Study of the Effect of Substrate on 3D Surface Roughness in Diamond-Like-Carbon Coating Process

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Abstract: This paper presents an experimental platform which is used to study the effect of DLC coating on surface roughness. Variety of experiments is conducted and the effect of variation of the coating process parameters and type and combination of sub layers on the surface roughness of the coated part is discussed.

Keywords: Surface texture, Diamond-Like-Carbon Coating, DLC, Surface Roughness, 3D Surface Metrology

1. INTRODUCTION

Diamond like carbon (DLC) is a thin film made from amorphous carbon with high concentration of sp3 carbon bonds. This type of coating has many applications due to its surface properties such as low coefficient of friction and roughness, high hardness and chemical inertness produced in manufactured parts. Various types of DLC coatings exist that are created by different methods and materials in order to achieve different tribological properties. These types include amorphous carbon (a-C), hydrogenated amorphous carbon (a-C:H), amorphous carbon nitride (a-C:N), fluorinated amorphous carbon (a-C:F), tetrahedral amorphous carbon (ta-C), hydrogenated tetrahedral amorphous carbon (ta-C:H) and some other more specialized varieties and alloys. These films are usually made by deposition of highly energetic ions onto the surface of a work piece. Some deposition methods are magnetron sputtering, chemical vapour deposition (CVD), physical vapour deposition (PVD), dielectric barrier discharge(DBD), and pulsed cathodic arc discharge (PCAD).

The specimens used in this research were prepared by physical vapour deposition using ion beam technology. Ti, TiN and TiCN sub-layers were created using magnetron sputtering and then the specimens were coated with DLC by using an ion beam and acetylene gas. Creation of sub-layers is also possible by using chromium (Cr) or titanium aluminum alloy (TiAl). A schematic of the process and some controls can be seen in figure 1. Firstly, a vacuum is created in the chamber by opening lock 1 only with the use of for vacuum and mechanical pump. In the meantime, diffusion pump is also activated. In order to speed this process, lock 2 can be opened and closed. Once the pressures equalize, lock 1 is closed and lock 2 and 3 open to use all three pumps to create a good vacuum. After this, argon cleaning is done on the specimens by supplying argon gas through the ion beam to clean any unwanted particles. Next, a thin titanium coating is done by magnetron sputtering, followed by TiN coating with inclusion of nitrogen gas and TiCN with inclusion of acetylene. Once the sub layers are done, acetylene gas is supplied from the ion beam for DLC coating. Simply, carbon atoms in acetylene gas are ionized by the ion beam and then they are accelerated towards the specimen in a vacuum by a magnetic field. When these ionized carbon atoms hit the surface of the specimen, they form sp3 and sp2 bonds on the surface. Due to the hydrogen content in acetylene gas, some hydrogen atoms also hit the surface and create bonds. In order to minimize the amount of weak hydrogen to carbon bonds, acetylene gas is used as it has lowest possible carbon to hydrogen ratio. Gavrilov et al. (2010) also stated that acetylene is most suitable choice for DLC deposition.

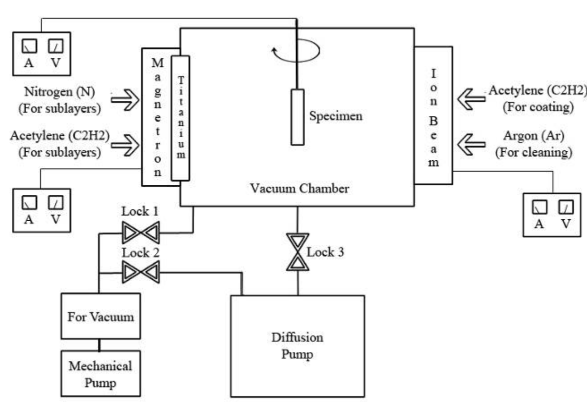

Fig. 1. Schematic of the coating apparatus.

