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Evaluation of the Possibility of Applying Thermal Barrier Coatings to AlSi7Mg Alloy Castings

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Abstract

This paper analyses the possibility of applying thermal barrier coatings (TBCs) onto a substrate made of the AlSi7Mg alloy, intended for, among other things, internal combustion engine components. Engine components made of aluminum-silicon alloys, especially pistons and valve heads, are exposed to high temperature, pressure and thermal shock resulting from the combustion of the fuel-air mixture. These factors cause degradation of these components and can lead to damage. To minimize the risk of damage to engine components caused by heat stress, one way is to apply TBCs. Applying TBCs coatings to engine components improves their durability, increases power output and reduces fuel consumption. The research scope includes the application of an Al2O3-TiO3 coating via the APS (Air Plasma Spraying or Atmospheric Plasma Spraying) method onto a substrate of the AlSi7Mg alloy, analysis of the microstructure and chemical composition of the substrate and coating material, and assessment of the quality of the coating's bond with the AlSi7Mg alloy substrate using the scratch test method.

Keywords: Thermal barrier coating, Aluminum-silicon alloy, Atmospheric plasma spraying

1. Introduction

Aluminum-silicon alloys are used where low weight of elements and good strength properties in relation to weight, low coefficient of thermal expansion and excellent resistance to wear and corrosion are required [1]. Due to their characteristic casting and mechanical properties, they have been used as innovative materials used in the aviation and automotive industries for components of internal combustion engines, such as engine blocks, pistons and cylinder heads [2-5].

Engine components made of aluminum alloys, in particular pistons and valve heads, are exposed to high temperature, pressure and thermal shock resulting from the combustion of the air-fuel mixture. These factors cause degradation of these components and may lead to their failure. Research by the authors of the publication [6] shows that the surface of pistons made of aluminum alloy may melt during long-term operation of the engine. Then, rapid cooling can lead to crack formation. The authors of papers [7-9] point out that with thin walls of valve seats, as a result of excessive heat load caused by the engine operation cycle and the combustion of the fuel-air mixture, high stresses may arise, and consequently cause cracks in them.

To minimize the risk of damage to engine components caused by thermal stress, it is important to use appropriate materials or technological treatments. One of the ways to improve resistance to heat loads is the use of TBCs (Thermal Barrier Coatings) coatings. These coatings have low thermal conductivity, which creates an insulating layer between hot exhaust gas and engine components. The authors of papers [10,11] confirm that the application of coatings significantly improves the durability of elements exposed to high temperatures and thermal shocks. The emission of gas from the combustion chamber is also reduced. In [12], it was also confirmed that applying TBCs coatings to engine components improves their durability, increases power and reduces fuel consumption.

The aim of the study was to analyze the possibility of applying TBCs onto a substrate made of the AlSi7Mg alloy to limit the thermal impact of the fuel combustion process on the microstructure. The research scope includes the application of an Al2O3-TiO2 coating via the APS method onto a substrate of the AlSi7Mg alloy, analysis of the microstructure and chemical composition of the substrate and coating material, and assessment of the quality of the coating's bond with the AlSi7Mg alloy substrate using the scratch test method.

2. Materials and Research Methodology

The material for the research was a casting made of the AlSi7Mg alloy (Table 1).

Table 1.
Results of the chemical composition analysis of the AlSi7Mg alloy, weight %

Si	Mg	Mn	Fe	Al
6.97	0.29	0.01	0.10	Remainder

Figure 1 presents an example of the microstructure of the AlSi7Mg alloy. This is a typical microstructure of sub-eutectic silumin, consisting of pre-eutectic dendrites of the α(Al) phase and the eutectic mixture α(Al)+β(Si) spread along the boundaries of these dendrites. Observation of the microstructure of this alloy also revealed the presence of bright precipitates in the areas of eutectic silicon.

