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ИЗГОТОВЛЕНИЕ ПОКРЫТИЯ ИЗ ВЫСОКОЭНТРОПИЙНОГО СПЛАВА AL-CO-Cr-Fe-Mn-Ni С ИСПОЛЬЗОВАНИЕМ ПРОВОЛОЧНО-ДУГОВОЙ АДДИТИВНОЙ ТЕХНОЛОГИИ

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Аннотация. *Целью данного исследования является исследование микроструктуры и механических свойств высокоэнтропийного покрытия Al-Co-Cr-Fe-Mn-Ni, изготовленного на подложке AA5083 с использованием проволочно-дуговой аддитивной технологии. Результаты показали однородное распределение элементов вдоль поперечного направления в покрытии, которое имеет следующий средний химический состав: Al 8 ат.%, Co 28 ат.%, Cr 13 ат.%, Fe 33 ат.%, Mn 3 ат. .%, Ni 15 ат.%. Скорость изнашивания покрытия уменьшилась в ~5 раз по сравнению с подложкой, а твердость по Виккерсу улучшилась в ~3 раза.*

Ключевые слова. высокоэнтропийный сплав, газовая дуговая сварка металла, проволочно-дуговое аддитивное производство, Al-Co-Cr-Fe-Mn-Ni,

*алюминиевый сплав, покрытие, микротвердость, скорость износа, микро*структура.

FABRICATION OF AL-CO-CR-FE-MN-NI HIGH-ENTROPY ALLOY COATING USING WIRE-ARC ADDITIVE MANUFACTURING

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Abstract. *The aim of this study is to investigate the microstructure and mechanical properties of the Al-Co-Cr-Fe-Mn-Ni high-entropy coating fabricated on AA5083 substrate using wire-arc additive manufacturing. The results showed homogeneous distribution of the elements alongside the transversal direction in the coating which has the following average chemical composition: Al 8 at.%, Co 28 at.%, Cr 13 at.%, Fe 33 at.%, Mn 3 at.%, Ni 15 at.%. The wear rate of the coating decreased by ~5 times comparing with the substrate, while the Vickers hardness improved by ~3 times.*

Keywords. *high-entropy alloy, gas metal arc welding, wire-arc additive manufacturing, Al-Co-Cr-Fe-Mn-Ni, aluminum alloy, coating, microhardness, wear rate, microstructure*

1. Introduction

Replacing steel components onto lightweight materials, such as aluminum and magnesium alloys, or composites is a crucial task for scientists and engineers around the globe [1]. The main issue in the weight reduction is to retain strength, durability, and other performance properties of machine parts. While aluminum alloys exhibit low density, high strength to weight ratio, good corrosion resistance and relatively low cost, they suffer from low wear resistance, as well as low hardness which restricts their applications [2].

There are several techniques which work well to fabricate hard coatings on Al alloys: hard anodizing [3], physical vapor deposition [4], thermal spraying of hard coatings [5], plasma electrolytic oxidation [6], and laser cladding [7]. For example, Al_2O_3 coating deposited by hard anodizing on AA6063 exhibited enlarged hardness by 5.7 times [3]. Laser cladding of Ni-WC coating onto AA5083 increases hardness of the alloy by about 12 times, while wear resistance rises by 2.5 times [7]. Cold spray deposited WC-CoCr coating followed by friction stir processing reinforced AA5083 matrix and increased the average hardness by 540% over the as-casted alloy [5].

Weld overlay cladding is a well-known technique in gas and mining industries that can provide thick coatings (up to 6 mm) by joining via welding a protec-

tion material to a base metal. This method is cost-effective because the deposition occurs at high rates (up to 8 kg/h) and the feeding material is a wire which is mainly cheaper than the powder used, for example, in laser cladding or thermal spraying [8]. Wire-arc additive manufacturing is a promising technology, but it has not yet been applied to fabricate high-entropy alloy coatings. Since HEA coatings obtained by other methods revealed excellent mechanical properties such as high hardness, wear, corrosion resistance, etc., a study of the application of wire-arc additive manufacturing to weld overlay HEA coatings can greatly expand this field and lay the groundwork for future research.

The aim of this study is to fabricate Al-Co-Cr-Fe-Mn-Ni HEA coating onto non-heat-treatable AA5083 substrate. Hardness was used to evaluate its mechanical performance, as well as scanning electron microscopy was carried out to investigate microstructure and distribution of chemical elements.

2. Materials and Methods

AA5083 plate with the chemical composition (wt.%) of 4.4-4.8 % Mg, 0.05-0.15% Cr, 0.6-0.9% Mn, 0.1% Cu, 0.25% Zn, 0.15% Ti, 0.4% Fe, 0.4% Si and Al – balanced (according to ASTM B209) and a size of 350 mm × 350 mm × 5 mm was selected as a substrate. The surface of the substrate was hand-held grinding wheel grinded until the surface showed a metallic luster.

