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Modulus of elasticity and yield bending stress of coating lubrotec 19985 produced by the metal spraying process †

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Abstract

Round bars of 13.6 mm diameter made from low alloy steel were sprayed by hard-coating Lubrotec 19985 under the following spraying parameters: the rotation speed varied from 500 to 900 rpm, the feeding speed from 0.1 to 1.0 mm/rev, and the nozzle tip distance from 100 to 200 mm; the sprayed bars were then subjected to bending test. Depending on the thickness of the produced coating, the modulus of elasticity and yield bending stress of the coating were calculated by applying the bending deflection formula and an equivalent cross-sectional area technique, respectively. The results obtained indicated that the thickness, hardness, yield bending stress, and modulus of the elasticity of coating were varied with the variation in spraying parameters. The optimum spraying parameter was a rotation speed of 700 r.p.m, a nozzle tip distance of 200 mm, and a feed rate of 0.1 mm/rev. This optimum parameter produced an acceptable thickness of 1.14 mm, a hardness of 148 HV, a bending stress of 404.9 MPa, and a modulus of elasticity of 91.47 GPa. The results obtained can also help determine the modulus of elasticity and yield bending stress of the various coating materials when a coated round bar is subjected to the bending test.

Keywords: Low alloy steel; Spraying process; Lubrotec 19985; Hardness test; Bending test

1. Introduction

Metal spraying has wide application in the restoration of worn surfaces to their original sizes. It is a very functional process for jobs especially when welding or brazing heat is impractical, or for applying deposits of dissimilar metals, which is otherwise not possible. The process involved is unique because there is no limit to the size of the object or structure that can be coated.

Metal spraying involves heating a metal to a molten or semi-molten condition by passing it through a high-temperature heat source and depositing it in a finely divided form on a substrate.

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The molten particles flatten out upon impacting the substrate and adhere to the surface. The subsequently deposited particles also flatten out and adhere to the previously deposited ones, thus forming a thin coating by mechanical bonding.

To produce good coating, the surfaces to be sprayed must be absolutely free from grease, oil, and contaminations; in addition, they must also be rough enough. This gives the surface a sort of irregularity which can help to provide a mechanical bonding for the sprayed metal particles. For plane and cylindrical surfaces, the mechanical bonding for the spray material can be made by grooving, rough turning, and abrasive blasting. However, rough turning is considered a faster method to cut the rough threads on the component-like round bar. In relation to this, Parmar [1] pointed out that the threading could be done with 12 to 16 threads/cm and with a maximum thread depth of 0.2 mm.

In the metal spraying process of a round bar, the spraying parameters can play an important role in controlling the coating thickness. It was established [2] that the coating thickness changes with the variation in spraying parameters: rotation speed (R.S), feed rate (F.R), and nozzle tip distance (N.D) to the substrate (round bar) (Fig. 1). When the rotation speed is increased, the thickness of the layer decreases, and voids may be produced. While decreasing the rotation speed under a correct value, a thick layer is produced which may result in oxidation due to the overheating of the substrate's surface. With regard to the feed rate, increasing it above the normal value may produce a very thin layer with a poor mechanical bond due to the use of insufficient spraying time, which does not let more molten particles build on the substrate. Using a very low feed rate, more particles can build, and consequently, a thick layer is produced. However, the mechanical bond is still poor due to more oxidation. With regard to the nozzle tip distance, the amount of torch heat for adequate particle melting must be balanced with the correct torch to substrate distance (see Fig. 1).

