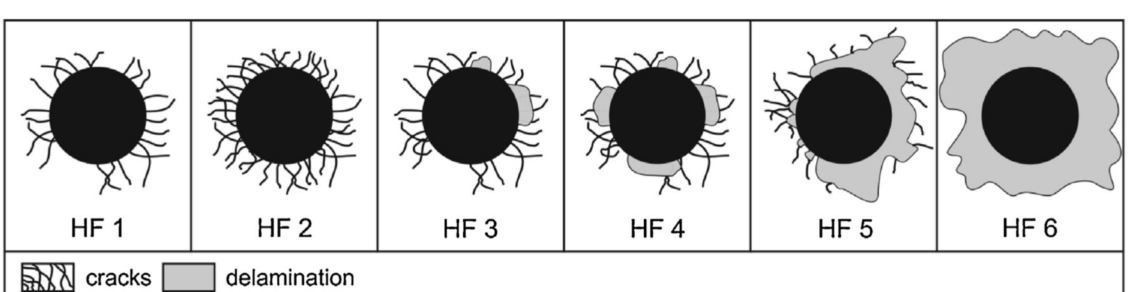

Fig. 2. Six classes of adhesion strength based on typical indentation results, according to [5]. Cracks in the immediate vicinity only are acceptable (HF 1–2). Delamination of NCDF is a sign of low adhesion strength between the bonding and the NCDF (HF 3–6).