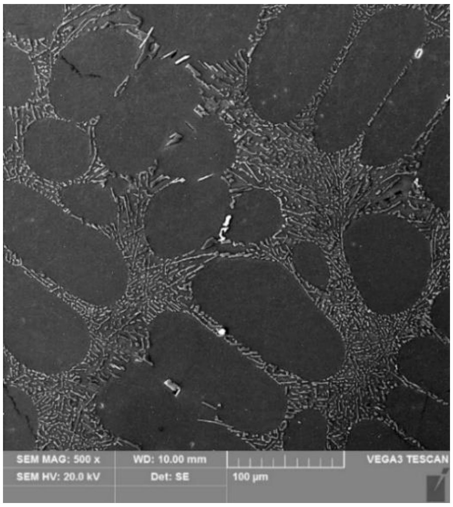
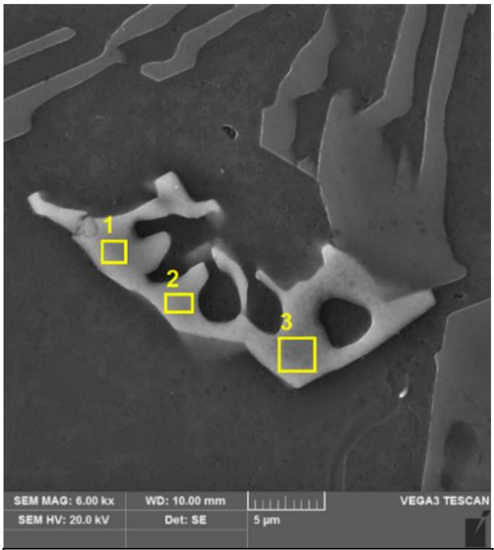


Fig. 1. SEM image of an example microstructure of the AlSi7Mg alloy

To identify intermetallic phase precipitates in the area of eutectic silicon precipitates, an X-ray microanalysis of the chemical composition was carried out show in Figure 2.



Point	Chemical composition, % wt.		
	Al	Si	Fe
1	45.96	39.18	14.86
2	48.92	39.33	11.75
3	70.81	12.00	17.19

Fig. 2. Results of the X-ray microanalysis of intermetallic phases in the microstructure of the AlSi7Mg alloy

From the group of TBCs, the Al2O3-TiO2 coating was chosen. The powder to make this coating contained: 60% Al2O3 and 40% TiO2. A view of the Al2O3-TiO2 powder particles is shown in Figure 3.

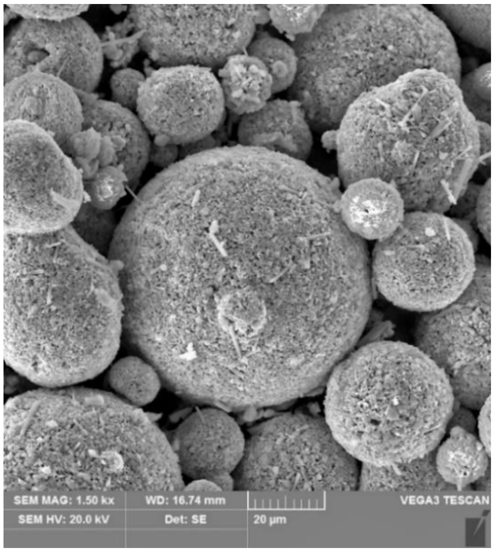
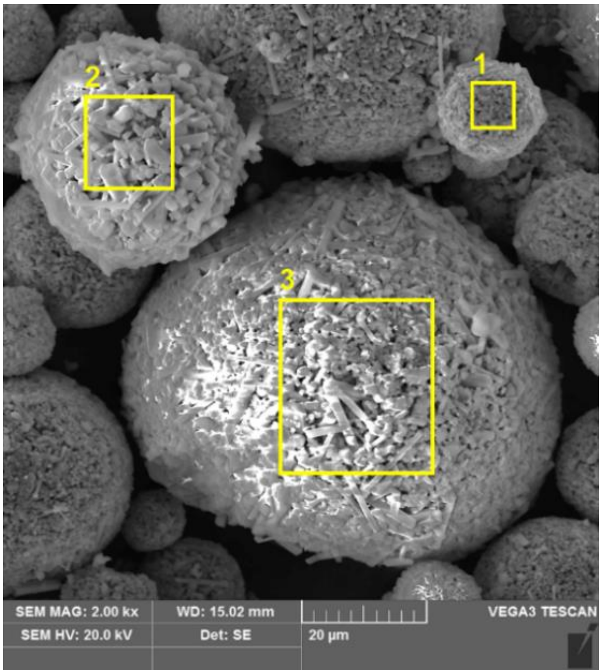


Fig. 3. SEM image of the Al2O3-TiO2 powder

In order to verify the chemical composition of the powder, which consisted of spherical grains with granulation from 10 to 70 μm, an X-ray microanalysis of the chemical composition was performed, the results of which are shown in Figure 4.



