# Analysis of PTA hardfacing with CoCrWC and CoCrMoSi alloys

## (Caracterização de revestimentos de ligas de CoCrWC e CoCrMoSi processadas por PTA)

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**Abstract**

*CoCrWC alloys are widely used to protect components that operate under wear and high temperature environments. Enhanced performance has been achieved with the CoCrMoSi alloys but processing this alloy system is still a challenge due to the presence of the brittle Laves phase, particularly when welding is involved. This work evaluated Plasma Transferred Arc coatings processed with the Co-based alloy CoMoCrSi – Tribaloy T400, reinforced with Laves phase, comparing its weldability to the CoCrWC – Stellite 6, reinforced with carbides. Coatings were also analyzed regarding the response to temperature exposure at 600°C for 7 days and subsequent effect on microstructure and sliding abrasive wear. Coatings characterization was carried out by light and scanning electron microscopy, X-ray diffraction and Vickers hardness. CoCrWC coatings exhibited a Cobalt solid solution dendritic microstructure and a thin interdendritic region with eutectic carbides, while CoCrMoSi deposits exhibit a large lamellar eutectic region of Laves phase and Cobalt solid solution and a small fraction of primary Laves phase. Although phase stability was observed by X-ray diffraction, coarsening of the microstructure occurred for both alloys. CoCrMoSi showed thicker lamellar Laves phase and CoCrWC coarser eutectic carbides. Coatings stability assessed by wear tests revealed that although the wear rate of the as-deposited CoCrMoSi alloy was lower than that of CoCrWC alloy its increase after temperature exposure was more significant, 22% against 15%. Results were discussed regarding the protection of industrial components in particular, bearings in 55AlZn hot dip galvanizing components.*

***Keywords**: CoMoCrSi Alloy, CoCrWC Alloy, Plasma Transferred Arc, Temperature Stability*

**Resumo**

*Ligas CoCrWC são largamente usadas para a proteção de componentes que operam sob condições agressivas de desgaste e elevada temperatura. Desempenho melhor tem sido obtido com ligas CoCrMoSi, entretanto, o processamento destas ligas ainda representa um desafio devido à presença de fase Laves frágeis, particularmente quando processos de soldagem estão envolvidos. Este trabalho avaliou revestimentos processados por Plasma com Arco Transferido com as ligas CoCrMoSi – Tribaloy T400 reforçada com fase Laves, comparando a sua soldabilidade à da liga CoCrWC – Stellite 6, reforçada com carbonetos. Os revestimentos foram também analisados considerando o impacto da exposição à temperatura de 600°C durante 7 dias sobre a microestrutura e o comportamento em desgaste abrasivo por deslizamento. A caracterização dos revestimentos foi realizada por microscopia ótica e eletrônica de varredura, difração de raios-X e dureza Vickers. Revestimentos CoCrWC apresentaram microestrutura dendrítica de solução sólida em Cobalto e região interdendrítica refinada com carbonetos eutéticos enquanto os depósitos CoCrMoSi apresentaram uma região eutética lamelar predominante com fase Laves e solução sólida em Cobalto e pequena quantidade de fase primária de Laves. Embora a estabilidade de fases tenha sido observada por difração de raios-X, o coalescimento da microestrutura ocorreu para as duas ligas. A liga CoCrMoSi apresentou lamelas mais espessas de fase Laves enquanto a liga CoCrWC apresentou coalescimento dos carbonetos eutéticos. A estabilidade medida por meio dos testes de desgaste revelou que embora o coeficiente da liga CoCrMoSi na condição como depositada tenha sido menor que o da CoCrWC, a primeira apresentou aumento mais significativo como consequência da exposição à temperatura, 22% perante os 15% da segunda. Os resultados foram discutidos considerando a proteção de componentes industriais que operam em banhos de galvanização por imersão a quente com liga 55AlZn.*

***Palavras-chave**: Liga CoMoCrSi, Liga CoCrWC, Plasma com Arco Transferido, Estabilidade em Alta Temperatura*

## 1. Introduction

The search for high performance materials for the fabrication of parts that operate under aggressive conditions aiming to reduce maintenance stops is an ongoing process in many manufacturing industries. The processing of coatings

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by Plasma Transferred Arc (PTA) to protect components with high performance alloys materials is a competitive procedure, as recently reported by Gonçalves et al. in their review of PTA processing [1] .

