

Parametric Optimization of Residual Stress of TiO₂ Composite Coating

Bhuwan Khare¹, Yashpal¹, Ratnesh Kumar Sharma^{2,*}

Abstract

The primary objective was to develop a composite coating by utilizing the HVOF thermal spray technique and including TiO₂. The substrate was covered with a high-quality composite layer utilizing the HVOF coating process. The TiO₂-based powder and carbon powder were initially combined in the mixer for deposition. The composite powders were applied via an HVOF torch, namely the PT F4 model. Firearms frequently produce a high-speed flow of extremely hot air. The Hybrid composite coating has a thickness ranging from 350 to 450 μm. The ultimate aim was to improve residual stresses by applying the Taguchi strategy. An ANOVA analysis was employed to assess the statistical significance of the process components in the composite coating based on TiO₂. According to the experimental results, temperature has the highest percentage influence (64.19%) on the change in residual stress, trailed by (21.82%) frequency and (6.31%) load. The expected optimal range is $CI_{CE}: 7.28 < \mu < 13.8$ while the expected mean range for $CI_{POP}: 7.24 < \mu < 12.24$. Three confirmation tests were undertaken to compute and predict the optimal scenario. The process parameters are established as follows: test 3 of frequency (A3) is configured at 27 Hz, test 3 of temperature (B3) is configured at 375°C, and test 1 of load (C1) is configured at 20N.

Keywords: Residual stress, Taguchi, composite coating, ANOVA, HVOF thermal spray, TiO₂ coating

INTRODUCTION

The current era is characterized by the enforcement of strong rules and regulations aimed at protecting the environment. These regulations, along with the technological and economic demands, place limitations on the regularly used tribo system in engines. The performance of piston rings in internal combustion engines has a significant influence on fuel efficiency. According to a research study, approximately 35-45% of the energy losses caused by friction in internal combustion engines can be attributable to the piston cylinder assembly.[1–3] Friction and wear are the main culprits for substantial energy dissipation in automobiles, accounting for around 33% of the whole fuel energy.(4) Nevertheless, these coatings typically exhibit limited thermal stability and induce significant internal stresses to which they are applied.[5–13] As a result of their limitations, the use of hard coatings in piston cylinders is decreasing. Presently, TiO₂-based coatings, such as thermal diamond, DLC are

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widely used to improve tribological properties (14) These coatings are easily accessible in the market and are frequently used in small-scale engines. Therefore, there is a need in the modern automotive industry to develop a new type of coating that reduces friction and wear for the piston cylinder arrangement.

Hence, the present work focuses on developing HVOF thermal spray spraying technique to create a Hybrid composite coating and the Taguchi approach to up surge the residual stress. The main objective is to develop a composite coating that demonstrates favorable surface morphology and outstanding residual stresses.

Experimental Procedure

The procedure entailed employing emery paper on steel substrate with a range of grit sizes from 120 to 2000, thereafter applying diamond paste for the purpose of polishing. The substrate was covered with a high-quality composite layer utilizing the HVOF coating process. The TiO₂-based powder and carbon powder were initially combined in the mixer for deposition. The composite powders were applied via an HVOF torch, namely the PT F4 model. The firearm frequently produces a high-speed flow of extremely hot air. The Hybrid composite coating has a thickness ranging from 350 to 450µm.

Residual stress

Table 1 displays the design parameters of the Hybrid composite coating for Taguchi L9 studies, while Table 2 presents the experimental data about the residual stress.

Equation 1 can be utilized to compute the residual stresses on the coated samples.

$$\sigma_x = -\frac{E}{1+\nu} \cdot \frac{1}{\sin 2\eta} \cdot \frac{1}{\sin 2\psi_o} \cdot \left(\frac{\partial \varepsilon \alpha_1}{\partial \cos \alpha} \right) \tag{1}$$

Table 1. Design parameters for Taguchi L₉

Process Parameter	Test 1	Test 2	Test 3	Designation
Frequency (Hz)	9	17	27	A
Temperature(°C)	125	250	375	B
Load (N)	20	40	60	C

