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EFFECT OF SOME ATMOSPHERIC PLASMA SPRAYING PARAMETERS ON TENSILE STRENGTH OF Cr_3C_2-NiCr COATING

Dang Xuan Thao[1]

[1]Vietnam - Japan Center, Hanoi University of Industry, Vietnam

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Research Paper

Abstract: *The quality and performance of thermal spray coatings is highly dependent on the coating-substrate adhesion and the internal cohesion of the coatings. Hence, it is essential to have an effective spray mode for the coatings. However, predicting and controlling the adhesion of the coating appears complicated, depending on the spraying process and other operating conditions such as type of base steel, surface roughness, type of coating powder and percentage of compounds present in the coating powder… The chromium carbide coating powder group is highly rated for wear erosion, and high temperature work (up to 900°C) but still retains good mechanical properties, so it is widely used in practice. In this study, the* Cr_3C_2 *- NiCr coating with 30%NiCr content was created on the surface of the E355 steel specimens using atmosphere plasma spraying (APS) method. The experiments are carried out based on Central Composite Design with 20 trials. The study uses analysis of variance (ANOVA) and a genetic algorithm to optimize and evaluate the influences of 3 spraying parameters on the internal cohesion of the coating (Tensile strength). The coating's tensile strength was determined using a multi tester, the results revealed that all 3 input parameters had a significant impact on the tensile strength, specifically, powder feed rate was the most influential, followed by stand-off distance, current intensity; at the same time, the optimal spray parameters were found, including* $I_s = 582.3A$, $m_s = 33.2g/min$ *and* $L_s = 170.2mm$ *with the calculated expected value of 121.5MPa. The experimental result for examining the optimal values of parameters was 118.7MPa, achieving 97.6% of the calculated value.*

Keywords: *Tensile strength, Cr3C2 - NiCr coating, plasma spraying, E355 alloy steel.*

1Corresponding author. dangxuanthao@haui.edu.vn (D. X. Thao)

1. Introduction

Cr_3C_2-NiCr powder commonly referred to be as "ceramic–metallic", is a multiphase composite, in which the ceramic phase is uniformly distributed in a tough metallic matrix, providing a well-balanced combination of hardness and toughness, that effectively solve the problems of erosion and corrosion. Previous studies have evaluated the performance and reported the effectiveness of the Cr_3C_2-NiCr coating against erosion at high temperatures (up to $800^0C \div 900^0C$) and against corrosion in environments with abrasive agents applying different coating methods (El Rayes, Abdo, & Khalil, 2013; Marcano et al., 2008; Yaghtin et al., 2015). However, it is necessary to choose an appropriate method to deposit the Cr_3C_2-NiCr coating, which highly resists wear and corrosion without reducing the adhesion strength of the coating to the substrate, also considering the internal cohesion of the coating. Many reports indicated that plasma spray is a preferred method as it creates high energy density and heat flow, which is important for completely melting the high-melting-point coating powders such as ceramic (Grand View Research, 2015). The Cr_3C_2-NiCr coatings attract attention from researchers as well as users worldwide, such as: A.R. Govande et al., conducted an evaluation looking at the performance characteristics of a post-spray treated carbide coating. The results show that the wear corrosion, and erosion resistance of the carbide coating produced by thermal spray mainly depends on the deposition technique, the composition of the coarse powder, the size of the carbide, and the structure. Micro and phase composition formed after coating deposition (Govande et al., 2022). In some other studies, chromium-carbide based coatings were performed by plasma spraying demonstrated high wear and corrosion resistance at elevated temperatures improving the operative life of the detail. In addition, the formation of a hard chromium oxide layer on the surface during deposition increases the protection of the substrate surface from degradation (Rakhadilov et al., 2021; Zhang et al., 2021). A recent study by Du, J.-y. indicated that the porosity and microcracks of the Cr_3C_2-NiCr/NiCrAl coating on FV520B steel surface using the plasma spraying process are decreased to a minimum, due to the NiCr metallic phase to be melted and filled into the porosity and microcracks, leading to an enhancement of sliding wear resistance. The research also showed that when the heat input is too high (above 42kW), the sliding wear loss of the coating is increased owing to delamination between the bonding layer and the steel surface (Du et al., 2019).

