DEPOSITION EFFICIENCY OF CERAMIC COATINGS OBTAINED BY ROBOTIC FLAME PROJECTION

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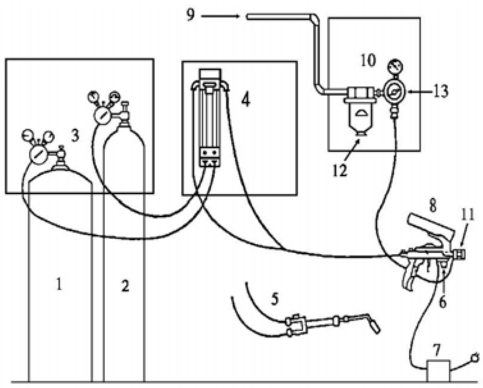
Abstract
In this paper are presented and discussed results obtained from robotic flame projection tests done on brass in the form of rigid sheet, carried out with the purpose to quantify the influence of the spray stream angle in the deposition efficiency of coatings of Nickel Aluminium-Molybdenum, Zirconia and Alumina. The coating thickness was obtained by three different methods: by coating weight, through non-destructive evaluation with a coating thickness gauges and by coating optical microscopy observation. The results obtained clearly suggest that the spray stream angle and the type of the projection material strongly influence the deposition efficiency. The analysis of the coatings microstructures, using optical microscopy, supports this observation.

Keywords: *Robotics, Thermospray, Deposition efficiency, Morphologic characterization*

1. Introduction

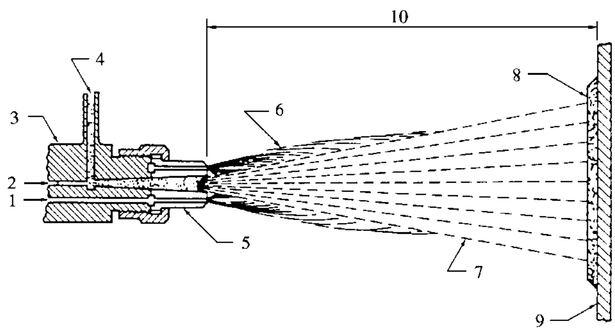
One of the possible applications of ceramic thermal barriers is in shells (permanent moulds – die casting) [Shimizu, *et al.*, 1990]. The shells` capacity to support very high temperatures plays a crucial role in the selection of materials due to the liquid state of the cast iron. The ceramic materials could be a possible choice owing to its morphologic structure. However, these materials due to its brittleness cannot support mechanical and thermal shocks. In order to overcome this problem the use of ceramic coatings on metallic substrates is a good alternative in the measure that this association can support the mechanical loads involved.

In order to ensure a high performance of these composite moulds it is essential optimize the robotic flame projection parameters to assure a coating with appropriate thickness and that it presents a good adhesion to the metallic substrate of the shell. Thermal spraying using the heat from a chemical combustion is known as flame spraying. The spraying material, initially in the form of powder, rod, cord or wire is warm for a fire produced by a flame spray gun that can be adapted to use several types of combustible gases, such as, acetylene, hydrogen, propane and natural gas. As the materials are heated, they change to a plastic or molten state, and are accelerated by a compressed gas. The confined stream of particles is conveyed to the substrate. The particles strike the surface, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared surface and to each other. As the sprayed particles impinge upon the substrate, they cool and build up, particle by particle, into a lamellar structure, thus a coating is formed [Mahood *et al.*, 1990, Clare and Crawmer, 1987 and Ducos, M., 1989]. Figure 1 shows a general view of the equipment used in powder flame projection and Fig. 2 illustrate the spray gun.



1 - Fuel gas
2 - Oxygen
3 - Gas control unit
4 - Gas flow meter
5 - Heating torch
6 - Vibrator
7 - Transformer
8 - Thermo spray gun
9 - Air supply
10 - Air control unit
11 – Air cooler
12 – Air filter
13 – Air regulator

Figure 1. Typical equipment of the powder flame spray.



1 - Oxygen input
2 - Fuel gas input
3 - Gun
4 - Powder
5 - Nozzle
6 - Flame
7 - Spray stream
8 - Coating
9 - Substrate (material to coating)
10 - Spraying distance: 75 to 254 mm

Figure 2. Cross section of a powder flame spray gun.

