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# Effect of Grinding Parameters on the Fracture Toughness of WC–10Co–4Cr Coating Deposited by HVOF

**M. Sadat Zoei[1*], M. H. Sadeghi[2], M. Salehi[3]**

1. Institute of Materials and Energy, Iranian Space Research Center, P.O. Box: 81955-174, Isfahan, Iran
2. Department of Mechanical Engineering, Tarbiat Modares University, P.O. Box: 14115-363, Tehran, Iran
3. Department of Material Engineering, Isfahan University of Technology, P.O. Box: 84154-83111, Isfahan, Iran

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## ABSTRACT

*Nowadays, application of cermet coatings deposited by High-Velocity Oxygen-Fuel (HVOF) has received considerable attention in a variety of industries. Carbide coatings have high surface roughness, so it is essential to grind the coated surface. The present investigation studied the effect of simultaneous changes in the grinding parameters including the depth of cut, feed rate and cutting speed on the fracture toughness of the WC-10Co-4Cr coating sprayed by HVOF. The fracture toughness was measured using the Vickers Indentation Test on the cross-sectional surface of the coating. A full factorial design of experiment was selected for experimental planning and the analysis of variance was employed to find the effect value of grinding parameters on output. The results revealed that the fracture toughness of the WC-10Co-4Cr coating increases after grinding due to the higher compressive residual stresses. The fracture toughness of coating increases with the decrease of the cutting speed and the increase of the depth of cut and feed rate. The most effective grinding parameters are depth of cut, feed rate and cutting speed, respectively. At the end of the current study, a mathematical model between grinding parameters and the fracture toughness of the coating was proposed using the regression analysis. Prog. Color Colorants Coat. 12 (2019), 231-239© Institute for Color Science and Technology.*

## 1. Introduction

Application of thermal spray coatings is extremely increased to improve wear resistance, corrosion resistance, etc. [1]. In the High-Velocity Oxygen-Fuel (HVOF) process, the coatings have low porosity and high adhesion strength as a result of the low temperature and high velocity of the particles [2, 3]. Carbide coatings deposited by the HVOF are an appropriate substitute for hard-chromium coatings that are not favorable due to their toxic production process [4, 5]. One of these carbide coatings deposited by HVOF is WC-10Co-4Cr coating. In most applications, the surface of these coatings should be ground to achieve the permissible roughness value [6, 7]. The grinding process may have effect on the final properties of the coating. Hence, it is essential to investigate the effect of grinding process on the final characteristics of the coatings. The fracture toughness of the coating may have effect on the properties of the coating such as wear resistance. In the thermal spray coatings, wear begins and develops by the fracture of the material. Therefore, the fracture toughness can be a measure for the coatings strength [5].

There are some investigations on the effect of

*Corresponding author: m.zoei@modares.ac.ir

grinding process on the final properties of the carbide coatings. Liu et al. [8-10] studied the influence of grinding parameters on the grinding forces, surface roughness, depth of subsurface, surface defects, and residual stress of n-WC/12Co coating deposited by HVOF method. Maiti et al. [11] investigated the wear resistance, hardness, and residual stress of the WC-CoCr ground coating at different grinding depths (100, 200, and 300 µm). Murthy et al. [6] studied the erosion resistance of the as-sprayed and as-ground carbide coating. Masoumi et al. [12, 13] determined the porosity, the grinding forces, material removal mechanism, residual stress, adhesion strength, and micro hardness of WC-CoCr coating after grinding process. Zoei et al. [14] studied the influence of grinding parameters on the residual stress and wear resistance of WC–10Co–4Cr coating sprayed by HVOF.

To date, the influence of simultaneous changes in the grinding parameters on the fracture toughness of carbide coatings by HVOF (or other coatings) has not been reported. This study evaluated the effect of the grinding parameters such as cutting speed, feed rate, and depth of cut on the fracture toughness of HVOF-deposited WC–10Co–4Cr coating by a full factorial design of experiment (DOE) and an analysis of variance (ANOVA).