In fact, so as for depositing a quality coating, it is also important to note that there must be a process with a combination of internal and external parameters besides choosing a suitable method, such as particle size, nozzle type, injection current, gas ratio, powder feed rate, speed, stand-off distance and preheat condition, etc. since it affect the characteristics and performance of thermal spray coating. Some papers demonstrated that the spraying condition plays a key role in creating a coating with high adhesion strength and low porosity (Davis, 2004; Wang et al., 2021). Georg Mauer et al. conducted a study to improve the quality of plasma coatings with 39.4kW of spraying power, 600A of injection current, 40slpm of Ar flow and 10slpm of H_2 flow, 4.5g/min of powder feed rate, 90° of injection angle and 80 mm of stand-off distance. The result showed that the most important parameter for improving the powder spraying process is the gas flow, however, it must be carefully adjusted to achieve optimal heat transfer and momentum. Furthermore, the highest particle temperature is reached as the particles are injected deep enough into the central region of the plasma torch (Mauer et al., 2011). Our previous studies also showed that three plasma spraying parameters, namely current intensity, powder feed rate and spraying distance for creating Cr_3C_2-NiCr coating on 16Mn steel, had a significant influence on the quality. Experimental results revealed that the coating bond strength is great as the the current intensity is between 550÷600 A, the powder feed rate ranges from 30-32 g/min, the stand-off distance is in the range from 160÷170 mm (Thao & Duc, 2022; Thao, Van Got, & Cuong, 2022). The latest report of Marek Goral et al. also showed the same, they used the plasma spraying method with spraying parameters including (current, H_2/Ar ratio and powder feed rate. The result stated that the friction, porosity, and hardness properties of the coating were greatest when the current intensity was 450A, the flow rate of H_2 was 5 NLPM, and the powder feed rate was 20g/min (Goral et al., 2023).

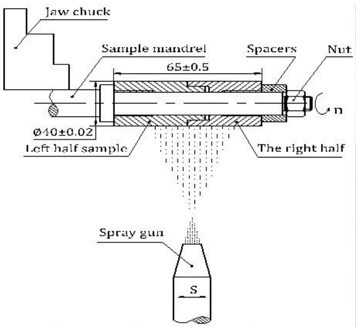
It is proposed that with optimized parameters, further improvements can be achieved. However, the research on optimization of spraying parameters for the coating process still faces many difficulties and obstacles. In this paper, the Cr_3C_2-30%NiC coating on steel E355 (St 52-3)/1.0060 was created using atmospheric plasma spraying (APS) method with the aim of finding the optimal spraying solution for the parameters to achieve the highest coating tensile strength. Experiments were carried out based on the Central Composite Design (CCD) method combined with analysis of variance (ANOVA) method and genetic algorithm so as for evaluating the influence of each parameter on the coating tensile strength (Du & Binh, 2011; Montgomery, 2017). In addition, the mathematical relationship between the parameters and the tensile strength is established.

In this study, the Nelder - Mead (NM) algorithm was used to solve optimization problems. This algorithm was built in the specialized statistical software Minitab. This software is currently being commonly used to model processes, analyze, and solve real-world experimental problems for highly reliable results. To solve optimization problems by algorithm (NM), use optimization function (Start/DOE/Responer Surface/Response Optimizer) included in Minitab19TM software (Du & Binh, 2011). In addition, genetic algorithm (GA) is also applied to solve the optimization problem of this study. GA is a general technique that helps to solve problems by simulating the evolution of humans or of organisms in general (based on the theory of species evolution of Darwin), under specified environmental conditions. GA's goal is not to give the exact optimal solution but to give the relatively optimal solution (Sivanandam & Deepa, 2008).

2. Experimental process and evaluation method

2.1. Coating material

Coating powder: Cr_3C_2-30%NiCr powder (Sulzer Metco-Singapore) is chosen for use in this study, Cr_3C_2-30%NiCr particles have an average diameter of (–30/+5 µm) with its chemical composition: C ≤ 0.2%, Si ≤ 0.5%, NiCr 29.5% and Cr_3C_2 69.8%.



a. Diagram of injection principal

b. The test piece is clamped on the lathe

Fig. 1. Spray chart and test specimen clamp on the machine

Coating sample: Tensile test specimen is selected and manufactured according to JIS-H-8664 standard, the test specimen consists of two halves, left half and right half, assembled into a block of the same size Ø40±0.02 mm and has total length is 65±0.5mm as shown in Fig. 1. The test specimen is made from alloy steel E355 (St 52-3)/1.0060 because this alloy steel is commonly used in industrial machine parts working under abrasive and temperature conditions, the composition and ratio of elements in E355 base steel include: C ≤ 0.22%, Si ≤ 0.55%, Mn ≤ 1.6%, P ≤ 0.03%, S ≤ 0.035%, Cr ≤ 0.04%, Ni ≤ 0.01%, Mo ≤ 0.01% , the rest is Fe. The coated sample surface is cleaned and roughened by abrasive blasting. The roughness of the sample (Rz ~ 71μm) for best adhesion is given (Thao et al., 2022).