Ceramic coatings obtained by flame spraying are used on several metallic materials, subjects to oxidation conditions and corrosion at room temperature or at high temperatures applied in components of furnaces, equipments for thermal treatments or processing of chemical substances, pieces of combustion motors and among others. The coatings done by flame spraying usually have thickness that can vary from 50µm to few millimetres. The thickness proposed for the coating will be an important factor in the selection of the appropriate type of the coating, because the materials presents distinguish properties to different thickness. Usually the properties intended for a coating that works as thermal barrier, they are [Duarte, M. T., 1992]:

- Good adhesion to the substrate in order to support the residual tensions involved that can cause fissures and the destruction by lifting of the coating;
- Low thermal conductivity (to avoid the transfer of heat for the substrate);
- Proximity of the thermal expansion coefficients among the ceramic or metallic elements of the coating and the substrate material;
- Appropriate stability of the crystalline structure to the service temperatures;
- High reflectivity;
- To be possible repair the coating after it has been deteriorated in service.

The ceramic materials used in thermal barriers should be porous, not only for strongly reduced the heat transfer (the air is bad conductive of heat) but also to improve the thermal shock resistance of the coating. These materials are based on oxides, cermets, nitrates, silicates, intermetallic compounds, some organic plastics and certain glasses. The materials more used in thermal barriers are the zirconia (ZrO_2) and the alumina (Al_2O_3).

2. Robotic flame spraying tests

The objective of the tests was to quantify the effect of the spray stream angle and the type of the sprayed material on the deposition efficiency of coatings on a metallic material typically used in the shells manufacture (permanent moulds – die-casting) used for the leak of metallic alloys, namely the cast iron.

To achieve this objective was selected the brass for the substrate to build permanent moulds, and the Nickel-Aluminium-Molybdenum for the bond coating, and the Zirconia and Alumina for the coating, which can support the very high temperatures due to the liquid state of the cast iron. Using these materials six spraying flame tests was performed, whose description is presented in the Tab. 1.

Table 1. Main specifications of the flame spraying tests.

Spraying test	*Sprayed material*	*Spray stream angle*
1	Ni-Al-Mo	90º
2	Ni-Al-Mo and Zirconia	90º
3	Ni-Al-Mo and Alumina	90º
4	Ni-Al-Mo	65º
5	Ni-Al-Mo and Zirconia	65º
6	Ni-Al-Mo and Alumina	65º

Thus, several spray flame tests were performed to cover specimens of brass with 130 mm of length, 90 mm of width and 20 mm of thickness. The area of the specimen that is covered corresponds to the area of 130 x 90 mm^2. Table 2 lists the main relevant properties of the material used for the substrate.

Table 2. Mechanical, chemistries and physics properties of the brass [ASM Handbook, 1990].

Tensile strength [MPa]	414
Elastic tensile strength [MPa]	138
Elongation [%]	30
Macrohardness [HB10]	110
Thermal conductivity [W/mK]	123
Coefficient of thermal expansion [µm/mK]	20,9 (20-300°C)
Typical composition	Cu - 57% Zn - 40% Pb - 3%
Density [kg/m3]	8200
Melting point [°C]	890

The flame spraying was made using a flame thermal spray robot type METCO AIR 2000 (Mitsubishi), shown in Fig. 3, which has an articulate construction of six rotation axes with the intent of guarantee precision and repetitively for the displacement of the spray gun. Figure 4 depicts the spray gun displacement that it was used in all the performed spraying tests in order to obtain different types of coatings on the brass substrates.

Figure 3.Flame thermal spray robot.

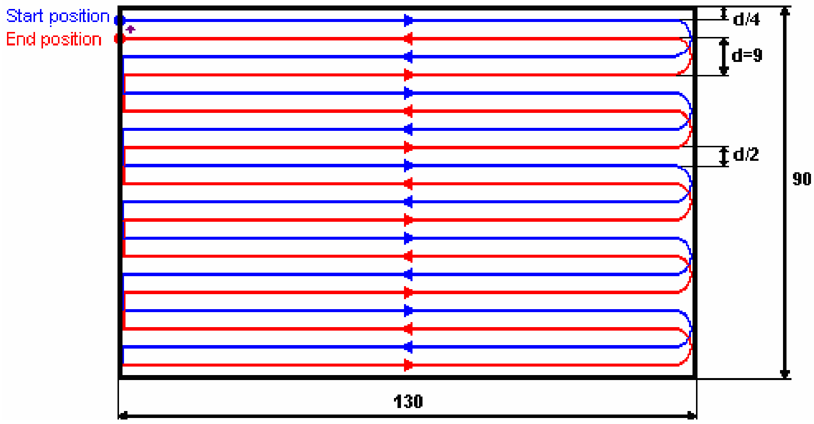


Figure 4. Spray gun displacement used on the brass specimens.