DLC coating has many properties that can be used for different applications; however, the main focus of this paper is the effect of DLC coating on the surface roughness of workpiece. There is a big industrial demand for improving surface roughness on a wide variety of parts and components. For cutting, milling and punching tools that are used for cutting aluminium alloys, graphite, printed circuit boards (PCB), and plastics or punching through steel sheets DLC coating increases hardness and wear resistance. This results in improving tools' life for up to 20 times longer. Longer tool life result is desired for the manufacturing processes due to saving in tool cost and the required tool set up times. Also, DLC decreases coefficient of friction of the coated surface by decreasing roughness on the cutting tools, requiring less lubricant fluid and lower operation temperatures. Due to this property the quality of the machined surface is also increased. For cold rolling tools, many common problems such as galling on mating surfaces, rolled-in scale, mill-sharing, scrabs and slivers are eliminated, resulting in better quality of end product. The maintenance interval is also increased 4 to 5 times, reducing costs. DLC is also highly suitable for the flow control devices, check and stop valves used in oil and gas industries. By reduced roughness and coefficient of friction, mating parts have trouble-free operations, without the problem of adhesion of mating parts. Also DLC creates corrosion and chemical resistance due to inert surfaces. For dies, molds and extruders that are coated with DLC, due to low friction and roughness, molds operate smoothly with no jamming and also parts get released from molds and dies more easily. DLC coating also increases the life of the molds, dies and extruders. For the automotive industry, use of DLC makes it possible to have higher efficiency, reduced maintenance and therefore, reduced energy and power demand. Camshafts, crankshafts, pistons, valves, differential and gear box components can all be coated. DLC is also applicable to any mechanical part such as shafts, bearings, bushings where it can raise efficiency, allow simplified designs and improve wear resistance. Figure 2 demonstrates some typical mechanical parts coated by DLC process.

Fig. 2. Some DLC coated parts and tools.

The goal of this research is to understand how DLC coating can affect the 3D surface roughness of the coated surface. Using an experimental approach and actual measurement of the resulting surface effect of DLC coating parameters and the employed sub-layers on the three-dimensional surface roughness parameters is studied.

2. LITERATURE REVIEW

Significant research has been conducted to study the effect of DLC coating on the tribological properties of parts and tools. There are two types of studies regarding the roughness of DLC coated parts, one type focuses on the effect of DLC coating and sub-layers on roughness of the part's surfaces, and the other type focuses on the effect of roughness on the properties related to the use of the part.

In terms of effect of DLC on surface roughness, Sui et al. (2006) stated that DLC coating decreases roughness of NiTi alloy. Saha et al. (2011) showed that nitrogen flow-rate increases roughness on Si:DLC:N parts. Liu et al. (2003) also demonstrated the same concept. Salvadori et al. (2006) showed that increasing DLC thickness first creates a slight increase in roughness and then starts to decrease it as the coating gets thicker. This is explained in their paper by the fact that DLC coating first starts to build up around the sharp edges due to the intensity of their magnetic fields and as the coating gets thicker, the gaps also start to fill up and that is when the roughness starts to decrease. Huang et al. (2004) also showed the same concept of decreasing surface roughness with increased coating thickness. Liu et al. (2006) showed that increasing the bias voltage results in decreasing of surface roughness.

In terms of effect on roughness on the properties of the part, Park et al. (2005) stated that increasing roughness results in decreased environmental reaction. Huang et al. (2004) showed that decreased surface roughness resulted in increased scratch resistance.

3. EXPERIMENTAL PLATFORM

There are many commercially available methods for measuring surface roughness. They can generally be divided into two categories of contact and non-contact methods. An example for contact method is the mechanical stylus method which has a resolution typically between 2 to 5 µm. (Xu and Hu, 2009). Due to some disadvantages of the Contact methods the non-contact methods have been developed and significantly improved in recent years. Some examples include atomic force microscopy (AFM), interference microscopy, vertical scanning interferometry, Confocal microscopy, and scattering modelling (Xu and Hu, 2009). In this research, a non-contact method is used by implementing a microscope with camera and sensor provided by PhaseView™. The developed software was used for taking stacked images from the surface and for combining them to create 3D images and data of the surface. By using this data, it will be easy to calculate the required 3D roughness surface parameters as described in Table 1 based on the Geometrical product specifications (GPS) provided in ISO 25178-2:2012 standard (ISO 25178-2, 2012). The resolution of the system was 0.091 µm which. A total of 20 measurements were done on each specimen of which 10 were taken before coating and 10 were taken after applying coating on the surface of the parts. A stratified-random sampling approach was used for sampling (Barari et al. 2007). The measurement points were selected randomly from the stratified regions of the surface. All surface roughness parameters including the average 3D surface roughness values (*Sa*) explained in Table 1 are calculated. Various specimens were used with different initial surface finishes to observe the effects of DLC. Three 3D images of surfaces with relatively low, average and high surface roughness can be seen in Figures 3 through 5 as examples of the observations.