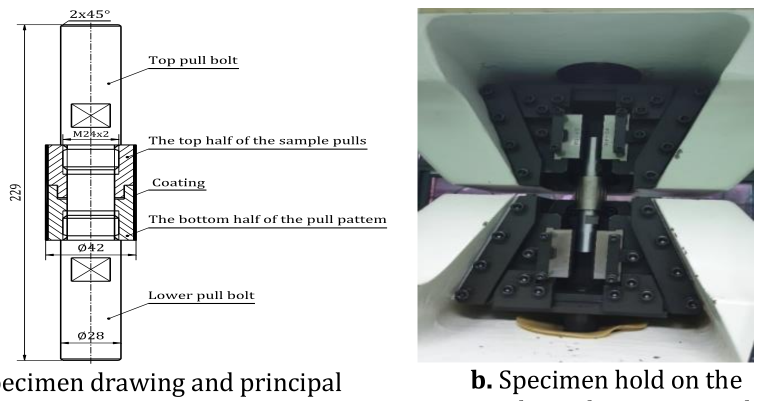
2.2. Methods of implementation

The spraying process is carried out on plasma spraying system 3710-PRAXAIR-TAFA (USA) with spray gun SG-100. To perform coating spraying on the specimen, the coating sample is inserted into the mandrel and clamped on the chuck of the lathe at a rotational speed of 10 (v/min). The spray gun is mounted on the machine tool table with a horizontal displacement of 2 (mm/rev), as shown in the diagram Fig. 1. The coating thickness after the process is ($1^{+0.2}_{0}$ mm) as shown in Fig. 2. In this study, the experiments are designed according to Central Composite Design method with the number of experiments is N = 2^k + 6 + 2k = 20 trials (k is the number of experimental variables). Where 2^k factorial experiments (coded as −1 and +1), 6 central points (coded as 0) and 2k axial points (placed at −α and +α, parameters of $\alpha = \sqrt[4]{2^3} = 1.682$) (Du & Binh, 2011; Montgomery, 2017). The values of each input at all the levels are shown in Table 1 and are submitted for implementation according to Table 2.

Table 1. Values of input parameters at levels

Parameters	Symbols	Unit	Levels				
			- α	-1	0	1	+ α
Current intensity	I_s	A	381.8	450	550	650	718.2
Powder feed rate	m_s	g/min	13.18	20	30	40	46.82
Stand-off distance	L_s	mm	92.72	120	160	200	227.28

For spraying experiments, the current intensity (I_s), powder feed rate (m_s) and stand-off distance (L_s) were changed in each trial as shown in Table 2. Other spraying parameters were kept constant, including the power of 35V, Ar gas flow P_{Ar} = 50 liters/min, H_2 gas flow P_{H2} = 5 liters/min and injection angle of 90°.



a. Specimen drawing and principal diagram of tensile test

b. Specimen hold on the universal tensile testing machine

Fig. 2. Diagram and specimen

2.3. Evaluation methods

Measurements are determined on each sample corresponding to the schematic diagrams as shown in Fig. 2. In the study, the output parameters (σ_{Ts}) are defined using a tensile-compression tester (Model BESTUTM 500HH, Korea), the result is calculated applying formula (1), where F is the coating surface area and P is the coating.

$$\sigma_{Ts} = \frac{P_d}{F} \quad (1)$$

Where: σ_{Ts} - Tensile strength (MPa/mm^2)

P_d - Tensile force (N)

F - Cross-section area of the coating (mm^2)

On the other hand, the coating area is determined by the formula (2).

$$F = \frac{\pi(d_1^2 - d_2^2)}{4} \quad (2)$$

Where: d_1 - Outer diameter of specimen including the coating (mm)

d_2 - Outer diameter of specimen without the coating (mm)

In this study, the cross-section area is: $F = \frac{3.14(1764 - 1600)}{4} = 128.74(\text{mm}^2)$ (3)