The programming of the spray gun displacement was made in the robot consoles, and it allows changing the distance among lines of the displacement (d), the number of passes, the speed of gun displacement and the spraying distance. The distance among lines of the displacement (d) was arbitrated, but it should be the smallest that does not induce an exaggerating heating in the substrate. On the other hand, as smallest it was, better will be the surface finish of the coating. According to Fig. 4, the distance between the start and end position of the gun displacement corresponds to a complete sprayed pass which, computes in 2770 mm. The number of sprayed passes used in the spraying tests depends on the thickness intended for the coating and of the spraying parameters of the powders used. Therefore, Tab. 3 lists the main characteristics of the powders sprayed and Tab. 4 present, in function of the thickness intended for the three sprayed coatings, the number of passes and spray gun velocity used in the performed spraying tests.

Table 3. Physical and chemistries properties and respective spraying parameters of the powders used [METCO, 1982].

Spraying parameters and powders properties	*Spraying powders*		
	METCO 447NS (Mo-Ni-Al)	METCO 201NS (zirconia)	METCO 105NS (alumina)
Nozzle type of the spray gun	K	K	K
Acetylene flow [l/min]	26,5	22	22
Oxygen flow [l/min]	42	30	37
Nitrogen flow [l/min]	6,9	6,9	6,9
Acetylene pressure [bar]	1,5	1,5	1,5
Oxygen pressure [bar]	4,5	4,5	4,5
Nitrogen pressure [bar]	5,5	5,5	5,5
Air jet pressure [bar]	-	-	5
Rotation speed of the powder feeder [rpm]	9,8	11,6	9,3
Spray rate [g/min]	34	30	15
Spray distance [mm]	140	75	75
Typical composition	Ni - 89,5% Al - 5,5% Mo - 5%	ZrO_2 - 93% CaO - 5% Al_2O_3 - 0,5% SiO_2 - 0,4% others - 1,1 %	Al_2O_3 - 98,5% SiO_2 - 1% others - 0,5 %
Melting point [°C]	660	2535	2000
Typical size range [µm]	+45 -88	+10 -53	+15 -53
Density [kg/m^3]	7200	5200	3200
Porosity [%]	< 2	10	2
Powder weight per area of coating thickness of 0,1 mm [Kg/m^2]	0,8	1,04	1,07
Coating weight per area of coating thickness of 0,1 mm [Kg/m^2]	0,72	0,52	0,32
Deposition efficiency [%]	90	50	30
Spray gun velocity [m/min]	15-25	12-24	1,22

Table 4. Number of passes and spray gun velocity for each sprayed material.

Sprayed powder material	*Thickness intended* [mm]	*Number of passes*	*Spray gun velocity* [m/min]
Ni-Al-Mo	0,1	2	20
Zirconia	0,2	6	20
Alumina	0,25	1	1,35 *

* It was not possible spraying with the gun velocity recommended (1,22 m/min), due to reason of the robot controller only to allow to select discrete values between 0 and 90 m/min with a minimum increment of 0,27 m/min.

The experimental spraying tests were performed according to the followings steps:

❶ - *Abrasive blasting of the specimen's surface*

To obtain a coating with the required mechanical adhesion it is necessary create a certain roughness in the substrate surface for the melted sprayed particles could adhere strongly. The increase of the roughness enhances the coating adhesion, due to the following reasons [Mahood *et al.*, 1990]:

- Originates compressive tensions in the coating;
- Promotes the connection between the layers of the coating;
- Increases the connection surface;
- Cleaning the surface.

❷ - *Robotic preheating with oxyacetylene flame*

It is used with the purpose to reduce the residual tensions of the coatings obtained by flame spraying, due to the expansion that causes in the substrate. In addition, the preheating of the substrate does not allow that the water vapour product of the oxyacetylene combustion condenses in the surface, which can originate decreasing of the coating adhesion. The temperature used to preheating the substrate is about 100 °C to guarantee that the surface be always drought. Figure 5 shows a phase of the robotic preheating with oxyacetylene flame.