Table 2. Experimental results

Experiments	Frequency (Hz)	Temperature (°C)	Load (N)	Percentage (%) change in residual stress			S/N ratio (db)
				R ₁	R ₂	R ₃	
1	9	125	20	45.11	45.11	45.11	-31.11
2	9	250	40	32.71	30.71	31.71	-28.77
3	9	375	60	33.31	31.55	33.72	-29.44
4	17	125	40	47.12	47.19	47.21	-31.22
5	17	250	60	36.11	37.85	38.72	-32.43
6	17	375	20	22.76	23.55	24.44	-22.78
7	27	125	60	31.45	25.42	24.35	-29.10
8	27	250	20	16.75	16.71	17.13	-23.41
9	27	375	40	12.28	13.27	14.78	-21.74

T= overall mean = 30.16

RESULTS AND DISCUSSIONS

Effects of Parameters

Table 3 displays the computation of the signal-to-noise ratio and primary effects for each process parameter. Figure. 1 illustrates the relationship between residual stress and the composite coating utilizing TiO₂. The residual stresses is represented in Figure 2.

Table 3. Effects of residual stress

Parameter	Trial	(Hz)		(°C)		(N)	
		Data	Ratio	Data	Ratio	Data	Ratio
Weight loss	T1	33.23	-30.21	32.81	-30.97	27.12	-27.10
	T2	27.71	-27.54	33.20	-31.48	22.45	-27.24
	T3	22.52	-25.98	17.47	-25.55	32.90	-28.99

Main effect	T2-T1	-7.82	2.57	-0.50	0.27	1.52	-0.11
	T3-T2	-4.59	1.25	-14.73	5.29	3.35	-1.55
Difference		2.63	-0.62		5.08	2.3	-1.20