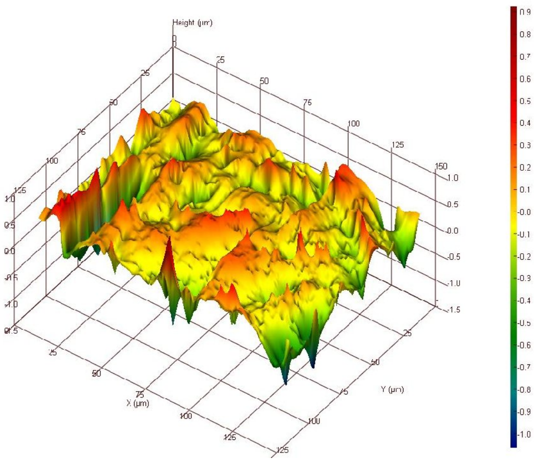

Fig. 3. Example of a surface with relatively low surface roughness. (0.141 µm)

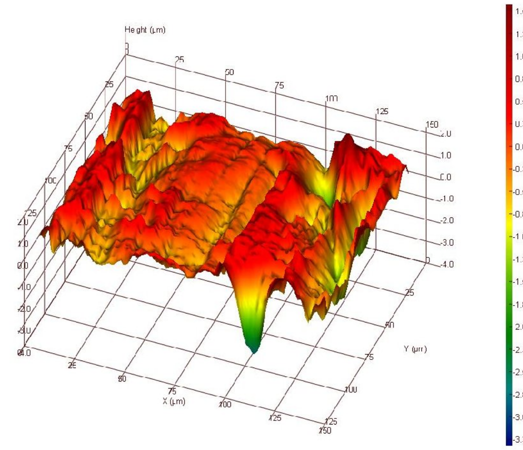

Fig. 4. Example of a surface with relatively average surface roughness. (0.335 µm)

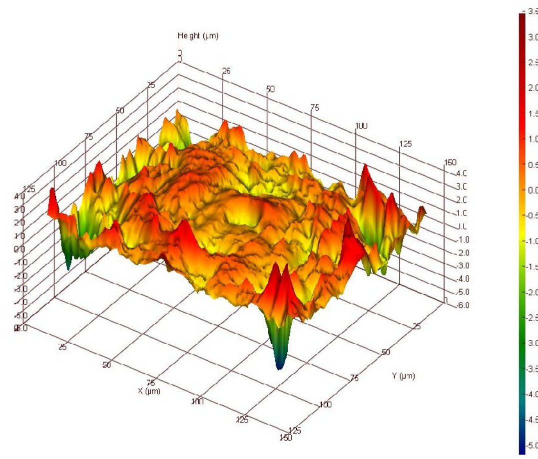

Fig. 5. Example of a surface with relatively high surface roughness. (0.552 µm)

Table 1. 3D Surface roughness parameters

Parameters	Name	Definition	Comments
Sa	Average Roughness	$S_a = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}\lvert z_{mn} - \bar{z}\rvert$	Average distance to mean
Sq	Root-mean-square roughness	$S_q = \sqrt{\frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}(z_{mn} - \bar{z})^2}$	Standard deviation of the surface
Ssk	Skewness	$S_{sk} = \frac{1}{MNS_q^3}\sum_{m=1}^{M}\sum_{n=1}^{N}(z_{mn} - \bar{z})^3$	Asymetry of the height distribution. Rsk<0 for a surface with holes, Rsk>0 for a surface with peaks.
Sku	Kurtosis	$S_{ku} = \frac{1}{MNS_q^4}\sum_{m=1}^{M}\sum_{n=1}^{N}(z_{mn} - \bar{z})^4$	Width of the height distribution. Rku=3.0 corresponds to Gaussian distribution
Sv	Valley depth	$S_v = \lvert\min(z_{mn})\rvert$	Depth of deepest valley
Sp	Peak height	$S_p = \lvert\max(z_{mn})\rvert$	Height of highest peak
St	Total roughness	$S_t = S_v + S_p$	Distance from the deepest valley to the highest peak, evaluated over entire surface

Sz	Averaged total roughness	$S_z = (S_v + S_p)_{eval.surf}$	Distance from the deepest valley to the highest peak evaluated over base surface and averaged

4. RESULTS

The results of measurements and the calculated 3D roughness parameters are listed in Table 2. Sequential coating of first Ti, then TiN, then TiCN, and finally DLC was applied on all the specimens that were tested. A total of 7 samples were analyzed. The 7th sample was selected to have two kinds of geometries, one flat and one round, with different uncoated surface roughness values, in order to see the effect of initial surface roughness on the final surface. Sample 1 was only coated with TiN sub-layers for studying the effect of nitrogen content on roughness.