The strength of the coating can be assessed by tensile, compression, and bending tests. The bending test is very useful because during bending, the outer surface of the coating undergoes tension and inner compression due to the increase in deflection load. When the deflection is large without coating failure, this means that the strength of the coating is good inversely, its weak when the deflection is small with coating failure. By studying the combined relation of bending load, bending deflection, and the start of coating failure, the bending behavior of the coating can be assessed. Some researchers derived formulas for stress evaluation [3-5]. By considering the coating deposit on one side of a strip substrate, the bending stress was evaluated [6] by applying the deflection method which includes a cantilever beam. Ohring [7] determined the coating stress which was developed due to a mismatched force at the coating/substrate interface, then bent the coated strip by considering the coating on one side of the strip substrate and assumed both coating and substrate to be homogeneous. In addition, the average stress in the coating on the disk substrate was determined from the amount of deflection at the center of the disk caused by the depositition of the coating on one side [8]. The bending stress of the thin film was also investigated using the flat cantilever beam method [9]. However, there have only been very few published papers that applied the bending test to study the bending behavior of the coating of a round bar [2]. In this paper, the bending test is applied to calculate the modulus of elasticity and the yield bending stress of coating Lubrotec 19985 of a round bar.

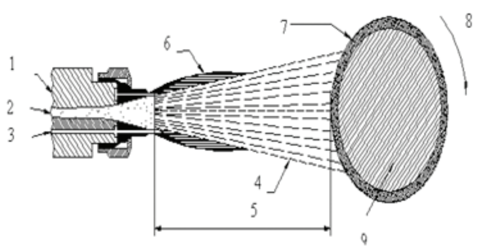


Fig. 1. Schematic of the general thermal spray process, 1-gun, 2-powder, 3-fuel gases, 4-spray stream, 5-nozzle tip distance, 6-burring gases, 7-sprayed material, 8-rotation, 9-bar.

2. Experimental work

A number of round bars of 13.6 mm diameter and 50 mm length made from low alloy steel were used. The chemical composition of this alloy is 0.075% C, 0.42% Mn, 0.52% Mo, 0.32% Si, 0.17% V, and 0.06% S. The yield bending stress is 1.56 GPa, and the hardness is 100 HV. For the coating process, two kinds of coating powder were used as spray metal. The primary one was Bond Coat (Xuper Bond) whose chemical composition is 43.6% Ni, 42% Al, 10.82% Pb, 0.3% Si, 1.90% Cr, 0.9% C, and 0.2% S. The function of the bond coat is to serve as a medium layer between the roughened surface of bars and the final coating. The final coating Lubrotec 19985 was chosen because it is suitable for overlay carbon and low alloy steels, cast iron, stainless steel, and nickel alloy; furthermore, its general-purpose, high-alloy powder provides coatings with outstanding frictional wear resistance. The chemical composition of Lubrotec 19985 is 67.26% Ni, 21.25% Cr, 7.3% Fe, 0.41% Mn, 3.52% Si, 0.25% V, 0.076% C, and 0.011% S.

Prior to the spraying process, the bars were roughened by the threading process with 14 threads /cm and a thread depth of 0.35 mm (Fig. 2).

After the roughening process, the surfaces were cleaned by heating them to a temperature of 110 ˚C at which grease, moisture, and other contaminations were evaporated. From the above, it can be noticed

Table 1. Results of the bending test, and the thickness and hardness of the produced coating.

Spraying parameters			Thickness of the coating (mm)	Bending test		Hardness (HV)
Rotation speed (r.p.m)	Nozzle distance (mm)	Feed rate (mm/rev)		Yield bending load (KN)	Yield deflection (mm)	
500	100	0.1	2.64	5.7	1.1	150
700	100	0.1	2.61	5.5	0.7	152
900	100	0.1	1.86	7.3	1.2	156
700	100	0.1	2.61	5.5	0.7	152
700	150	0.1	1.55	8.86	1.47	155
700	200	0.1	1.14	8.93	1.51	148
700	100	0.1	2.61	5.5	0.7	152
700	100	0.5	0.35	7.86	1.32	138
700	100	1.0	0.30	8.16	1.43	136

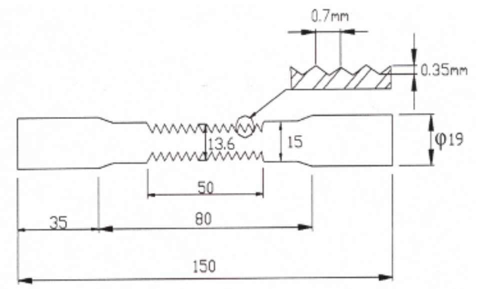


Fig. 2. The prepared specimen for the spraying process.