According to the previous studies the following wires were selected for stranding into a cable-type wire: pure Co wire (Co 99.9 at.%, Ø 0.47 mm); Autrod 16.95 welding wire (Fe 65.3 at. %, Cr 19.6 at. %, Ni 7.3 at. %, Si 1.6 at. %, Mn 6.2 at. %, Ø 0.7); Ni80Cr20 wire (Cr 22.5 at. %, Fe 1.5 at. %, Ni 72.1 at. %, Al 0.8 at. %, Si 2.9 at. %, Mn 0.2 at. %, Ø 0.4 mm). The wires were stranded using special stranding equipment. The average diameter of the combined cable wire was 1.2 mm, with the lay length of 10 mm.

To deposit a single-layer coating, we used metal inert gas (MIG) automated setup with the following parameters of overlay cladding: wire feed speed 10 m/min, amperage ~100 A, voltage 22 V, inductance 3 H, travel speed 200, layer length of 100 mm. The gun moved with the drag travel angle of 10°. Argon (99.99 %) was used as a shielding gas.

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) of the cross-sectional view of the obtained samples was performed by «LEO EVO 50», Carl Zeiss equipped with a dispersive energy analyzer INCA Energy. Microhardness tests were carried by Vickers microhardness tester with the indenter load of 0.5 N and dwell time of 10 s.

3. Results and Discussion

Fig. 1 (a) shows a fragment of the Al-Co-Cr-Fe-Mn-Ni high-entropy alloy coating fabricated via gas-metal arc welding. The microstructure of the coating represents various areas with the different tonality: darker and brighter, which might be attributed to the inhomogeneous content of the chemical elements in these local regions and, correspondingly, different phases. The overall chemical composition of the coating is quite uniform, according to the Fig. 1 (b). The standard deviation from the average content of each component is not more than 1.4 % (for Al which reveals the highest deviation). This might be related to not complete

solid solubility of the main element of the substrate in the crystal lattice of the coating. The amount of Al atoms increases when approaching to the substrate, and in the beginning of the transition zone between the coating and the substrate reaches its maximum value of 32 at. % (Fig. 1 (d)). After the distance of 160 μm its value sharply drops down to 11 at.%, and gradually increases as the distance from the transition zone increases. The concentrations of Fe and Co slightly rise at 160 μm and after this distance steadily decrease with the following complete disappearing at 730 μm.