❸ - *Robotic spraying of the bond coating (Nickel-Aluminium-Molybdenum)*

This type of materials based in Nickel-Aluminium, creates coatings with good adhesion because during its flame spraying occurs an exothermic reaction among the aluminium and the nickel that brings additional heat to the process. Therefore, it could be observed some local welding which increases the adhesion between the sprayed particles and the substrate [Duarte, M. T., 1992]. Figures 6 and 7 show, respectively, a phase of the robotic spraying of the bond coating and the final appearance of the coating.

Figure 5. Robotic oxyacetylene preheating (spray angle 65°).

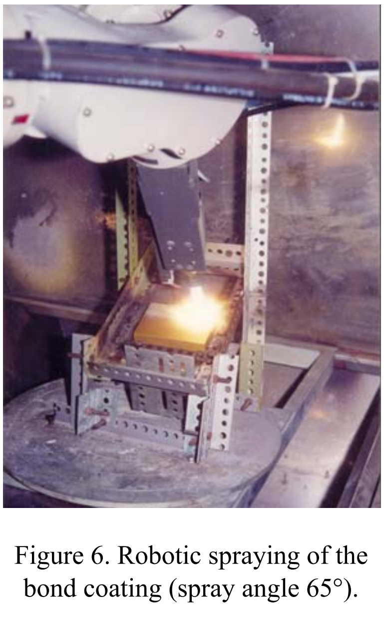


Figure 6. Robotic spraying of the bond coating (spray angle 65°).

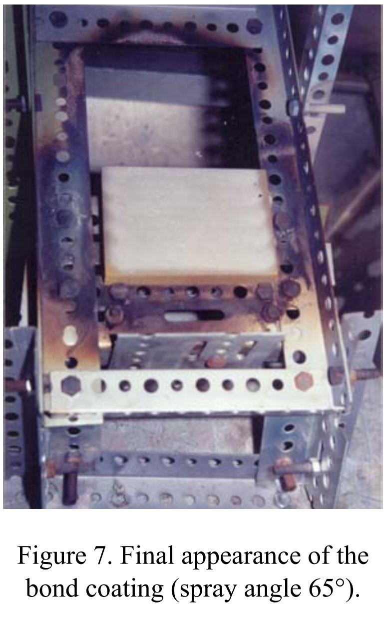


Figure 7. Final appearance of the bond coating (spray angle 65°).

❹ - *Robotic spraying of the zirconia coating* (this step was only performed for the spraying tests 2 and 5)

The objective of the spraying of zirconia was using a material that for their properties is considered a thermal barrier [Ingham and Shepard, 1967]. Figures 8 and 9 show, respectively, a phase of the robotic zirconia spraying and the final appearance of the coating compose by the bond coating and zirconia.

❺ - *Robotic spraying of the alumina coating* (this step was only performed for the spraying tests 3 and 6)

The objective of the spraying of alumina was using a material that for their properties is considered a thermal barrier [Ingham and Shepard, 1967]. Figure 10 shows a phase of the robotic spraying of the alumina coating using an air jet with a pressure of 5 bar.

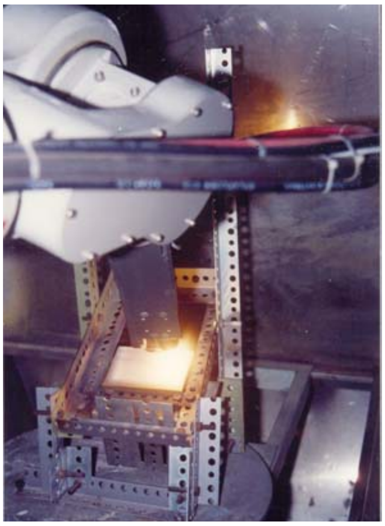


Figure 8. Robotic spraying of the zirconia coating (spray angle 65°).

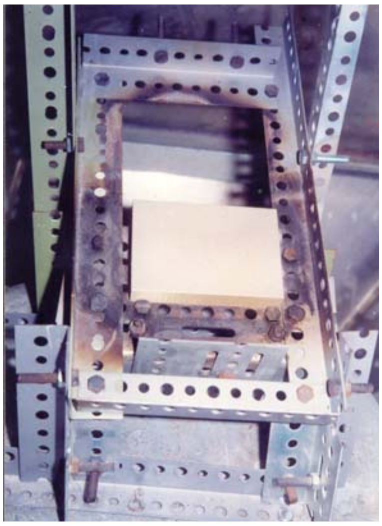


Figure 9. Final appearance of the zirconia coating (spray angle 65°).