## 2. Experimental Methods and Materials

### 2.1. HVOF thermal spraying

In this work, the substrate was AISI 1010 steel plates with dimensions of 20×20×4 $mm^3$. Before HVOF process, specimens were sand blasted with SiC particles to increase the binding force between the coating and the substrate. WC–10Co–4Cr powder (WOKA 3652) with a grit size of 15 to 45 µm was used as the coating material. The coating spraying was performed using the MetjetIII system (Metallization, UK). Table 1 shows the parameters of the HVOF thermal spraying.

### 2.2. Grinding process

The coated samples were ground using the surface grinding machine (Industrial Machine Tool, Inc., USA). The grinding wheel was a diamond abrasive with a resin bond. Table 2 shows the specifications of the grinding wheel.

**Table 1:** HVOF thermal spraying parameters.

| Spray parameters | Value |
|---|---|
| Spray distance(cm) | 34.5 |
| Combustion chamber pressure(MPa) | 0.7 |
| Powder feed rate(g/min) | 55 |
| Fuel flow rate(mL/min) | 270 |
| Oxygen($O_2$) flow rate(slpm) | 830 |
| Carrier gas($N_2$) flow rate(L/min) | 5 |

**Table 2**: Specifications of the grinding wheel.

| Parameters | Value |
|---|---|
| Average grain size(µm) | 75 |
| Grade | R |
| Concentration number | 75 |
| Outside diameter(mm) | 350 |
| Width(mm) | 15 |
| Diamond thickness(mm) | 5 |

## 2.3. Design of experiments

A full factorial design of experiment was employed to investigate the influence of simultaneous changes in three grinding parameters, i.e. cutting speed ($v_c$), feed rate ($v_w$), and depth of cut ($a_p$), on the fracture toughness of the coating. For each grinding parameters, three levels were selected as shown in Table 3. Therefore, the number of experiments in the full factorial design of experiment was $3^3$ (=27), using Minitab 17 software. The levels of grinding parameters were selected based on the previous investigations, limits of grinding parameters on the target grinding machine, and a limited number of primary experiments.

## 2.4. Determination of coating fracture toughness

There are various techniques to measure fracture toughness of bulk materials, but all of them are not appropriate for coatings. The Vickers indentation technique is appropriate to determine the fracture toughness of brittle materials such as thermally sprayed coatings [15-18]. In this study, the fracture toughness of the coating, Kc, as an indication of coating cohesive property, was determined by Vickers indentation test on the cross-sectional surface of the coating [19, 20]. In the indentation test, the Vickers indenter is applied with different loads on the polished cross-section to create a semi-circular crack along the width of the indentation, as shown in Figure 1. Afterwards, the length of the crack (a) is measured by optical microscopy for each indentation test.

There are different equations to display the relation between the fracture toughness and the length of the cracks. In this investigation, the fracture toughness was determined with Evans and Charles model based on the material of coating [21]:

$$K_c = 0.016 \frac{p}{a^{3/2}} \left( \frac{E}{H} \right)^{1/2} \quad (1)$$

Which P is the applied load, a is the crack length within the coating, E is the modulus of elasticity of the coating and H is the coating hardness.

In this study, Vickers indentation test was performed on Dia Tester hardness testing machine (type 2RC-S, Wolpert Company) with loads varying from 3 to 40 kg. For each force, the experiment was repeated five times and the mean value was considered. The modulus of elasticity of the WC-10Co-4Cr coating was 310 GPa [15].