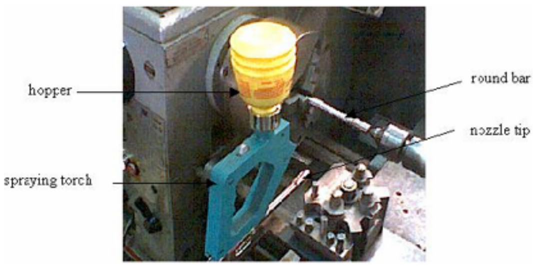


Fig. 3. The heating and spraying process of the specimen by moving the torch manually.

(b) Bent coated specimen with a thin layer

(b) Bent coated specimen with a thick layer

Fig. 4. Typical photograph of the bent coated bar with (a) thin layer, (b) thick layer.

that the roughening and cleaning processes are very important conditions before the actual spraying process. To continue the preparation for thermal metal spraying, the molten powder was prepared by heating it to a melting temperature inside the heating chamber using oxy-acetylene flam to the spraying torch (Fig. 3).

To carry out the spraying process, the roughened surfaces were sprayed by bond coat under the following spraying parameters: rotation speed of 700 r.p.m, feed rate of 1 mm/ rev, and nozzle tip distance to the substrate of 150 mm. One pass was sufficient to spray the bond coat. The maximum produced thickness of this layer was nearly 0.1 mm. Afterwards, the surface of the bond coat was heated by moving the flame torch manually along this surface until the temperature reached 200 ˚C. After this, the surface was immediately sprayed by final coat Lubrotec 19985. The

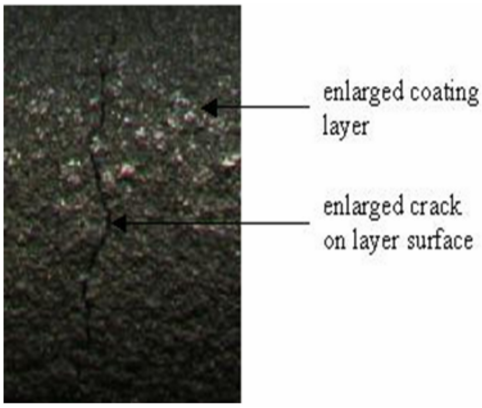


Fig. 5. Typical photograph of the crack initiation on the layer surface.

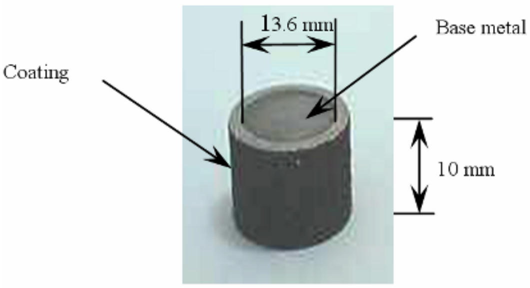


Fig. 6. Prepared specimen for the thickness and hardness measurement.

spraying process was conducted in three passes to ensure sufficient thickness of the coating under the spraying parameters given in Table 1. At the end of the spraying process, the bar was left to cool slowly.

The sprayed bars were gradually subjected against the bending load until the crack appeared on the coating surface. Figure 4 shows two bent coated bars with thin and thick coatings, respectively. The crack appeared on the surface of the thick coating, and the enlarged photograph of the crack is shown in Fig. 5.

To measure the thickness of the coating layer, a small piece was cut from the coated bar to the dimension shown in (Fig. 6). The thickness was measured by two methods: the first method employed a digital caliper, and the other, a moving microscope. The results obtained were nearly the same. With regard to the measurement of hardness, the same piece shown in Fig. 6 was used, and the hardness was measured on the outer surface of the coating. For each measurement, five readings were taken, and the average value was used. The results of the measurements are given in Table 1.