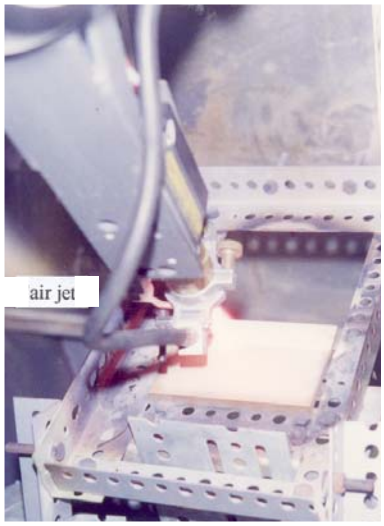


Figure 10. Robotic spraying of the alumina coating (spray angle 65°).

3. Results and discussion

Table 5 presents for the spraying tests performed with a spray angle of 90° and 65° a comparison among the values of coating thickness, obtained by three methods, such as, by coating weight, through non-destructive evaluation with a coating thickness Eddy currents gauge (was not used in the coatings sprayed to 65º) and by coating optical microscopy observation.

Table 5. Comparison of the values of the coatings thickness obtained by several methods.

Spraying test	*Spray angle*	*Coating*	*Coating thickness* [mm]		
			Weight	*Gauge*	*Optical microscopy*
1	90º	Bond coating (Ni-Al-Mo)	0,13	0,43	0,12
2		Bond coating (Ni-Al-Mo)	0,13*	0,43*	0,12
		Zirconia (ZrO_2)	0,13	0,15	0,13
		Bond coating + Zirconia	0,26	0,58	0,25
3		Bond coating (Ni-Al-Mo)	0,13*	0,43*	0,12
		Alumina (Al_2O_3)	0,10	0,11	0,11
		Bond coating + Alumina	0,23	0,54	0,22
4	65º	Bond coating (Ni-Al-Mo)	0,12	----	0,11
5		Bond coating (Ni-Al-Mo)	0,12*	----	0,11
		Zirconia (ZrO_2)	0,10	----	0,10
		Bond coating + Zirconia	0,22	----	0,21
6		Bond coating (Ni-Al-Mo)	0,12*	----	0,11
		Alumina (Al_2O_3)	0,07	----	0,07
		Bond coating + Alumina	0,19	----	0,18

* The assumption that the bond coating (Ni-Al-Mo) has approximately the same thickness in the spraying tests performed with an equal spray angle, due to being similar the spraying conditions, it was demonstrated by the coating optical microscopy observation.

Analysing Tab. 5 it can be verified that the coatings thickness measure using the Eddy currents gauge are much higher than the expected ones. This is due to the reason of the material of the bond coating (metallic alloy: Ni-Al-Mo) to be electrical conductor and for that, its thickness was incorrectly measured by the Eddy currents gauge. This probe type only allows to correctly measuring the thickness of insulating coatings, as they are the ceramic coatings of zirconia and alumina. Furthermore, it can be conclude that a good correlation exists between the thickness values obtained through the weight of the coating and by the microscopic observation of the coating. According to this statement, some conclusions can be drawn, namely: the veracity of the porosity value considered in the mass density (Tab. 3) which was used in the determination of the thickness of the coatings through the weight and that the porosity of the coatings sprayed to 65 and 90° is equal.

Figures 11, 12, 13, 14, 15 and 16 show optical microscopy microphotographs of the coatings on brass substrate, respectively, obtained in the spraying tests 1, 2, 3, 4, 5 and 6. The coating porosity corresponds to the darker points in the microphotographs which are indicated by the letter P.