Point	Chemical composition, % wt.		
	O	**Al**	**Ti**
1	53.35	10.18	36.47
2	37.87	27.77	34.37
3	49.40	16.41	34.19
4	38.57	11.86	49.57

Fig. 4. Results of the X-ray microanalysis of the Al2O3-TiO2 powder

The coating process was carried out using the APS method. The parameters of applying the Al2O3-TiO2 coating by the APS method are presented in Table 2. Before applying the coating, the substrate material was subjected to blasting treatment to achieve better adhesion of the coating to the substrate.

Table 2.
Parameters of applying the Al2O3-TiO2 coating using the APS method

Carrier gas:	4 l/min
Feeder disk speed:	0.9 rpm
Mixer:	90%
Amperage:	600 A
Ar plasma-generating gas:	55 l/min
H_2 plasma-generating gas:	15 l/min
Air jet:	3 bars
Spraying distance:	100 mm
Linear speed of the burner:	250 mm/min
Layer thickness:	325-350 μm
Number of burner passes:	27

A view of the surface of the Al2O3-TiO2 coating applied to the AlSi7Mg alloy casting is shown in Figure 5.

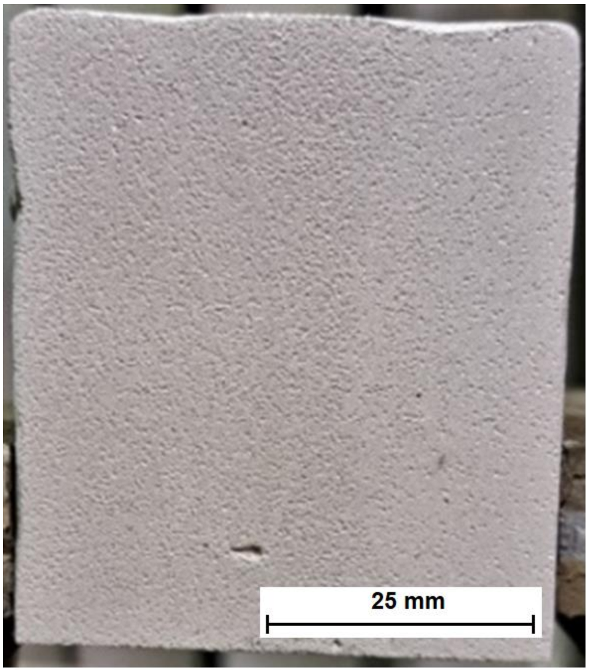


Fig. 5. View of the surface of the Al2O3-TiO2 coating applied to the AlSi7Mg alloy casting

Microstructure observation was carried out on metallographic specimens. To reveal the microstructure, the specimens were ground and polished, and then etched with a 3% solution of hydrofluoric acid.

Microstructure analysis and X-ray microanalysis of the chemical composition were performed using the TESCAN Vega 3 scanning microscope with the INCA X-ACT attachment for chemical composition microanalysis (OXFORD).

To assess the quality of the substrate-coating connection, scratch tests were carried out. The scratching was done using the Revetest Scratch Tester RST. The scratch, from the substrate material (AlSi7Mg alloy) to the coating, was 1 mm long. A constant Rockwell indenter load of 5N was used. The scratching speed was 5 mm/min.

3. Research Results and Their Analysis

An example view of the Al2O3-TiO2 coating applied to the AlSi7Mg alloy casting is shown in Figure 6. An X-ray microanalysis of the chemical composition of the coating was also carried out shown in Figure 7.

The results of SEM observations and chemical composition analysis of the coating indicate that its phase composition includes titanium oxides and aluminum oxides, partially or completely melted in the plasma arc stream.