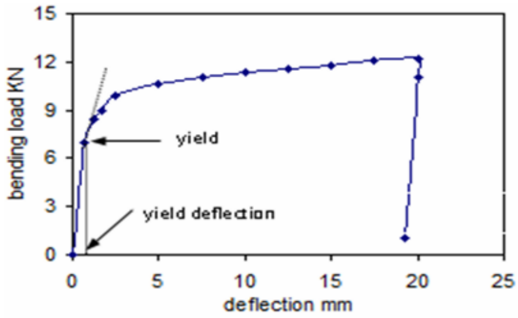


Fig. 7. The variation in bending loads with the deflection of the uncoated bar.

3. Results

During the bending test, the bending load against the bending deflection was plotted and recorded, as shown in Fig. 7.

For a given spraying parameter, the yield bending load and deflection were determined by plotting a tangent line to the straight line of the elastic limit of the load-deflection curve. The point of separation between the curve and the tangent line was considered the yield point. The same method was applied to the curves (Figs. 8-10), and the results obtained are given in Table 1. Figs. 8-10 illustrate the bending behavior of the coated bar. Generally, they show a narrow plastic zone because the material of the coating is hard. From Fig. 8, it can be seen that the total deflection at the rotation speed of 500 r.p.m. is larger than that of the others because after the appearance of the crack, it was difficult to stop the bending machine immediately. However, in this research, the total deflection and maximum bending load were out of calculation. Only the yield load and deflection were taken to calculate the yield bending stress and the modulus of elasticity in the elastic limit zone.

From Table 1, it can be concluded that generally, increasing any of the rotation speed, nozzle tip distance, and feed rate increases both the yield bending load and deflection; however, this decreases the layer thickness. In addition, the hardness slightly increases with an increase in the rotation speed and nozzle tip distance. However, it decreases with an increase in the feed rate to 0.5 and 1.0 mm/rev. This can be attributed to the production of a very thin layer of coating, which was responsible for the difficulty in precisely measuring the hardness. The lowest value of the hardness was 136 HV, and the highest value was156, which is considered acceptable.

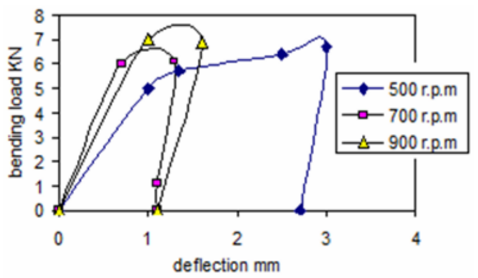


Fig. 8. The variation in bending loads with the deflection of the coated bar. N.D. = 100 mm, F.R. = 0.1 mm/ rev.

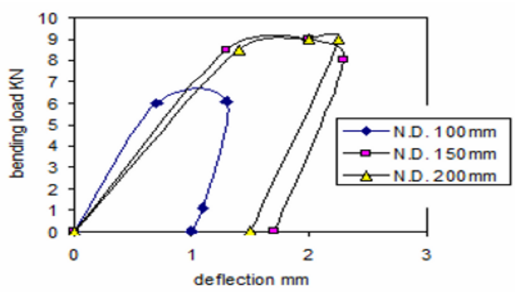


Fig. 9. The variation in bending loads with the deflection of the coated bar. R.S. = 700 r.p.m, F.R. = 0.1 mm/ rev.

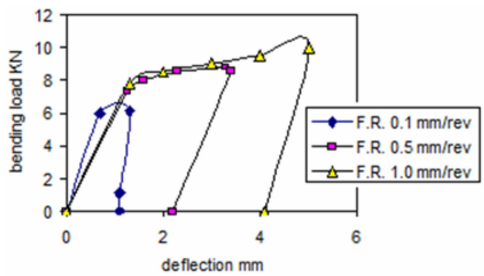


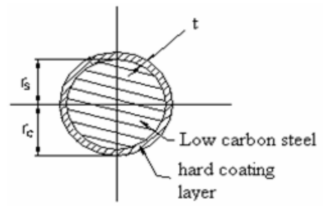
Fig. 10. The variation in bending loads with the deflection of the coated bar. R.S. = 700 r.p.m, N.D. = 100 mm.