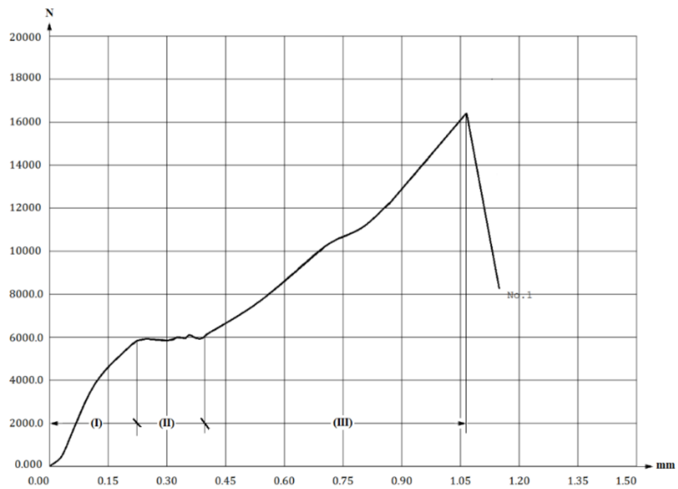


Fig. 3. Characteristic curve of tensile strength

The coating's tensile strength of each sample is displayed on the characteristic curve in Fig. 3. Observation of the graph shows that there seems to be 3 stages: In the initial stage (I), the strength increases gradually and slowly, that means the coating likely has elastic deformation; in the stage II, the characteristic curve is almost parallel to the horizontal axis, that reflects the coating with plastic and elastic deformation; in the stage III, the values begin to increase rapidly to the maximum and then decrease. At this point, the modules of the coating material are separated, and this stage is called the destruction stage. Thus, the Cr_3C_2-30%NiCr coating, created by plasma spraying method, has all the typical stress-strain properties. For each set of spray parameters, samples were generated, and measurements were made at least 3 times on 3 different samples as shown in Fig. 4. The average value is shown in Table 2, it should be noted that the difference between the measured values of the 3 samples > 5% will be eliminate.

a. The tensile test specimen is removed from the tester

b. The tensile test specimen is removed from the shaft

Fig. 4. Specimen with the coating to be pulled apart

3. Results and discussion

The process of spray coating on the samples is carried out according to Table 2. The results of measuring the tensile strength of each experiment are the average of 3 measured samples which are also presented in Table 2.

Table 2. Experiment matrix and result

No.	Parameters			Results
	I_s (A)	m_s (g/min)	L_s (mm)	σ_{Ts} (MPa)
1	-1	-1	-1	99.40
2	1	-1	-1	102.6
3	-1	1	-1	107.2
4	1	1	-1	111.2
5	-1	-1	1	105.5
6	1	-1	1	110.7
7	-1	1	1	108.2
8	1	1	1	115.4
9	-α	0	0	100.4
10	+α	0	0	109.7
11	0	-α	0	101.1
12	0	+α	0	110.5
13	0	0	-α	98.10
14	0	0	+α	108.6
15	0	0	0	121.1
16	0	0	0	120.4
17	0	0	0	120.8
18	0	0	0	120.5
19	0	0	0	120.2
20	0	0	0	119.8

3.1. Contribution of parameters on tensile strength

Analysis of variance (ANOVA) for the objective function (σ_{Ts}) is displayed in Table 2, the analysis results are presented in Table 3.

Table 3. Results of ANOVA on tensile strength of the coatings

Source	Degree Freedom (DF)	Sum squared deviation. (Seq SS)	Contribution to the model	Average squared. (Adj MS)	Statistical value (F-Value)	Probability value (P-Value)
Model	9	1148.61	95.98%	127.623	26.56	0.000
Linear	3	306.37	25.60%	102.125	21.25	0.000
I_s	1	90.94	7.60%	90.936	18.92	0.001
m_s	1	114.88	9.60%	114.877	23.90	0.001
L_s	1	100.56	8.40%	100.561	20.93	0.001
Square	3	827.75	69.17%	275.916	57.42	0.000
I_s*I_s	1	210.55	17.60%	312.988	65.13	0.000
m_s*m_s	1	218.26	18.24%	278.381	57.93	0.000
L_s*L_s	1	398.93	33.34%	398.928	83.01	0.000
Interaction	3	14.49	1.21%	4.828	1.00	0.430
I_s*m_s	1	0.98	0.08%	0.980	0.20	0.661
I_s*L_s	1	3.38	0.28%	3.380	0.70	0.421
m_s*L_s	1	10.13	0.85%	10.125	2.11	0.177
Error	10	48.06	4.02%	4.806		
Lack-of-Fit	5	47.02	3.93%	9.404	45.51	0.000
Coefficient of determination R^2: 95.98%						
Adjusted coefficient of determination ($Radj^2$): 92.37%						

The data in Table 3 revealed that: Probability value (P) in the first-order model is greatly low and notably lower than the significance level α (α = 0.05). It means that all the spraying parameters (I_s, m_s, L_s) of the model affect the tensile strength of the coating (σ_{Ts}).