Samples 2 and 3 were coated until the 3rd sub-layer, which is TiCN, to see how the carbon content affects roughness. Samples 4 through 7 were all coated with DLC. As can be seen in Table 2, it is possible to obtain all the 3D surface roughness parameters with this measuring method. For the scope of this study, only the average 3D surface roughness (*Sa*) was compared between the samples. The reason for not using the other parameters is to avoid the effect of some impurities on the surface from the machining process, such as some local holes on the original surface. For example if the total roughness (*St*) value was used, the holes that are not produced by the DLC process were going to increase the calculated roughness of a coated surface. Using the average roughness minimizes this effect. In order to have a better comparison of the observations, the 10 *Sa* values were averaged as the major roughness indicating value for coated or uncoated analysis of each sample. The results can be seen in the graph presented in Figure 6. The grey columns represent the uncoated surfaces, sample one (yellow column) represents TiN coating, Samples 2 and 3 (purple columns) represent TiCN coating, and the rest of samples (black columns) represent DLC coating.

Table 2. Experimental Data

		Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7 (Flat)**	**Sample 7 (Round)**
3D roughness parameters before coating	Sa (µm)	0.2729	0.4875	0.3834	0.384	0.3845	0.4223	0.2939	0.3688
	Sq (µm)	0.3844	0.6965	0.5345	0.5396	0.5704	0.5826	0.4645	0.5513
	Ssk	-0.9125	-0.59923	-0.8694	-0.49116	-0.5569	-0.29615	-1.478	-0.15821
	Sku	9.082	7.854	7.319	9.591	12.142	7.143	21.266	12.595
	Sv (µm)	-2.999	-4.182	-3.669	-3.987	-4.702	-3.875	-4.936	-4.412
	Sp (µm)	2.533	3.765	2.995	3.728	4.106	3.47	3.635	4.795
	St (µm)	5.532	7.949	6.666	7.718	8.807	7.347	8.571	9.206
	Sz (µm)	1.805	2.689	2.393	2.409	2.596	2.814	1.8512	3.001
	Sds (summits /mm2)	32375.43	35938.66	32265.57	19550.88	25558.64	30675.48	23275.24	13504.22
	Sdr (%)	1.1195	2.762	2.115	2.167	2.179	2.985	1.3098	0.69725
	Sci	1.009	1.052	1.05517	0.75787	1.0766	1.19862	0.5271	1.11213
3D roughness parameters after coating	Sa (µm)	0.3448	0.3619	0.2434	0.3433	0.2739	0.2578	0.1835	0.1609
	Sq (µm)	0.4816	0.4876	0.3291	0.4836	0.3772	0.3679	0.2871	0.2204
	Ssk	-0.8513	-0.2346	-0.57915	-0.55309	-0.52677	-1.0984	-0.7872	-0.7551
	Sku	6.736	4.849	5.496	7.133	5.984	10.826	14.441	6.441
	Sv (µm)	-3.062	-2.481	-1.813	-3.168	-2.0999	-2.9	-2.774	-1.5637
	Sp (µm)	2.112	2.312	1.389	2.592	1.7575	1.975	2.307	1.1609
	St (µm)	5.175	4.792	3.202	5.763	3.858	4.874	5.076	2.724
	Sz (µm)	2.017	2.065	1.354	2.237	1.5821	1.724	1.773	1.0915
	Sds (summits /mm2)	31900.28	41393.95	27231.28	19091.84	26391.56	21927.05	3701.605	15986.47
	Sdr (%)	1.5186	1.939	0.635	1.747	1.072	1.041	0.203784	0.4388
	Sci	1.075	1.1097	1.318	1.298	1.205	0.8927	0.687	1.071

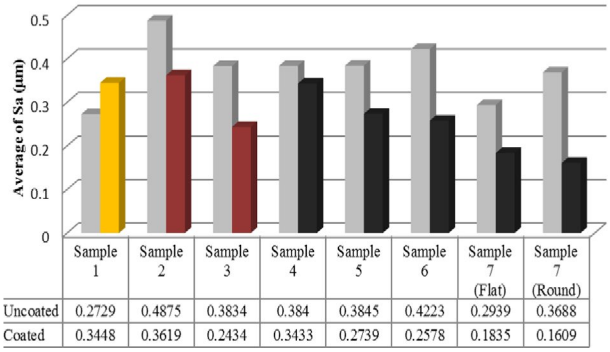

Fig. 6. 3D average surface roughness values of samples. The grey columns represent the uncoated surfaces, sample one represents TiN coating, Samples 2 and 3 represent TiCN coating, and the rest of samples represent DLC coating.