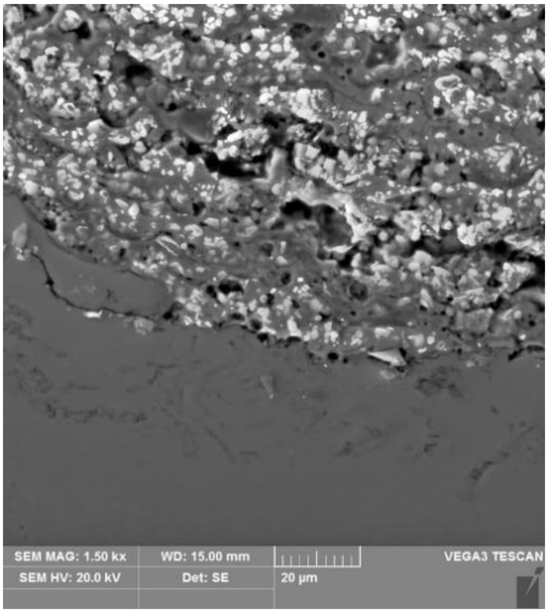
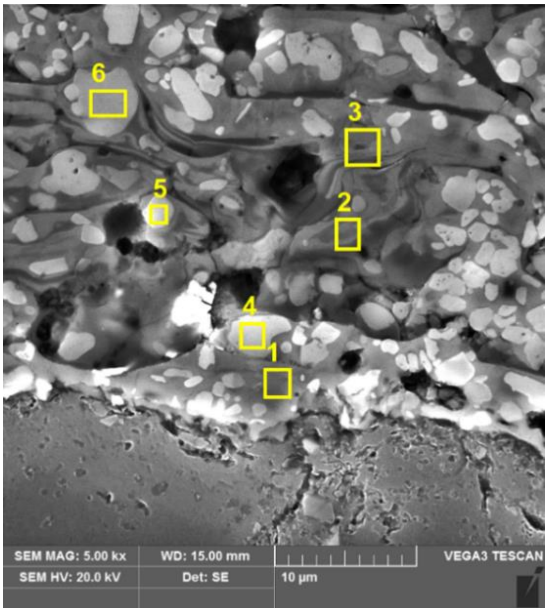


Fig. 6. SEM image of the Al2O3-TiO2 coating applied to a casting made of the AlSi7Mg alloy



Point	Chemical composition, % wt.		
	O	Al	Ti
1	43.07	6.09	50.84
2	45.55	19.32	35.14
3	50.72	31.62	17.66
4	49.49	26.65	23.87
5	48.59	40.88	10.52
6	51.42	39.90	8.68

Fig. 7. Results of X-ray microanalysis of the chemical composition of the Al2O3-TiO2 coating

The results of the scratch test are presented in Figure 8. During scratching, the penetration depth of the indenter, friction force and normal force values, coefficient of friction, and EA (acoustic emission) signal were analyzed.

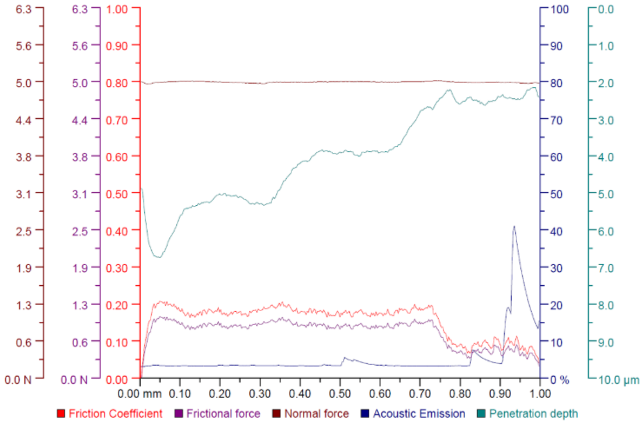


Fig. 8. Changes in scratch test parameters during scratching of the substrate material and coating

Figure 9 presents a view of the scratching in the area of the substrate-coating transition boundary, while Figure 10 presents the measurements of the width of the scratch in the substrate and the coating.

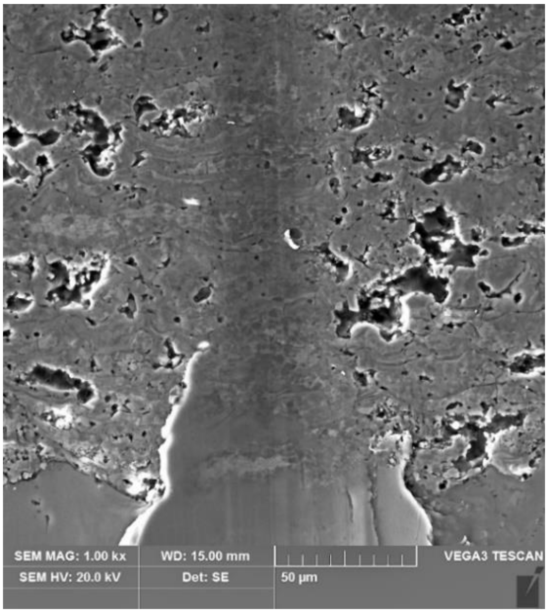


Fig. 9. View of the scratch in the area of the substrate-coating transition boundary