Based on the data given in Table 1 and referring to Fig. 11, the bending stress can be calculated by applying the following flexure formula [10]:

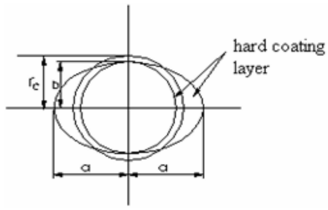
$$\sigma = \frac{M \cdot y}{I} \tag{1}$$

where σ = bending stress, MPa, M = bending moment N.m, y = distance from the centriod to the outer surface mm, and I = moment of inertia mm^4.

The final shape shown in Fig. 11(a) can be considered as a composite bar having two different materials. The inner material is the solid bar of low alloy steel, while the outer material is Lebrotec 19985. Hence, Eq.



(a) Cross-section of a composite bar



(b) Equivalent cross-sectional area

Fig. 11. Illustration of the transformation of the circular cross-section of a coated bar to an equivalent section: (a) cross-section of a composite bar, (b) equivalent-cross sectional area.

(1) together with the equivalent sectional area technique [10] can be applied to calculate the bending stress for both low alloy steel and coating material. Briefly, this technique is accomplished by changing the dimensions of the cross-section parallel to the neutral axis in the ratio of the elastic moduli of the materials. In this research, the cross-section of the coating material is considered as an equivalent section therefore, the dimensions corresponding to this material do not change. The horizontal dimension of low alloy steel is only changed by a ratio *n*, where $n=E_s/E_c$, E_s is the modulus of elasticity of low alloy steel, and E_c is the modulus of elasticity of the coating material. Mathematically, by knowing the modulus of elasticity of both materials, the ratio n can be found, and consequently, the equivalent cross-sectional area is determined.

Based on the above technique, the bar diameter 13.6 mm in the horizontal direction is only changed by a ratio n. With this, the cross-sectional area of the bar is changed from circular to elliptical section (Fig. 11(b)). Hence, the final shape consists of two sections (circular and elliptical) which have the same coating material. For the ellipse, the major axis 2a is changed depending on the ratio *n*, while the minor axis 2b is unchanged and is equal to 13.6 mm. To calculate the bending stress for the coating material, Eq. (1) is applied, and the moment of inertia *I* should be equal to the summation of both the inertia moment of ellipse I_e

and the circle (coating) I_c *(i.e.,* $I=I_e+I_c$*)*.

By assuming that the composite bar is simply a supported beam, the modulus of elasticity E can be found by applying the following deflection formula [10]:

$$\delta = \frac{P \cdot L^3}{48IE} \quad (2)$$

where δ= deflection mm, P= bending load KN, and L= distance between two supports of the bending machine = 110 mm. To determine E, Eq. (2) can be wrtten in the following form:

$$E = \frac{P \cdot L^3}{48I\delta} \quad (3)$$

By using Eq. (3), the modulus of elasticity of the coating material can be calculated by taking the values of P and δ from Table 1. Note that the moment of inertia of low alloy steel is taken as $I_s= (\pi/4)r_s^4$, and the moment of inertia for the coating layer $I_c=\pi t r_c^3$, where t = layer thickness and r_c = distance from the centroid to the surface of the coating layer (Fig. 10(a)). For a given spraying parameter, the modulus of elasticity of the coating material was calculated, and the results obtained are shown in Table 2. Moreover, two uncoated bars of low alloy steel were subjected to a bending test, and the load-deflection chart showed that the values of the yield bending load P_{ys} and deflection δ_{ys} were 7 KN and 0.7 mm, respectively. Based on these values and applying Eqs. (1and 3), the calculated values of the yield bending stress σ_{ys} and E_s of low alloy steel were 780 MPa and 165 GPa, respectively.