The change in surface roughness values of each sample are summarized in Table 3. Estimation of the coating thickness, including sub-layers and DLC coating are also shown, in order to see the effect of thickness of the coatings on roughness. The coating thickness is estimated by considering the growth rate of the coating based on the process parameters and the actual measured coating time.

Table 3: Coating time and change in roughness

Sample	Total coating thickness (µm)	Percent change in average roughness (Sa)
1	0.5	26.3% increase
2	0.5	25.8% decrease
3	0.5	36.5% decrease
4	0.8	10.6% decrease
5	1.2	37.1% decrease
6	1.2	39% decrease
7 (Flat)	2	37.57% decrease
7 (Round)	2	56.4% decrease

5. DISCUSSION

In the light of the results that were presented in the previous section, it can be stated that DLC coating reduces the roughness of a surface by 30% in average. By looking at the results, the main criteria for the amount of reduction in roughness is found to be the thickness of the DLC coating, or similarly, the time that DLC coating is applied on the specimen. It can be seen in Table 3 that when the estimated DLC thickness is only 0.8 µm, only 10.6% decrease in roughness observed; whereas with an estimated DLC coating thickness of 2 µm, the reduction reached 56.4%. This proved the studies that have been done before by Salvadori et al. (2006) and Huang et al. (2004) on the relation with DLC and roughness with different roughness measurement methods.

Apart from the effect of DLC coating on roughness of the surface, the sub-layers were also found do have effect on the properties of the final surface. Sample 1, which was coated with only TiN sub-layer, although, creates good adhesion for the following carbon atoms, showed a 26.3% increase in roughness compared to the original part. However, samples 2 and 3 that which were coated with TiCN had 25.8% and 36.5% decrease on roughness respectively. This showed that the nitrogen content in the coating resulted in a rougher surface, but when carbon content starts to increase, the roughness started to decrease. This proved the studies done by Saha et al. (2011) and Liu et al. (2003) on different types of metals and with different coating methods and surface roughness measurement methods. This also demonstrates that no matter what coating method is used, nitrogen content increases surface roughness.

The last discussion of this study is the effect of the original surface roughness on the final roughness properties. Sample 7 was the best example for showing this effect. This sample, as discussed in the earlier sections, had two different types of surfaces, one flat surface and one round surface, with different initial roughness values. The flat surface had an uncoated roughness of 0.2939 µm and after coating, this value decreased to 0.1835 µm. On the other hand, the round surface had an uncoated surface roughness of 0.3688 µm which decreased to 0.1609 µm after the coating process. This change is visualized in figure 7. As can be seen from the figure, even though the uncoated roughness values are different, the coated roughness values are approximately the same. The slight difference is found to be caused by the different rate of roughness change on surfaces with different roughness values. This showed that with a coating that is thick enough, approximately same surface roughness can be obtained in parts with different uncoated surface roughness values. Based on this observation, it can be concluded that if a part is going to be coated with DLC, in order to reduce manufacturing costs and time, some finishing processes such as grinding and polishing can be reduced or even eliminated.

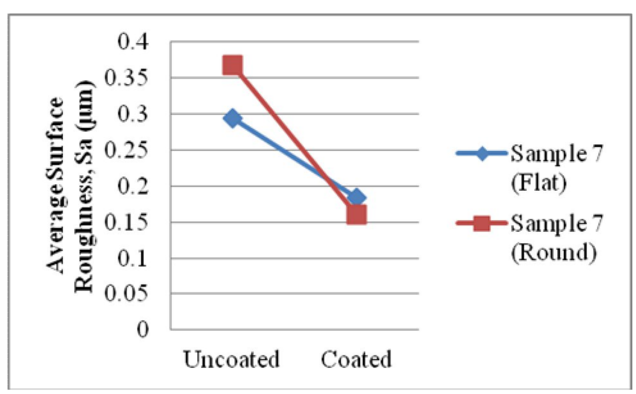

Fig. 7. Reduction in surface roughness of sample 7 with different uncoated surface roughness values.

6. CONCLUSION

Several important conclusions can be made based on the findings of this study. It is shown than a DLC coating decrease the surface roughness and the amount of surface roughness reduction has a direct relationship with the thickness of the coating. Also it is seen that the nitrogen content in the sub-layer coating increases the surface roughness, but is a crucial sub-layer for the strong adhesion of the DLC coating. Another important observation is, no matter what the uncoated surface roughness is, with a thick enough DLC coating, the coated surface roughness values can be approximately the same. This means that expensive and time consuming manufacturing processes for surface finishing such as grinding and polishing can be reduced or even eliminated if the part will go through appropriate DLC coating.

7. ACKNOWLEDGEMENTS

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