**Table 3:** Grinding parameters and levels.

| Parameters | Unit | Levels | | |
|---|---|---|---|---|
| | | Level 1 | Level 2 | Level 3 |
| Depth of cut($a_p$) | µm | 4 | 10 | 16 |
| Feedrate($v_w$) | mm/s | 273 | 413 | 550 |
| Cutting speed($v_c$) | m/s | 25 | 30 | 35 |

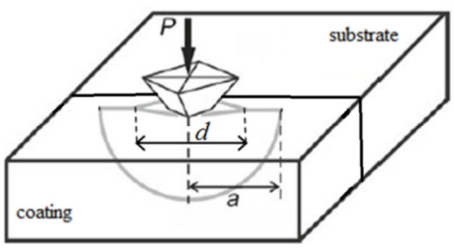


**Figure 1:** Schematic illustration of the Vickers indentation impressions on the cross-sectional surface of the coating: d, indent diagonal at the coating; a, the value of crack length at the coating [20].

## 3. Results and Discussion

The 27 grinding experiments were carried out to estimate the effect of the grinding parameters on the fracture toughness of the WC–10Co–4Cr coating deposited by HVOF. Figure 2 shows an optical microscopy image of crack formation within the coating from Vickers indentation test.

Table 4 illustrates the DOE matrix and the measured results of the experiments. Figure 3 compares the measured fracture toughness of as-sprayed and as-ground coatings, in which the coating fracture toughness of the ground coating is the mean value of all the specimens prepared with different grinding parameters.

The results show that the fracture toughness values improved after grinding. This may be caused by the influence of the grinding on the residual stress. In fact, compressive residual stresses prevent the creation and propagation of cracks [22-24]. Moreover, compressive residual stresses reduce interatomic spacing and increase the required forces for breaking the atomic bonds (fracture toughness of the coating) [25].

It was shown in our previous study [14] that the residual stress in the as-sprayed WC-10Co-4Cr coating is compressive and the grinding process increases this compressive residual stress, enhancing the fracture toughness of the coating.

Analysis of variance (ANOVA) using Minitab 17 software was utilized to identify the significance of the main and interaction effects of grinding parameters. Table 5 shows the ANOVA results for the fracture toughness of the coating. Analysis of variance was performed to a confidence level of 95%, i.e. the sources with a P-value less than 0.05 have a significant effect on the $K_c$. Results show that the fracture toughness of the ground WC-10Co-4Cr coating depends not only on the feed rate, depth of cut, and cutting speed, but also on the interaction between the feed rate and the depth of cut. Figure 4 demonstrates the response surface plot for fracture toughness versus feed rate and depth of cut at the cutting speed of 30m/s. It is clear in Figure 4 that the effect of the depth of cut is more considerable in higher feed rates.

The values of the contribution (C%) in the ANOVA results demonstrate that the depth of cut is the most significant parameter for the fracture toughness (C=45.1012%). The effect of feed rate (C=41.8925%) is close to that of depth of cut, but the effect of cutting speed (C=9.4852%) is very small in comparison with that of other grinding parameters.

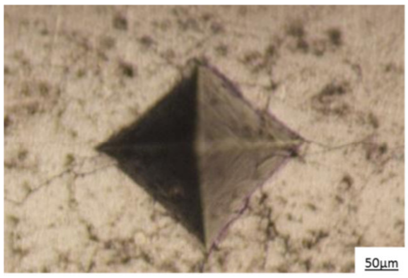


**Figure 2:** The optical microscope image of crack development on the cross-sectional surface of WC–10Co–4Cr coating deposited by HVOF.