3.1 Sample of the calculation

At the beginning, the moduli of elasticity for both low alloy steel and coating material were calculated by applying Eq. (3). The modulus of elasticity of low alloy steel is calculated as follows:

$$E_s = \frac{P_{ys} \cdot L^3}{48 I_s \delta_{ys}} \quad (4)$$

P_s=7 KN, δ_s= 0.7 mm, L=110 mm. By substituting these values in Eq. (4),

$$E_s = \frac{7 \cdot 10^3 \cdot (110)^3}{48 \cdot 0.7 \cdot 1679.28} = 165.12 GP_a$$

For the coating material, the modulus of elasticity depends on the values of the yield bending load, the yield deflection, and the moment of inertia. From Table 1, by selecting the first parameter, we take

P_l=5.7KN, δ_l=1.1 mm,

$$I_c = \pi t r_c{}^3 = \pi \cdot 2.64 \cdot (\frac{13.6}{2} + t_1)^3 =$$
$$= \pi \cdot 2.64 \cdot (6.8 + 2.64)^3 = 6977.01 mm^4$$

Therefore, E_c can be calculated as follows:

$$E_c = \frac{P_1 \cdot L^3}{48 I_1 \delta_1} = \frac{5.7 \cdot 10^3 \cdot (110)^3}{48 \cdot 1.1 \cdot 6977.01} = 20.59 GP_a$$

To calculate the yield bending stress of low alloy steel σ_{ys}, Eq. (1) is applied:

$$\sigma_{ys} = \frac{M \cdot y}{I_s} = \frac{P_{ys} \cdot L \cdot y}{4 \cdot I_s}$$
$$= \frac{7 \cdot 10^3 \cdot 110 \cdot 6.8}{4 \cdot 1679.28} = 780 MP_a$$

To calculate the yield bending stress of the coating material σ_{yc}, Eq. (1) is again applied in the following form:

$$\sigma_{yc} = \frac{M \cdot y}{I} = \frac{P_1 \cdot \frac{L}{4} \cdot (\frac{13.6}{2} + t_1)}{I_e + I_c} \quad (5)$$

P_l= 5.7 KN, L=110 mm, t_l=2.64 m, I_c=6977.01 mm^4, $I_e= \pi a b^3/4$. To calculate I_e, a can be found as follows:

$$a = n\frac{d}{2} = \frac{E_s}{E_c} \cdot \frac{13.6}{2} = \frac{165}{20.59} \cdot 6.8 = 54.46 mm ,$$

where d= bar diameter. Therefore,

$$I_e = (\pi \cdot 54.46 \cdot (6.8)^3)/4 = 13449.13 mm^4 \text{ , and}$$
$$I_e + I_c = 13449.13 + 6977.01 = 20426.14 mm^4$$

By substituting the values in Eq. (5), the bending stress of coating material can be found:

$$\sigma_{yc} = \frac{5.7 \cdot 10^3 \cdot 110 \cdot 9.44}{4 \cdot 20426.14} = 72.43 MP_a$$

For a given spraying parameter, the same method described above is applied to calculate the modulus of elasticity and the yield bending stress of coating; the results obtained are given in Table 2. From the table, it can be concluded that the modulus of elasticity and the yield bending stress of the coating increase with an increase in the spraying parameters.