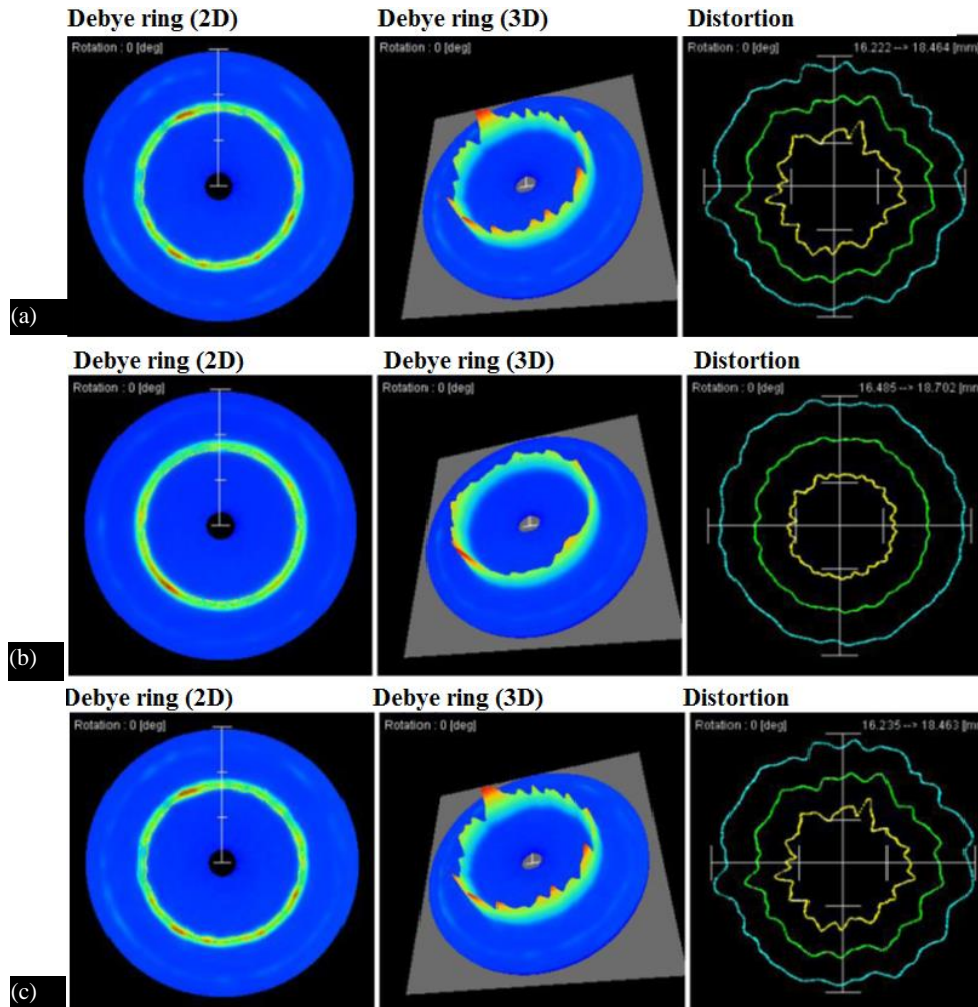


Figure 1. (a-c) Residual stress variation

Figure 2 (a) illustrates the fluctuation in the percentage alteration of residual stress in relation to frequency. The experimental results indicate that the highest residual stress occurs at a frequency of 9 Hz, while the lowest is observed at a frequency of 27 Hz. The maximum S/N ratio was found at a frequency of 27 Hz, while the minimum was seen at a frequency of 9 Hz. Tyagi et al [15] conducted research that established a correlation between an increase in sliding velocity and a decrease in residual stresses. This behavior can be attributed to the presence of a rigid coating, the graphitization effect, and a reduction in the thermal expansion coefficient [15–17].

Figure 2(b) depicts the relationship between temperature fluctuation and the residual stress. The test findings for the coating indicate that the residual stresses is at its lowest point at a temperature of 330°C, and at its highest point at a temperature of 125°C. Conversely, the signal-to-noise ratio is at its lowest point when the temperature reaches 125°C, and at its highest point when the temperature reaches 375°C. The decrease in residual stress levels may be attributed to the reduced thermal expansion coefficient, leading to a decrease in thermal residual stresses [15–17] As the temperature rose from 125 to 375 degrees Celsius, the coated samples saw an increase in residual stress and the improvement of tensile stress. This layer serves as a pliable barrier that absorbs any residual pressures that may arise on the coating. The discovery was examined by Skordaris et al [16] in their study.

The graph shown in Figure 2(c) illustrates the correlation between the load and residual stress for the Hybrid composite coating. The experimental results indicate that the maximum level of residual stress is achieved when a force of 60 N is applied, while the minimum level of residual stress is obtained with a load of 20 N. Additionally, it was noted that the signal-to-noise ratio reaches its highest point when the load is 20 N. Tyagi et al. (15) conducted studies that show a direct relationship between an increase in load and a proportional rise in the percentage change in residual stresses. This phenomenon can be linked to the generation of tensile stress and a reduced thermal expansion coefficient, as indicated by references [15–17]. The reduction in residual stress levels can be related to the generation of sulphides, oxides, a layer of graphite (leading to an augmentation in the amount of TiO₂), tribo-films, and composite powders with micron-sized particles when the test conditions are intensified.

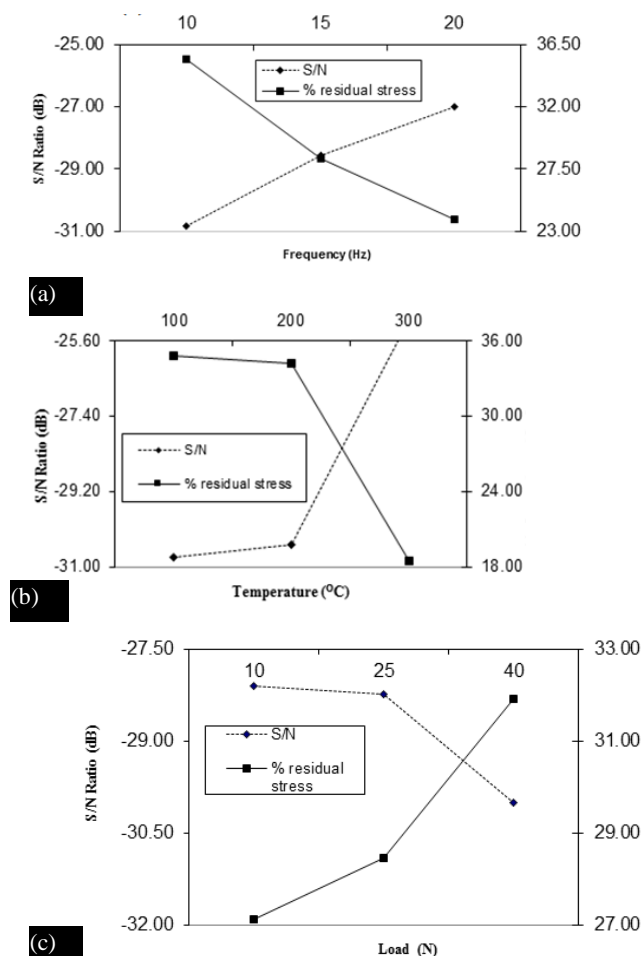


Figure 2. shows deviation of parameters, (a) Effect of Frequency on S/N ratio and % Change in residual Stress (b) Effect of Temperature on S/N ratio and % Change in residual Stress (c) Effect of Load on S/N ratio and % Change in residual Stress