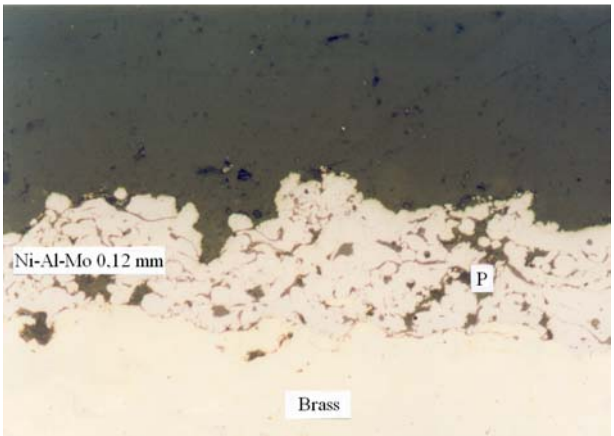


Figure 11. Enlargement 200x. Nickel- Aluminium-Molybdenum sprayed to 90°.

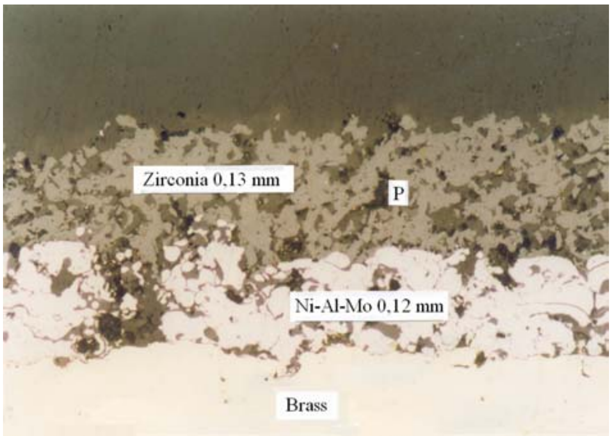


Figure 12. Enlargement 200x. Nickel- Aluminium-Molybdenum and zirconia sprayed to 90°.

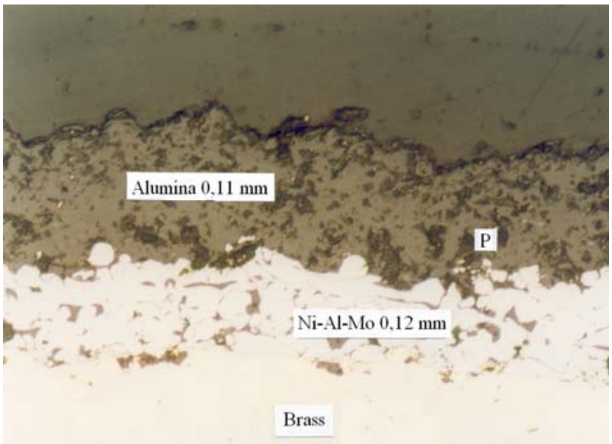


Figure 13. Enlargement 200x. Nickel- Aluminium-Molybdenum and alumina sprayed to 90°.

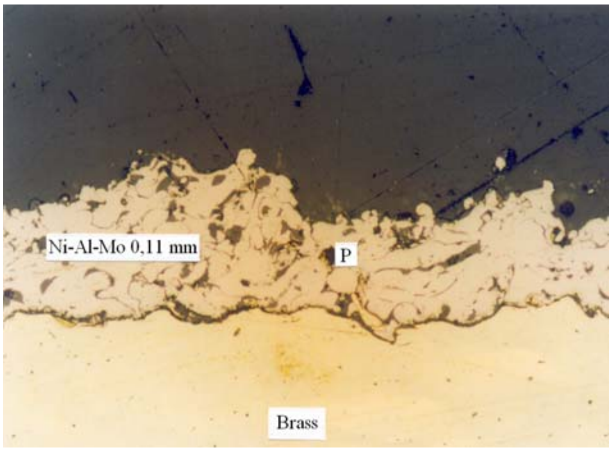


Figure 14. Enlargement 200x. Nickel- Aluminium-Molybdenum sprayed to 65°.

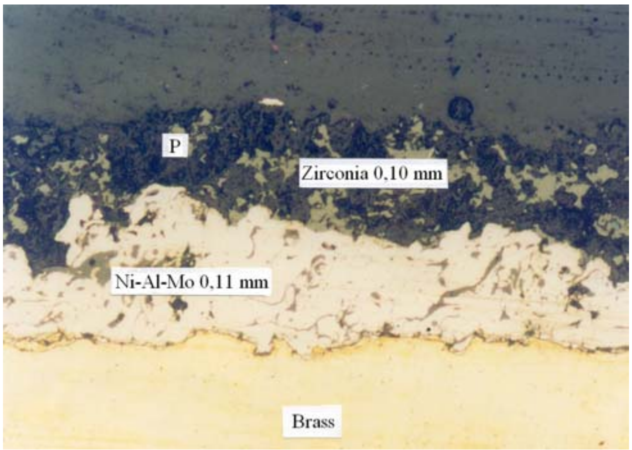


Figure 15. Enlargement 200x. Nickel- Aluminium-Molybdenum and zirconia sprayed to 65°.