4. Discussion

The coating layer is so thin, thus it was very difficult to determine how the strength of this coating is influenced by the various spraying parameters. From Tables 1 and 2, it can be seen that increasing the rotation speed from 500 to 900 r.p.m decreases the layer thickness from 2.64 mm to 1.86 mm. This can be attributed to the use of a high rotation speed that will result in short spraying time. This in turn allowed less molten particles to build on the surface of the bar, thus a thin layer was produced. In contrast, a thick layer was obtained at low rotation speed because the spraying time was sufficient to let more molten particles build up on the surface of the bar. Accordingly, the strength of the coating is affected by the variation in layer thickness. When the coating layer was thick, the yield bending stress and modulus of elasticity were low. However, the decrease in thickness improved the yield bending stress and modulus of elasticity. The low strength of the produced coating may be due to the existence of voids and oxidations, which were observed by metallurgical examination. These undesirable defects resulted because of the greater heat produced during the spraying passes. Meanwhile, producing a thin layer allows less voids and oxidations to exist. The same trend was obtained when either the nozzle tip distance or feed rate was increased. As a result, a thick layer is not desired because the production of such thick layer needs more heat to be provided by spraying several times, using a short distance for the nozzle tip, and using a low rotation speed and low feed rate. These factors can cause low impact of the molten particles to the surface of the round bar. Consequently, there is a low density of the molten particles. A thin layer is therefore desirable. It can be concluded that coating strength is significantly influenced by the variation in layer thickness. From Table 2, it can be noted as well that when the feed rate is increased to 0.5 and 1 mm/rev with a rotation speed of 700 r.p.m and a nozzle tip distance of 100 mm, the values of both modulus of elasticity and bending stress increase sharply. This can be attributed to the production of a very thin coating layer of 0.35 and 0.30 mm, which in turn result in a low moment of inertia of 401.82 and 337.32 mm^4, respectively. Thus, these low values of the moment of inertia sharply increase the values of both E_c and σ_{yc}. Although these very thin layers produce a high E_c and σ_{yc}, they are not recommended because it is difficult to control the production of such thin layers during the spraying process, and their life span is also short. Hence, the 1.14 mm layer thickness is acceptable and recommended. Moreover, it is believed that this layer

Table 2. Results of the modulus of elasticity and the yield bending stress of coating.

Spraying parameters			Coating thickness (mm)	Calculated values of E_c and σ_{yc}					
Rotation speed (r.p.m)	Nozzle distance (mm)	Feed rate (mm/rev)		E_c (GPa)	$n = Es/Ec$	nd=2a (mm)	I_c (mm^4)	I_e (mm^4)	σ_{yc} (MPa)
500	100	0.1	2.64	20.5	8.01	54.46	6977.2	13449.13	72.4
700	100	0.1	2.61	31.8	5.18	35.22	6832.1	8697.5	91.6
900	100	0.1	1.86	44.4	3.71	25.22	3795	6226.8	174
700	100	0.1	2.61	31.8	5.18	35.22	6832.1	8697.5	91.6
700	150	0.1	1.55	58.9	2.79	18.97	2834.9	4684.64	270
700	200	0.1	1.14	91.4	1.80	12.24	1792.7	3022.05	404
700	100	0.1	2.61	31.8	5.18	35.22	6832.1	8697.5	91.6
700	100	0.5	0.35	410	0.40	2.73	401.91	674.14	1436
700	100	1.0	0.30	469	0.35	2.38	337.32	587.74	1722

E_s= modulus of elasticity of low alloy steel=165 GPa, d=13.6 mm.
E_c= modulus of elasticity of the coating layer, I_c= moment of inertia of the coating layer.
n= moduli ratio, σ_{yc} = bending yield stress of the coating layer.

thickness is applicable for repairing worn surfaces by using the metal spraying process.

5. Conclusion

(1) When the rotational speed, nozzle tip distance, and feed rate are increased, generally, the layer thickness decreases.
(2) A thick layer is not desirable because a low bending stress and modulus of elasticity are produced.
(3) A very thin layer is not recommended either because it is very difficult to control this during the metal spraying process.
(4) Applying a low rotation speed, low feed rate, and short nozzle tip distance provides more heat to the surface of the bar.
(5) For a round coated bar, the yield bending stress of the coating can be found by applying an equivalent cross-sectional area technique.
(6) Providing more heat to the round substrate may produce an oxidizing area. The existence of oxidation with voids results in the low mechanical interlock between the base metal and the coating.
(7) The hardness of the coating increased slightly with an increase in both the rotation speed and nozzle tip distance, and it decreased with an increase in the feed rate.
(8) The optimum spraying parameter was a rotation speed of 700 r.p.m, a nozzle tip distance of 200 mm, and a feed rate of 0.1 mm/rev. This optimum parameter produced a layer thickness of 1.14 mm, an E_c of 91.47 GPa, an σ_c of 404.9 MPa, and a hardness of 148 HV.

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