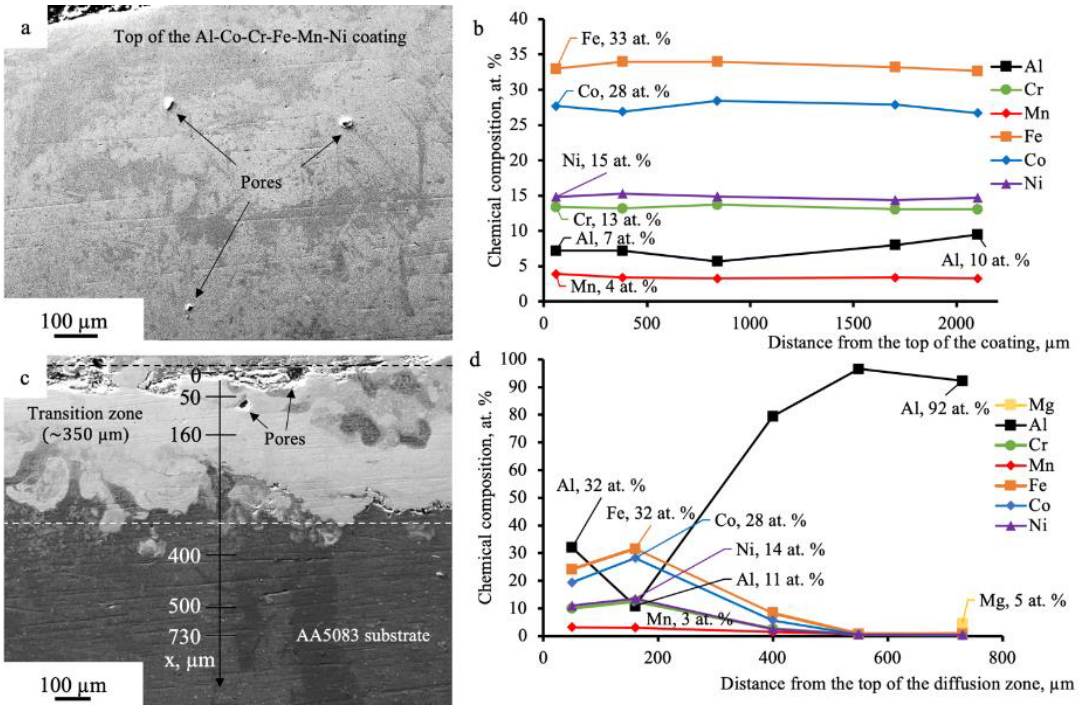

Figure 1 - (a) SEM of the Al-Co-Cr-Fe-Mn-Ni HEA coating, (b) the results of EDS analysis accomplished from the top of the coating, (c) SEM of the transition zone between the coating and the substrate. The distances from the top of the transition zone in which EDS analysis was carried out are marked on the axis, (d) the results of EDS analysis alongside the axis indicated in (c)

The thickness of the obtained coating is around 4.5 mm; its average Vickers hardness equals to 294 ± 53 HV, which is higher than the hardness of the substrate by 3 times. Comparing to the casted $Al_{0.5}CoCrFeMnN$ alloy [9] whose hardness is 175 HV, the hardness of the coating obtained in this study is relatively higher (by about 1.7 times); however, it is by about 1.2 times less than in the conventionally sintered $Al_{0.5}CoCrFeMnNi$ HEA, which is probably due to the higher density of the sample, attributed to the simultaneous combination of pressure and temperature during the compaction of the powders [10].

In the area adjacent to the coating, the hardness of Al-Co-Cr-Fe-Mn-Ni reaches the highest value of 1010 ± 80 HV. This value is comparable with the Vickers hardness of $Al_{1.5}CoCrFeMnNi$ HEA fabricated by high-frequency induction heat sintering (HFIHS) (830 $HV_{0.3}$) because the samples sintered using the HFIHS method exhibit higher densification than the conventional sintering

(Fig. 2) [10].

Then as the distance from the beginning of the transition zone into the depth of the sample increases, the hardness rapidly drops down to 232 ± 9 HV and levels to the values of the substrate of 107 ± 8 HV.

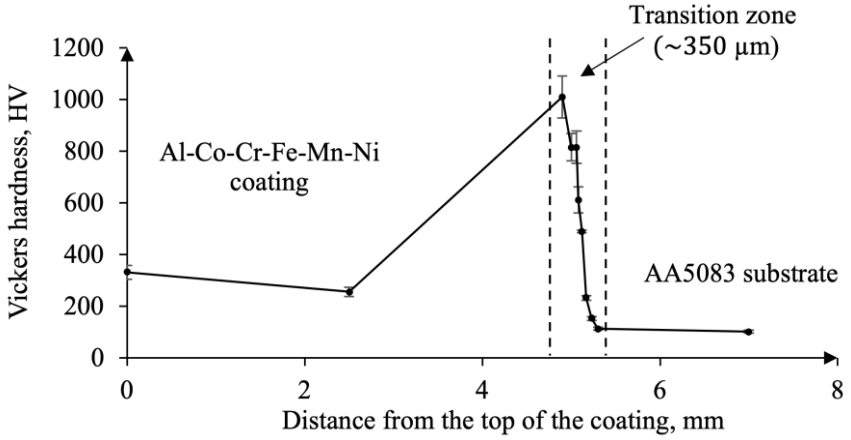

Figure 2 - Variations of Vickers hardness values across the coating and the substrate

4. Conclusions

In this study we fabricated Al-Co-Cr-Fe-Mn-Ni high-entropy alloy 4.5 mm thick coating on the AA5083 substrate using wire-arc additive manufacturing. The following results could be drawn:

1. The obtained coating has larger hardness (294 ± 53 HV) than that of the substrate (107± 7 HV) by ~3 times. The highest hardness (1010 ± 80 HV) was observed in the transition zone between the coating and the substrate.

2. The chemical composition of the coating is homogeneous, while in the transition zone there are areas enriched with the Al atoms.

3. The results show an applicability of wire-arc additive manufacturing technique for fabrication of a thick high-entropy alloy coating on Al-Mg aluminum alloy.

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КАВИТАЦИОННОЕ РАЗРУШЕНИЕ ИНТРЕМЕТАЛЛИДНОГО ГАЗОДЕТОНАЦИОННОГО ПОКРЫТИЯ СИСТЕМЫ TI-AL

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Аннотация. *В статье приводятся результаты исследования на кавитационную стойкость газодетонационного покрытия, напыленного из СВС порошка, состава 64 % Ti + 36 % Al по мас. %. Напыляемый порошок варьировался по фракционному составу. Выявлено, что основная убыль покрытия от ультразвукового воздействия происходит на первых 30 минутах, а затем происходит многократный спад убыли на 60 и 90*

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