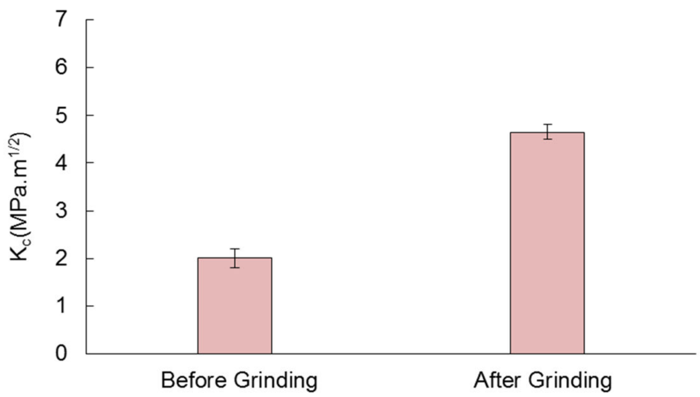


**Figure 3:** Comparison of the coating fracture toughness values (Kc) before and after grinding.

**Table 4:** Design matrix and the experimental fracture toughness values.

| Run No. | $v_c$ | $v_w$ | $a_p$ | $K_c$ |
|---|---|---|---|---|
| 1 | 25 | 273 | 4 | 3.66 |
| 2 | 25 | 273 | 10 | 4.35 |
| 3 | 25 | 273 | 16 | 4.78 |
| 4 | 25 | 413 | 4 | 4.28 |
| 5 | 25 | 413 | 10 | 5.14 |
| 6 | 25 | 413 | 16 | 5.64 |
| 7 | 25 | 550 | 4 | 4.80 |
| 8 | 25 | 550 | 10 | 5.75 |
| 9 | 25 | 550 | 16 | 6.24 |
| 10 | 30 | 273 | 4 | 3.44 |
| 11 | 30 | 273 | 10 | 4.05 |
| 12 | 30 | 273 | 16 | 4.42 |
| 13 | 30 | 413 | 4 | 3.99 |
| 14 | 30 | 413 | 10 | 4.78 |
| 15 | 30 | 413 | 16 | 5.25 |
| 16 | 30 | 550 | 4 | 4.21 |
| 17 | 30 | 550 | 10 | 5.22 |
| 18 | 30 | 550 | 16 | 6.37 |
| 19 | 35 | 273 | 4 | 3.28 |
| 20 | 35 | 273 | 10 | 3.83 |
| 21 | 35 | 273 | 16 | 4.18 |
| 22 | 35 | 413 | 4 | 3.76 |
| 23 | 35 | 413 | 10 | 4.49 |
| 24 | 35 | 413 | 16 | 4.93 |
| 25 | 35 | 550 | 4 | 4.19 |
| 26 | 35 | 550 | 10 | 5.04 |
| 27 | 35 | 550 | 16 | 5.53 |

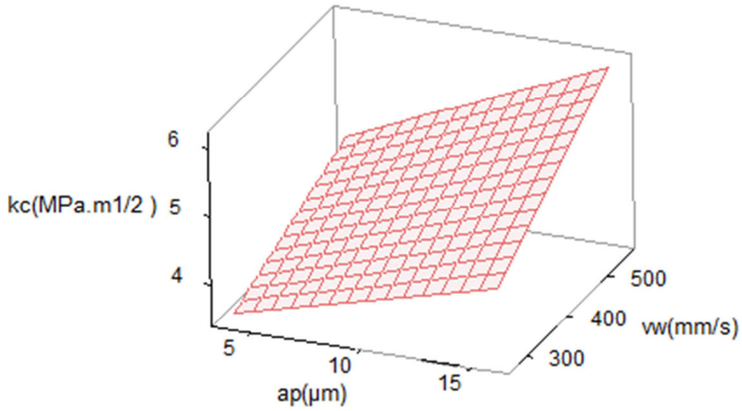


**Figure 4:** Response surface plot for fracture toughness of ground WC-10Co-4Cr coating at $v_c$=30 m/s.

**Table 5:** Analysis of variance for fracture toughness of ground WC-10Co-4Cr coating.

| Source | DOF | Sum of squares, SS | Mean squares, MS | P-value | Contribution, C (%) |
|---|---|---|---|---|---|
| $v_c$ | 2 | 1.62912 | 0.81456 | 0.000 | 9.4852 |
| $v_w$ | 2 | 7.19521 | 3.59760 | 0.000 | 41.8925 |
| $a_p$ | 2 | 7.74632 | 3.87316 | 0.000 | 45.1012 |
| $v_c \times v_w$ | 4 | 0.02788 | 0.00697 | 0.842 | 0.1623 |
| $v_c \times a_p$ | 4 | 0.09417 | 0.02354 | 0.397 | 0.5483 |
| $v_w \times a_p$ | 4 | 0.32015 | 0.08004 | 0.047 | 1.8640 |
| Error | 8 | 0.16256 | 0.02032 | - | - |
| Total | 26 | 17.17541 | - | - | - |