Cobalt-based alloys are widely used to extend service life of components in a range of industrial sectors, including valves, valve seats, bearings, bushings, sleeves, dies and punches. The good corrosion resistance of cobalt-based alloys allows the use of these alloys for combating wear in corrosive mediums, and find applications in the chemical, petrochemical, food processing and steelmaking facilities. These properties are associated with the presence of Chromium as a solid solution strengthener and carbide formation, the former contributing forms an oxide film that enhances corrosion resistance and the latter, together with W, the good wear resistance [2]. However, performance under wear and corrosion-wear conditions is still an issue whenever parts operate in aggressive environments. Corrosion-wear can cause loss of material from solid surface phase as a result of mechanical-chemical action that is enhanced by the wear debris reducing the service life of components as found in the molten metal corrosion in hot dip galvanizing pot hardware [3, 4].

To face this demanding service conditions alloy selection should be carried out considering its ability to be processed and to perform under a complex set of variables.

The CoCrWC alloy system can be use to fabricate components that meet a wide range of service requirements. Moreover, these alloys exhibit a good weldability facilitating hardfacing procedures. However, under harsh environments the response of components produced with alloys from the CoCrMoSi system has been reported to show better results. These two alloy systems have different features: the carbide reinforced CoCrWC (Stellite) alloys show a hypoeutectic structure with a Co-rich solid solution (FCC) dendrites surrounded by an eutectic lamellar of a Co-rich phase and carbide phase ($M_7C_3$ and/or $M_{23}C_6$, M being Cr or W). The intermetallic Laves phase reinforced CoCrMoSi alloys (Tribaloy) exhibit hard intermetallic Laves phase in a eutectic lamellar of a Co-rich solid solution and Laves phase. The intermetallic phase formed is the close-packed hexagonal (hcp) compound of Co, Mo and Si, as $Co_3Mo_2Si$ and/ or CoMoSi.

Considering the extreme service conditions of 55AlZn hot dip galvanizing pot hardware where temperature, wear and molten metal attack act simultaneously leading to a very short campaign, two alloy systems were tested in this work. The carbide reinforced Stellite 6 alloy although easier to weld exhibits a limited molten metal corrosion resistance as a consequence of the large amount of Co-rich solid solution. On the other hand the CoCrMoSi Tribaloy T800 performs better against molten metal attack but it is difficult to process, because of the large fraction of the low toughness intermetallic primary Laves phase. Aiming to improve the soundness of the molten metal attack resistant CoCrMoSi alloys, an alloy with reduced Cr and Si has been developed, the Tribaloy T400. However there is a lack of information on its weldability and performance.

This work aims to reduce the gap of information on the weldability and performance of this alloy. The weldability of CoCrMoSi (Tribaloy T400) alloy coatings processed by Plasma Transferred Arc was analyzed and correlated with CoCrWC (Stellite 6) coatings; characteristics were also assessed by the stability of microstructure and wear performance after a long-term exposure at 600°C.

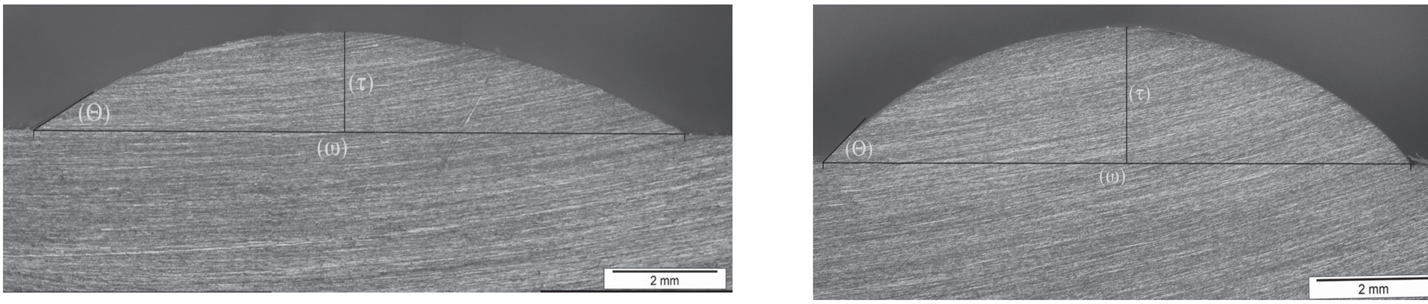
## 2. Materials and Methods

Atomized CoCrWC and CoCrMoSi alloys, grain size within the range 90-150 μm, with the chemical composition shown in Table 1, were processed. Plasma Transferred Arc (PTA) hardfacing on AISI 316L stainless steel 12,5 mm thick plate was carried out as single layers with the processing parameters summarized in Table 2. Coatings were characterized in the as-deposited condition and after temperature exposure in an air furnace at 600 ºC for 7 days (168 h).