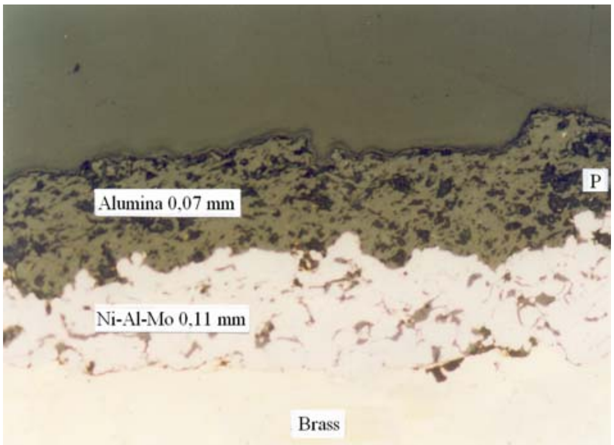


Figure 16. Enlargement 200x. Nickel- Aluminium-Molybdenum and alumina sprayed to 65°.

Analysing the Fig. 11, 12 and 13 that correspond to the three coatings sprayed to 90º, it can be verified that the bond coating of Ni-Al-Mo have the same thickness and presents little porosity (darker points - letter P) that is typical in this type of coating. However the zirconia coating (Fig. 12) presents more porosity than the bond coating that is natural since the zirconia doesn't melted unlike what happens with the Nickel-Aluminium-Molybdenum and the alumina coating (Fig. 13) present little porosity. The obtained values are in agreement with the literature where are expected porosities of < 2% in the bond coating, 10% in the zirconia and 2% in the alumina.

On the other hand, observing the Fig. 14, 15 and 16 that correspond to the three coatings sprayed to 65º, it was also concluded that the bond coating of Ni-Al-Mo have the same thickness and the porosities in the bond coating, zirconia and alumina are similar to those obtained in the coatings sprayed to 90º. It should be mentioned that the zirconia coating, illustrate in Fig. 15, presents many darker points - letter P, but they are not all due to the porosity, many of them were originated in the polishing of the sample.

Figures 17 and 18 depict the influence of the spraying angle, respectively, in the coating thickness and in the deposition efficiency, for the three spraying coatings.

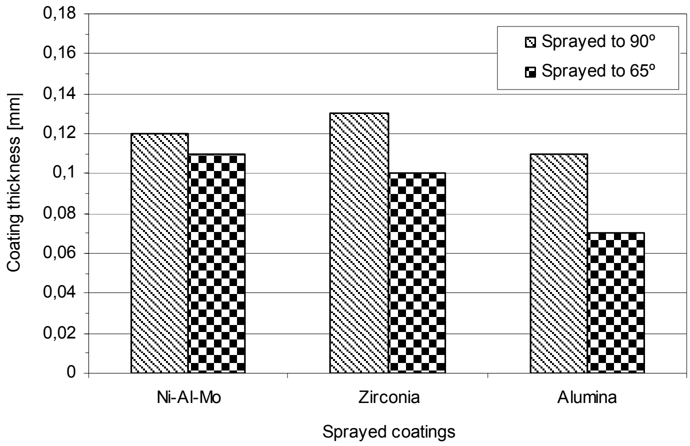


Figure 17. Influence of the spray angle in the coating thickness obtained by optical microscopy observation.

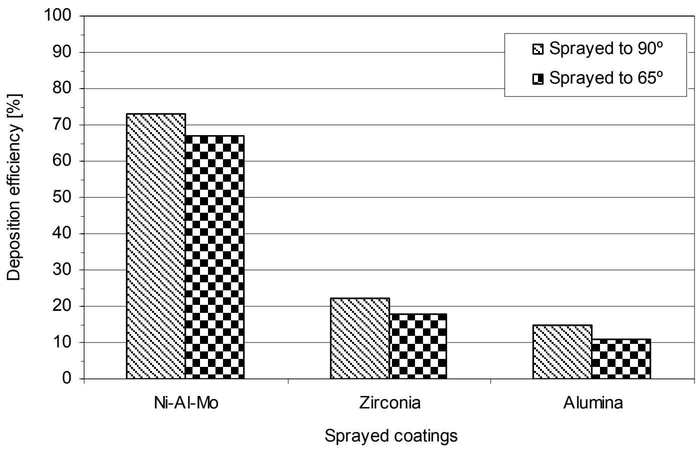


Figure 18. Influence of the spray angle in the deposition efficiency of the coatings.