Moreover, it can be found that mp has the greatest impact on the output objective function (9.60%/25.60%), followed by Lp (8.40%/25.60%) and the injection current intensity (7.60%/25.60%). This influence is also shown in the graph Fig. 5. Observation of Fig. 5 reveals the difference between the first and last points of the curves in the graph by altitude (H_1, H_2 and H_3), where (H_2) has the greatest height, followed by (H_3) and finally (H_1). That means ms is the parameter that has the highest influence on the objective function, Ls is the second and the parameter with the lowest impact on the main objective function is I_s.

At the same time, based on the analysis result of the influence of the factors included in the second-order model (Table 3), the contribution of the parameters to the objective function (σ_{Ts}) is significant (69.17%/100%), and the probability values (P-values) of the factors in this model is extremely low (~ 0.0001), greatly lower than the significance level α (α = 0.05). This proves that the appearance of the elements is considerable for the objective function (σ_{Ts}). On the other hand, the probability value in the Low-of-Fit section of the model has a value (P ~ 0.0001) enormously smaller than the significance level α, which indicates the form of the functional equation to likely match the measured data. The coefficient of determination of the regression function (R^2) proves that (95.98%) of the experimental data are suitable with the predicted data based on the model. Therefore, the selection of input parameters as well as the value of the survey area of the parameters ensured the maximum of the coating's tensile strength.

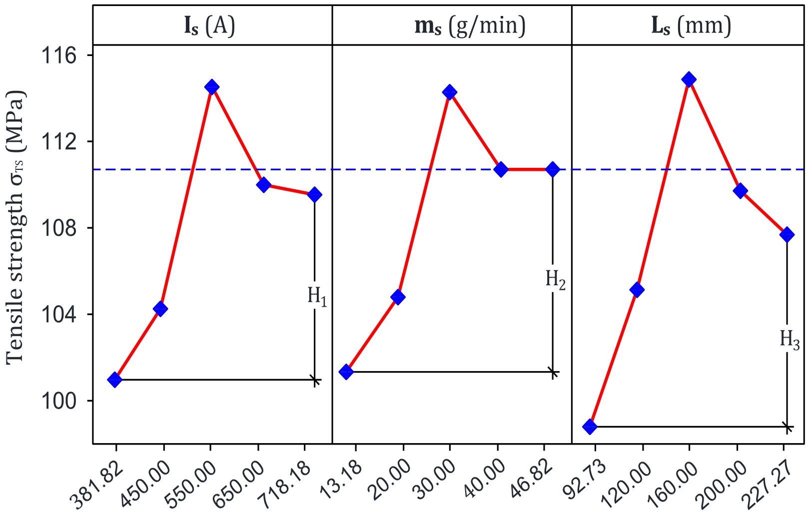


Fig. 5. Influence of parameters on tensile strength

To understand the interaction between the factors, an interaction matrix diagram is built as shown in Fig. 6. The graph shows the influence of the interaction between input parameter pairs on the output objective function. Observation of the cells in the graph shows that the effect of the input parameters on the coating's tensile strength is complex.

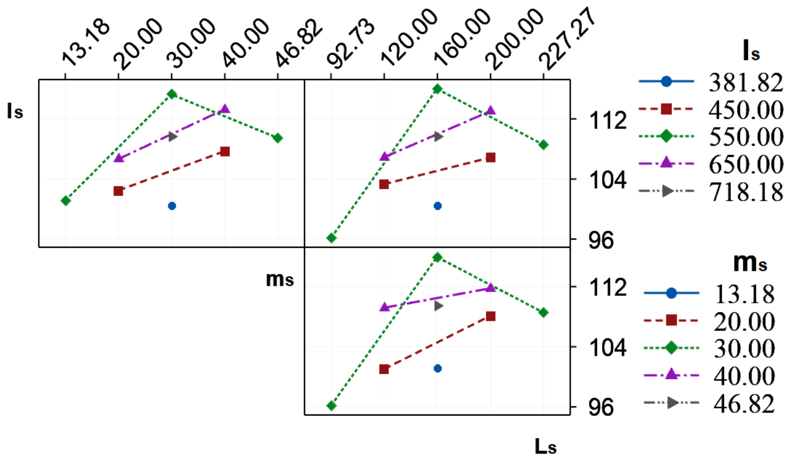


Fig. 6. Influence of interaction between parameters on tensile strength

Each pair of the interactions included in the graph Fig. 6 is analyzed as follows:

The influence between I_s and m_s: At 550A of a current intensity, the coating's tensile strength increases as m_s increases from 13.18÷30 g/min. However, when m_s continues to increase in the range from 30÷46.82 g/min, the coating's tensile strength starts to decrease. On the other hand, in both the cases of 450A and 650A of I_s, the increase of m_s from 20 to 40g/min leads to the increase of the coating tensile strength. However, the impact of m_s on the tensile strength at 650A of the current intensity is higher than at 450A. This can be explained that I_s raised causes the temperature in the combustion chamber to go up, then the spray particles are melted more conveniently, and the coating cohesion is probably higher. The higher the powder feed rate into the spraying area, the more difficult it is for the particles to melt due to heat dissipation by the number of particles, which can also reduce the bonding between the spray particles leading to a decrease in the coating tensile strength.

Second, the influence between I_s and L_s also shows that: At 550A of the current intensity, the tensile strength of the coating increases when L_s increases in the range from 92.73 to 160mm. Conversely, when L_s continues to increase in the range from 160÷227.27 mm, the coating's tensile strength starts to decrease. The tensile strength of the coating is improved in both cases of current intensity (450A and 650A) as L_s varies from 120 to 200mm, however, the influence of the stand-off distance to the tensile strength at 650A is greater than at 450A. This can be explained that: The increase of spraying distance leads to re-solidification of the particles due to cooling (the smaller the particles, the faster the re-solidification), at the same time, more oxidized particles cause a decrease to coating cohesion and decrease to the tensile strength. On the other hand, the short distance limits the spraying effectiveness owing to the strong impact force with the steel causing the particles to be thrown out.

Third, the influence between m_s and L_s reveals that: At 30g/min of powder feed rate, the tensile strength of the coating increases as the stand-off distance increases from 92.73 to 160mm and it decreases as the distance increases from 160 to 227.27mm. In both cases of spraying with the powder feed rate at 20g/min and 40g/min, an increase of stand-off distance in the range of 120 to 200mm will cause the tensile strength to be improved. However, the influence of L_s on the tensile strength at 20g/min is greater than at 40g/min. This can be explained that the increases of (L_s) which lead to the decreases of the kinetic energy of the particles cause the decreases in the coating cohesion. When m_s is small, the tensile strength of the coating increases, this may be due to the decrease in the density of particles fed into the spray chamber, resulting in more heating efficiency of the spray particles. On the contrary, increasing m_s too high causes the arc temperature in the combustion chamber to go down and the particle velocity also decreases, which reduces the quality and tensile strength of the coating. Accordingly, it is important to reduce L_s to improve the coating quality as the powder feed rate is high.

3.2. Regression model of tensile strength determination

The empirical equation based on regression analysis showing the relationship between the coating's tensile strength and the spraying parameters is built as expression (4).

$$\sigma_{Ts} = -171.5 + 0.5019I_s + 3.184m_s + 1.115L_s - 0.000466I_s*I_s - 0.04394m_s*m_s - 0.003288L_s*L_s + 0.000350I_s*m_s + 0.000163I_s*L_s - 0.00281m_s*L_s \quad (4)$$

The empirical equation (4) has the coefficient of determination $R^2 = 0.9598$ which is close to 1. That means the obtained equation has a high compatibility with the experimental data. Equation (4) is the basis for selecting the values of the spray parameters (I_s, m_s and L_s) to ensure that the coating's tensile strength reaches a specific suitable value. In addition, the model is used to predict the tensile strength of the coatings. The results of the comparison between the predicted and experimental tensile strength are presented in Table 4 and described in Fig. 7.