Figure 5a-c illustrates the fracture toughness values of the ground WC-10Co-4Cr coating with respect to the cutting speed, feed rate, and depth of cut. The results show that the fracture toughness increases with the decrease of the cutting speed and the increase of the feed rate and depth of cut. The reason can be explained by the relation between the fracture toughness and the residual stress. According to our previous investigation [14], the increase of compressive residual stress, which is caused by the lower value of the cutting speed and the higher value of the feed rate and depth of cut, improves the fracture toughness of the WC-10Co-4Cr coating.

Regression analysis was used to obtain a mathematical model between the grinding parameters and the fracture toughness. The model contains principle grinding parameters and their interaction which were significant factors by the ANOVA. Therefore, the mathematical model for fracture toughness of WC–10Co-4Cr coating can be presented as Eq. (2):

$$K_c=4.292-0.06011v_c+0.002614v_w+0.0285a_p+0.000194v_wa_p \quad (2)$$

In this equation, $K_c$ is expressed in MPa.m$^{1/2}$, the cutting speed ($v_c$) in m/s, feed rate ($v_w$) in mm/s, and depth of cut (ap) in μm. The validity of the model was examined by the normal plot of residuals. The residual for fracture toughness of the ground WC-10Co-4Cr coating was on a straight line (Figure 6). Therefore, the distribution of errors was normal and the model was valid.