To attain enhanced results, a characteristic with a lower value, which is more desirable, was selected. Figure 2 data indicates that the most advantageous and lowest values for the % change in residual stress are found in test 3 for parameter A (27Hz) and B (370°C), as well as test 1 for parameter C (20N). The Debye ring, which emerges following a brief exposure to X-rays, indicates the accumulation of intense residual stress in the substrate material. The residual stress can be determined by precisely measuring the location of the Debye rings, as their positions directly correspond to the magnitude of strain. The distribution of residual stress is seen using various combinations of colors. Biberger et al. (18) did a study on thermal spray painting using hard chrome finish. The decline in residual stress levels can be ascribed to the creation of sulphides, a layer of graphite (resulting in an increase in the concentration of TiO₂), tribo-films, and micron-sized composite powders under the given experimental conditions. The

coated samples exhibited a rise in residual stress as the temperature escalated from 30 to 350 degrees Celsius, resulting in the formation of tensile tension. (16)

ANOVA was employed to evaluate and determine the significance of parameters in the production of the composite coating utilizing TiO₂. Table 4 displays the discrepancy of the combined analysis of variance (ANOVA). The experimental results clearly establish that factors have a significant impact on the residual stress of the Hybrid composite coating. According to the experimental results, it has been determined that temperature has the most significant influence (64.19%) on the change in residual stress, trailed by (21.82%) frequency and (6.31%) load.

Table 4. Pooled ANOVA

Source type	DOF		SS		V		F-Ratio		SS'		P (%)	
	Data	S/N	Data	S/N	Data	S/N	Data	S/N	Data	S/N	Data	S/N
Frequency (Hz)	2	2	618.57	22.16	309.28	11.08	46.43	64.25	605.25	21.82	25.70	24.42
Temperature (°C)	2	2	1544.69	61.58	772.34	30.79	114.96	178.56	1531.37	61.23	64.19	67.85
Load (N)	2	2	109.71	6.65	54.85	3.28	8.23	19.29	96.39	6.31	4.56	7.33
E (Pooled)	20	2	133.20	0.34	6.66	0.17	-	-	173.16	1.38	5.53	0.38
Total	26	8	2403.18	90.75	-	-	-	-	2406.18	90.75	100	100

Optimal characteristics estimation

Table 5 and Equation 2(19-23) shows the significant parameters of residual stress.

$$\mu\% \text{ change in residual stress} = A_3 + B_3 + C_3 - 2T \quad (2) = 12.19$$

Equations 3 and 4 was used to calculate the CI_{POP} and CI_{CE}

$$CI_{CE} = \sqrt{F_a(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (3)$$

$$CI_{CE} = \pm 3.71$$

$$CI_{POP} = \sqrt{\frac{F_a(1, f_e) V_e}{n_{eff}}} \quad (4)$$

$$CI_{POP} = \pm 2.45$$

$$R = 3; V_e = 6.66; N = 27; n_{eff} = 3.86; f_e = 20; F_{0.05}(1, 20) = 3.49$$

Table 5. mean values of residual stress

Tests	Residual stress
A ₃	22.82
B ₃	17.47
C ₁	25.12
T	30.16

- % residual stress is given by:
- CI_{CE}: 7.28 < μ < 13.8
- CI_{POP}: 7.24 < μ < 12.24

The predicted optimal values of parameters are:

- Frequency (A₃) = 27 Hz
- Temperature (B₃) = 375°C
- Load (C₁) = 20N

Three confirmation tests were undertaken to compute and predict the optimal scenario. The process parameters are established as follows: test 3 of frequency (A₃) is configured at 27 Hz, test 3 of temperature (B₃) is configured at 375°C, and test 1 of load (C₁) is configured at 20N (19-23). The TiO₂ based composite coating exhibited an average residual stress value of 11.09, which is within the optimal range.

CONCLUSIONS

The present study successfully demonstrated the fabrication of a composite coating employing TiO₂ powder, by the HVOF thermal spray process.

- Based on the experimental findings, it has been established that temperature has the greatest impact (64.19%) on the alteration of residual stress.
- The expected optimal range is $CI_{CE}: 7.28 < \mu < 13.8$
- The expected mean range for $CI_{POP}: 7.24 < \mu < 12.24$

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