Geometry of welding overlays was analyzed by light microscopy using a software to measure the thickness (t), width (w), and wettability angle (Θ), Figure 1. Dilution was determined for single layer deposits on the transverse cross section as the ratio between the substrate molten area and the total molten area. Microstructure analysis included light and scanning electron microscopy on the transverse cross section and X-ray diffraction (XRD) analysis on the top surface of coatings. XRD used $K_a$Cu from 20 to 120º with time of exposed channel of 3 s. The Vickers hardness of coatings, before and after exposure at 600 ºC was measured under 0,5 kgf load as the average of 10 measurements.

Table 1. Chemical Composition of the materials used (wt.%)

| **Co-Based Alloys** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Alloy / Element** | **Co** | **Cr** | **W** | **Mo** | **C** | **Fe** | **Ni** | **Si** | **Mn** |
| CoMoCrSi (Tribaloy T400) | Bal. | 8,8 | .... | 29,1 | 0,05 | 0,4 | 0,6 | 2,4 | .... |
| **Alloy / Element** | **Co** | **Cr** | **W** | **Mo** | **C** | **Fe** | **Ni** | **Si** | **Mn** |
| CoCrWC (Stellite 6) | Bal. | 27,9 | 4,7 | 0,2 | 1,3 | 1,8 | 2,1 | 1,2 | 0,4 |
| **Stainless Steel** | | | | | | | | | |
| **Substrate** | **%C** | **%Mn** | **%Si** | **%P** | **%S** | **%Cr** | **%Ni** | **%Mo** | **%Al** |
| AISI 316L | 0,020 | 1,350 | 0,430 | 0,026 | 0,008 | 16,780 | 10,120 | 2,126 | 0,002 |




(a) (b)

Figure 1. Geometry of welding overlays: (a) CoCrWC – thickness (τ): 1,75mm, width (ω): 12,20mm and wettability angle (Θ): $30,5^0$ and (b) CoCrMoSi – thickness (τ): 2,20mm, width (ω): 10,25mm and wettability angle (Θ): $44,0^0$.

Table 2. Plasma Transferred Arc processing parameters.

| **Parameters** | |
|---|---|
| Plasma gas flow rate (l/min) | 2 |
| Protection gas (l/min) | 15 |
| Powder feeding gas (l/min) | 2 |
| Main arc current (A) | 150 |
| Powder feed rate | Constant in volume |
| Travel speed (mm/min) | 100 |
| Distance torch / substrate (mm) | 10 |
| Electrode diameter (mm) | 3,125 |
| Nozzle constriction diameter (mm) | 4,76 |
| Welding Position | Flat |

Abrasive sliding wear tests were carried out on a pin-on-disc sliding apparatus against silicon carbide paper (#320) assembled on a 63 HRC hardness metal disc, under 1kgf axial load and tangential speed of 1,5 m/s. Pins with a transverse section of 4 x 4 mm were removed and machined from the deposited coatings. Wear was measured by the mass loss of pins, weighting before every test and after each 250 m sliding distance up to 1000 m at room temperature and the results presented as the average of 5 measurements.

## 3. Results and discussion

### 3.1. Soundness

The weldability of both Co-based alloys was good when assessed by the soundness of coatings. Visual inspection of the coatings processed with the two alloys revealed a smooth surface without welding defects. No evidences of spatter, undercut, porosity or cracks were found. This macroscopic evaluation is coherent with the literature predictions that the Tribaloy T400 has an improved weldability compared to other Cr and Si richer CoCrMoSi alloys. However, limited data is available on the response of the T400 to the effects of dilution and the solidification rate imposed by welding processes and in particularly PTA hardfacing.

Notwithstanding the soundness of coatings processed with both Co-based alloys, differences on the geometry of single track deposits were measured and associated with the wettability of each alloy, Figure 1. For the processing parameters used, the CoCrMoSi alloy resulted on coatings with a lower wettability, confirmed by the higher Θ, higher overlay thickness and shallower width compared to coatings processed with the CoCrWC alloy. A good wettability is of relevanc e whenever is required to protect large areas by the overlapping of tracks. A low wettability can cause porosity between tracks compromising the soundness of the coated areas. In order to minimize the deleterious effects of wettability, larger overlapping areas between track or further optimization of the processing parameters are among the procedures that can be used though both will contribute to a higher dilution.

Processing the CoCrWC – Stellite 6 and CoCrMoSi – Tribaloy T400 alloys with the listed parameters resulted on coatings with a thickness ranging from 1.75 to 2.20 mm and a dilution with the substrate below 15% (14,7% for CoCrWC and 14,4% for CoCrMoSi alloy), confirming the superior quality of the PTA deposits processed when compared to conventional welding processes.