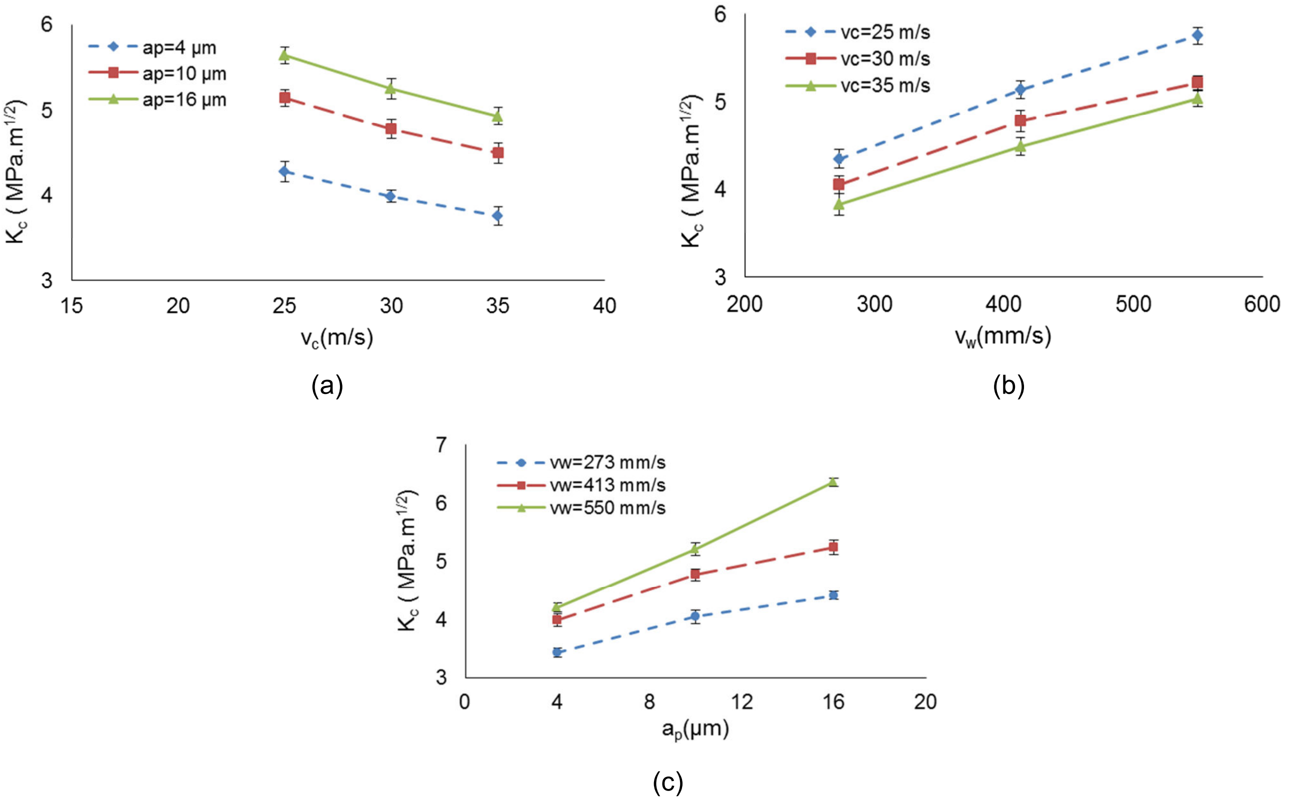


**Figure 5:** Fracture toughness of the ground WC-10Co-4Cr coating vs. (a) cutting speed and depth of cut (at feed rate of 413mm/s), (b) feed rate and cutting speed (at depth of cut of 10 µm), and (c) depth of cut and feed rate (at cutting speed of 30 m/s).

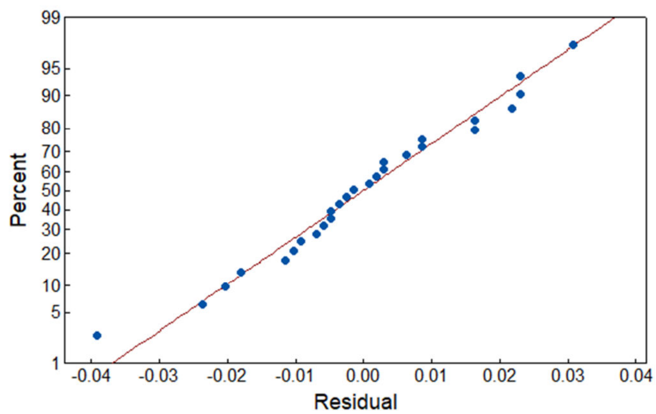


**Figure 6:** Normal probability of the residuals for fracture toughness of the ground WC-10Co-4Cr coating.

The most important outcome of the current study is the determination of the relation between the fracture toughness of the coating and the grinding parameters that has not been reported yet. With this mathematical model, the values of grinding parameters can be selected for obtaining desirable fracture toughness for ground WC–10Co-4Cr coating sprayed by HVOF. In addition, for particular applications in which grinding parameters are selected based on other considerations (such as roughness), the final fracture toughness of the ground coating can be determined by our proposed mathematical model.

## 4. Conclusion

In this investigation, the influence of grinding parameters such as cutting speed, feed rate, and depth of cut on the fracture toughness of the WC-10Co-4Cr coating deposited by HVOF was studied. The most significant results are:

1- The fracture toughness of the WC-10Co-4Cr coating improved after grinding process. The higher compressive residual stresses which are produced during grinding prevent from the formation and propagation of cracks and also reduce the interatomic spacing and the required forces for breaking the atomic bonds.

2- After grinding process, fracture toughness of the coating increased with the increase of feed rate or depth of cut and the decrease of cutting speed.

3- The depth of cut and feed rate had more effect on the coating fracture toughness in comparison with the cutting speed.

4- Fracture toughness of the ground coating depended not only on the depth of cut, feed rate, and cutting speed, but also on the interaction between the depth of cut and the feed rate.

The mathematical model between the fracture toughness and grinding parameters was helpful in selecting the grinding parameters to control the fracture toughness of the WC–10Co–4Cr coating deposited by HVOF.

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