It can be concluded observing Fig. 17 and 18 that the spraying angle of 65°, relatively to 90º, originates coatings with smaller thickness and deposition efficiency for all the sprayed coatings.

The maximum value of deposition efficiency is obtained with a spraying angle of 90° (perpendicular to the substrate surface) because does not have horizontal spraying component (parallel to the substrate surface) that provokes great material losses for "skidding". In the case of the sprayed to 65° the horizontal spraying component implicates larger material losses, that it originates smaller deposition efficiency and consequently smaller thickness of the coating.

The sprayed to 65° decrease more the deposition efficiency in the coatings of zirconia and alumina than in the bond coating (Ni-Al-Mo). This can be explained due to the different spraying distances used. For the sprayed of Ni-Al-Mo the spraying distance used was 140 mm and for the zirconia and the alumina was only 75 mm. As greater it is the spraying distance lesser will be the velocity of the particles when they reach the substrate surface. Therefore, for the sprayed of the zirconia and alumina the distance is smaller than in the spraying of the Ni-Al-Mo and the particles strike the surface with more velocity and they happen more material losses due to the horizontal spraying component. In the case of the sprayed of the alumina it was more stronger this effect due to the use in the spraying of air jet (compressed air) that still accelerates more the particles, what originates the worst spraying results.

Figure 19 shows, for the three spraying coatings, a comparison among the value of deposition efficiency obtained in the tests sprayed to 90° with the corresponds manufacturer catalogue value (Tab. 3).

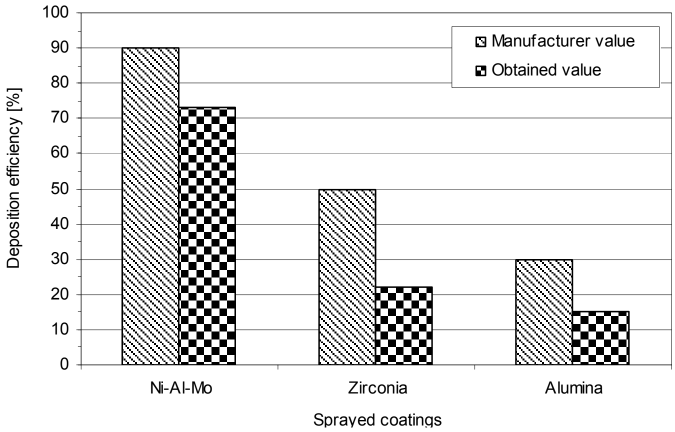


Figure 19. Deposition efficiency versus manufacturer value for the coatings sprayed to 90º.

Analyzing Fig. 19 is verified that the values of deposition efficiency of the sprayed to 90° are much smaller than the values provided by the manufacturer, especially for the zirconia and alumina coatings.

It can be justified be the reason of the spraying conditions have not been identical, such as, the spray gun displacement, the preheating substrate temperature, the material of the substrate, and others.

4. Conclusions

In this paper a study of the deposition efficiency of flame sprayed ceramic coatings obtained by robotic projection are presented and discussed and the main conclusions observed throughout this work are listed in what follows:

(i) the connection among the layers of the sprayed coatings seems good because fissures are not visualized;

(ii) the coatings sprayed to 65 and 90° have similar porosities that correspond to the values provided by the manufacturer;

(iii) the deposition efficiency for all the sprayed materials reaches the maximum value with the spraying to 90° therefore they are obtained the largest thickness of the coating for same time and spraying rate;

(iv) the values of deposition efficiency of the sprayed to 90° are lesser than the manufacturer catalogue values, especially for the zirconia and alumina coatings;

(v) the sprayed to 65° decrease more the deposition efficiency, relatively to 90º, in the ceramic coatings of zirconia and alumina than in the bond coating (Ni-Al-Mo).

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6. Responsibility notice

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