The results obtained indicate a good quality connection of the Al2O3-TiO2 coating with the AlSi7Mg alloy casting. No delamination was found at the substrate-coating boundary. Surface analysis of the scratch in this area show in Figure 9 also did not reveal the presence of microcracks.

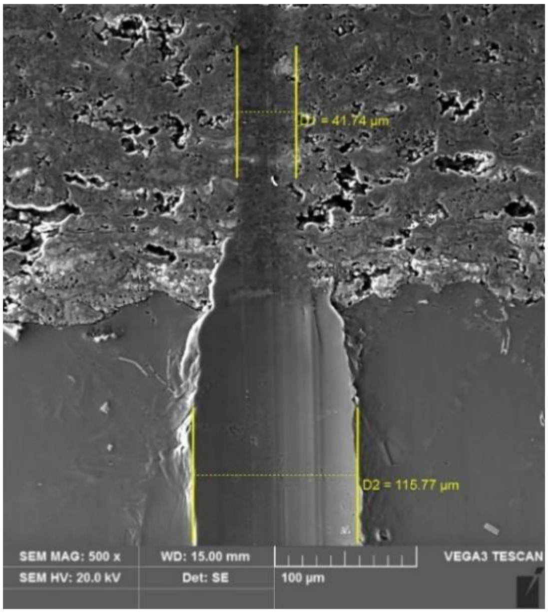


Fig. 10. Results of measurements of the scratch width in the substrate and the coating

Observation of the transition boundary between the substrate and the coating indicates a good quality connection. The use of blasting treatment resulted in surface development, which during the application of the coating, created characteristic hooks marked in Figure 11, which increasing its adhesion.

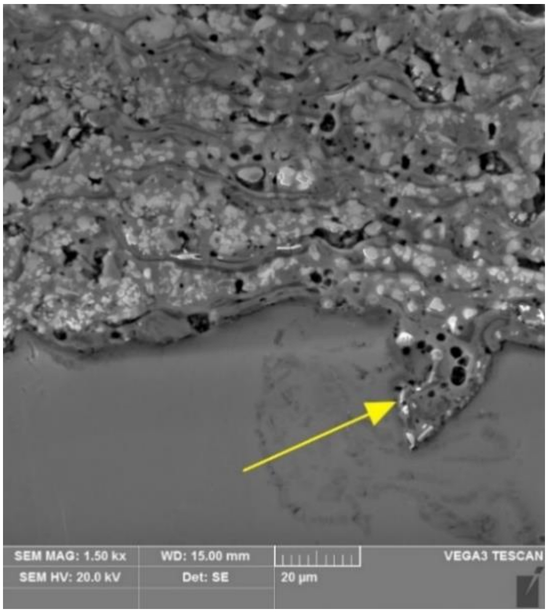


Fig. 11. View of the Al2O3-TiO2 coating with characteristic hooks indicated by an arrow in the figure

Table 3 presents the results of measuring the depth and width of the scratch in the substrate and the coating.

Table 3.
Parameters of scratch geometry in the substrate and coating

Area	**Value, µm**	
	Depth	**Width**
substrate	6.75-3.71	115.77
coating	3.71-2.17	41.74

The analysis of the geometric parameters of the scratch indicates a value approximately three times smaller for the width of the scratch in the coating compared to the substrate material. The depth of the scratch in the coating is also significantly smaller. This indicates a higher scratch resistance of the coating compared to the AlSi7Mg alloy.

4. Conclusions

Based on the conducted research, the possibility of using thermal barrier coatings on AlSi7Mg alloy castings has been confirmed. Further research will be focused on the possibility of using the TBC to improve the thermal load resistance of engine components made of the AlSi7Mg alloy, for example, valve heads, pistons, or other components, in order to limit the thermal impact of the fuel combustion process on their operational durability.

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