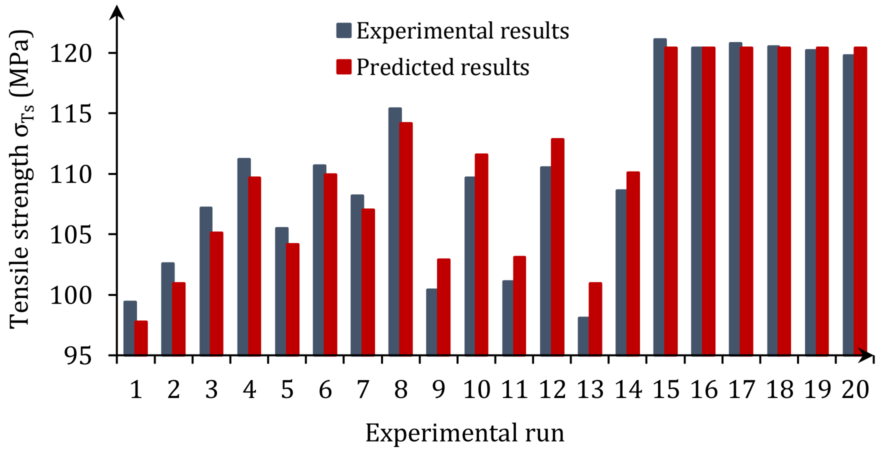


Fig. 7. The predicted and experimental results of tensile strength

Table 4. Comparison between the predicted and experimental results

No.	Experimental results	Predicted results	Difference (%)
1	99.4	97.8	1.7
2	102.6	100.9	1.6
3	107.2	105.1	1.9
4	111.2	109.7	1.4
5	105.5	104.2	1.3
6	110.7	109.9	0.7
7	108.2	107.0	1.1
8	115.4	114.2	1.0
9	100.4	102.9	2.5
10	109.7	111.6	1.7
11	101.1	103.1	2.0
12	110.5	112.9	2.1
13	98.1	100.9	2.9
14	108.6	110.1	1.4
15	121.1	120.4	0.6
16	120.4	120.4	0.0
17	120.8	120.4	0.3
18	120.5	120.4	0.1
19	120.2	120.4	0.2
20	119.8	120.4	0.5
	Average difference		1.2

The comparison result indicates that the calculated coating's tensile strength likely matches the measured data, the greatest error is 2.9% and the average error is 1.2%. Thus, the equation of the output objective function (σ_{Ts}) has been examined and can be used to predict as well as to optimize this indicator.

3.3. Optimization result for tensile strength

To solve the problem of optimizing the tensile strength of the coating with the highest value in specific conditions, Minitab 19™ software is applied. The optimization results were obtained Fig. 8.

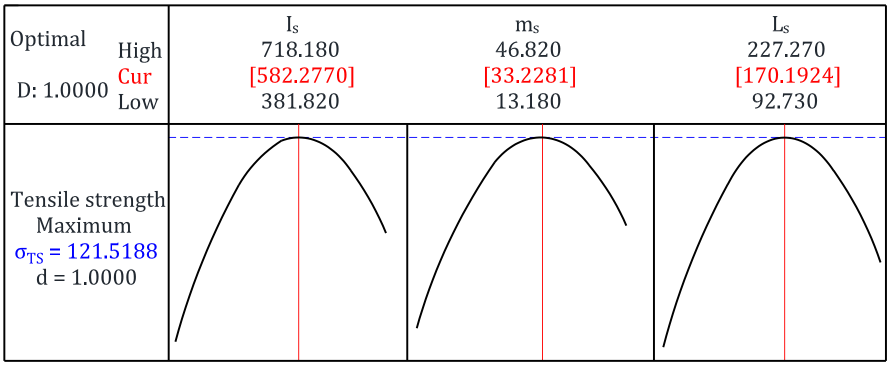


Fig. 8. Graphs showing relationship of spraying parameters and tensile strength.

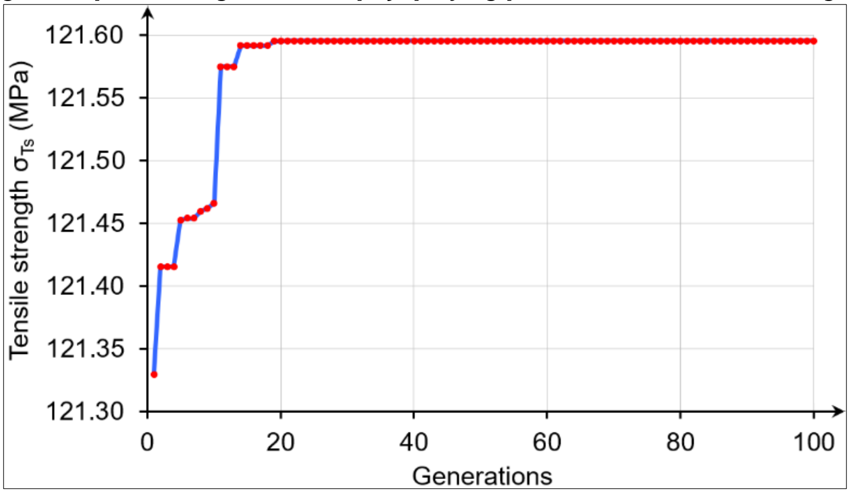


Fig. 9. Optimization results using GA.

Next, the genetic algorithm (GA) was also used for optimization with the following parameters 100 of population, 0.25 of crossover probability, 0.05 of mutation probability and 4 of mutation parameter. The results of the optimization problem are shown in Fig. 9. The results of solving the problem with the goal of the tensile strength of the Cr_3C_2-30%NiCr coating using two methods are shown in Table 5. Comparing the results found by the two methods reveals that the parameter is the most greatly different, namely 6.33%, especially the results of predicting the tensile strength output are extremely close. Thus, this set of parameters is the optimal to achieve the tensile strength of coating.

Table 5. Result of the optimal set of parameters by two methods (ANOVA) and (GA)

Solution	I_s	m_s	L_s	σ_{Ts} (Fit)
ANOVA	582.3	33.2	170.2	121.5
GA	580.7	31.1	169.8	121.6
Difference (%)	0.27	6.33	0.24	0.08

3.4. Results for examining the optimization according to ANOVA and GA

To assess the suitability of the spraying parameters achieved after the optimization, an experiment was conducted to examine 5 specimens with each set of optimal spray parameters according to Table 5. The measurement results of each sample and average results examined by two methods are listed in Table 6.

Table 6. Measurement results on samples for examining optimization.

Solution	Results by sample					Result (MPa)		Difference (%)
	1	2	3	4	5	Experimental results	Predicted results	
ANOVA	119.5	120.2	116.7	118.3	118.8	118.7	121.5	2.4
GA	120.4	122.6	119.9	121.5	120.1	120.9	121.6	0.6

Based on the results in Table 6, it can be said that the experimental results of both methods are extremely close to the calculated results (the largest error is 2.4%). It proves that the optimization of parameters obtained by both methods is suitable for practical application, however, the optimized values of spraying parameters according to GA is slightly more stable and able to achieve a higher tensile strength than ANOVA (difference is 0.6 %). Thus, for coating Cr_3C_2-30%NiCr powder on E355 steel base with plasma spraying method for the practical application, the optimized spray parameters according to (GA) might be more rational with the values I_s = 580.7A, m_s = 31.1g/min and L_s = 169.8mm to achieve the maximum tensile strength.

Comparing the results of this experimental study with the results of another similar experimental study, the coating tensile strength in their study was achieved at 76.8MPa, but this result was improved by them it is extremely excellent by heat treatment of the coating after spraying, the test result is 404.75MPa (Got & Trung, 2012). Meanwhile, the coating tensile strength results in this study before heat treatment were achieved at 118.7MPa and 120.9MPa, respectively. Thus, the results of this study, if learning and applying the post-spray heat treatment method to continue for this study, it is expected to get much better results. This is also a suggestion for further research with the desire to find the best coating quality to apply in real life.

Conclusion

This research work, Cr_3C_2-30%NiCr coating is created on steel E355 (St 52-3)/1.0060 by plasma injection (APS) technique. 3 parameters of the plasma spraying process including plasma current intensity (I_s), powder feed rate (m_s), and stand-off distances (L_s) were studied and optimized using central composite design (CCD), combining with (ANOVA) and Genetic Algorithm (GA) with respect to the tensile strength of the coating. The results are summarized as follows:

Among the three spraying parameters considered, the powder feed rate (m_s) has the greatest influence on the tensile strength of the Cr_3C_2-30%NiCr coating, followed by the stand-off distance (L_s) and the spraying current intensity (I_s).

With the ANOVA method, the recommended optimization is I_s = 582.3A, m_s = 33.2g/min, L_s = 170.2mm) for the coating with the predicted maximum tensile strength of 121.5MPa. The examination result of the tensile strength is 118.7MPa. It is lower than the predicted result with the optimization (error is 2.4%). That affirms the optimal spraying parameters for great quality coatings with enhanced tensile strength.

As the GA method is applied, the recommended optimization is I_s = 580.7A, m_s =

31.1g/min, L_s = 169.8mm) for the coating with the predicted maximum tensile strength of 121.6MPa. The examination result of the tensile strength is 120.9MPa. It is also lower than the predicted result with the optimization (error is 0.6%). This affirms the optimal parameters by the GA method for great tensile strength quality of the coating and they likely have more stability than the optimization using ANOVA method.

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Abbreviations

APS: Air Plasma Spray
CCD: Central Composite Design
USA: United States of America
ANOVA: Analysis of Variance
NM: Nelder Mead
GA: Genetic algorithms

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