### 3.2. Temperature exposure

Albeit weldability is typically associated with the soundness of coatings in this study it was extrapolated in order to be assessed by the stability of the microstructure and wear behavior of coatings. The consequences of PTA hardfacing were assessed by the microstructure stability of coatings processed with both Co-based alloys, by comparing coatings in the as-deposited condition and after a long term exposure at 600°C. X-ray diffraction analysis, Figure 2 and Figure 3, showed phase stability which, on itself might suggest that the measured dilution did not compromise the microstructural stability of neither one of the alloys.

Evidences of a distinct response to temperature exposure of each alloy coating were given by hardness measurements, Figure 4. The high hardness of CoCrMoSi coatings measured in the as-deposited coatings was not altered after the 7 days at 600°C contrasting with the 28,5% hardness increase exhibited by the as-deposited CoCrWC coatings .

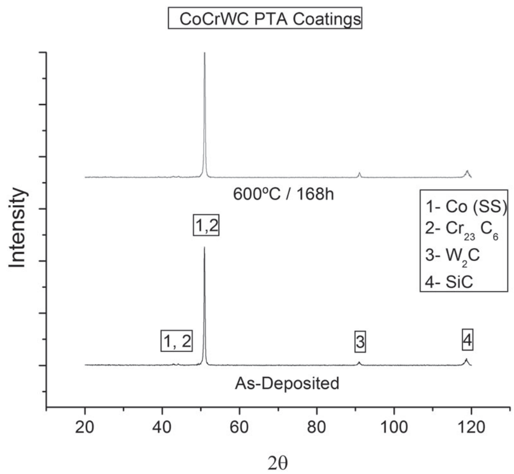



Figure 2. X-ray diffraction analysis on CoCrWC coating in the as-deposited condition and after temperature exposure.

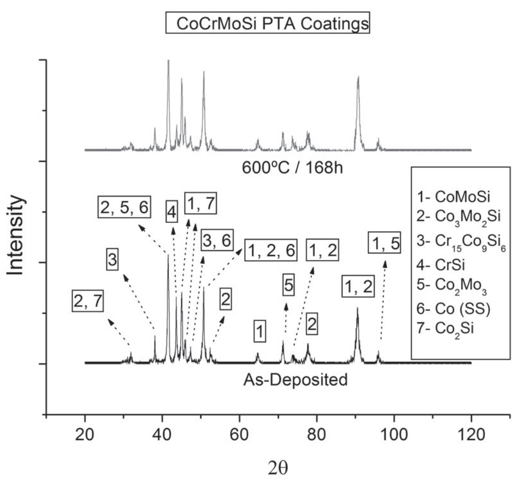



Figure 3. X-ray diffraction analysis on CoMoCrSi coating in the as-deposited condition and after temperature exposure.

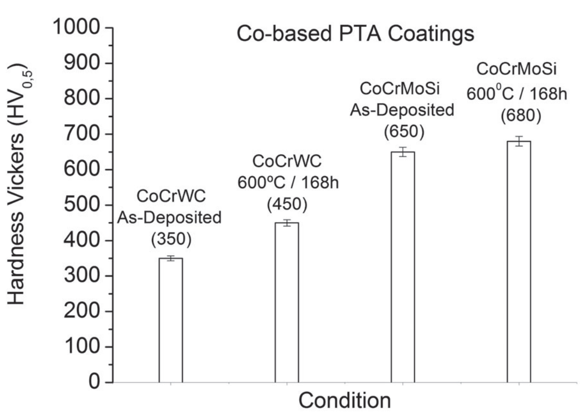



Figure 4. Vickers Hardness of coatings in the as deposited condition and after temperature.

Further understanding of the hardness variation of coatings processed with each alloys was offer by microstructure analysis in the as-deposited condition and after exposure to 600°C, Figure 5 and Figure 6. In the as-deposited condition the CoCrWC alloy coating (350 HV) showed a hypoeutectic structure with primary face centered cubic (FCC) cobalt dendrites surrounded by a network of eutectic lamellar composed of FCC cobalt and eutectic carbides, Figure 5a. The analysis of transverse section of the CoCrMoSi alloy deposits (650 HV) revealed fine grains of a lamellar eutectic and low amount of primary Laves phase dendrites and Laves free regions of cobalt solid solution, Figure 5b. The observed microstructure and phase distribution as well as the measured hardness agree with literature results [2].

Temperature exposure at 600ºC for 7 days induced microstructure changes in the coatings as observed on the transverse section, Figures 6a and 6b. CoCrWC alloy coatings showed a coarser and network of eutectic lamellar when compared to the as-deposited condition, which can be attributed to the carbides coarsening and solid solution precipitation. Although no phase changes were identified significant alterations on their distribution and size account for the measured hardness differences. CoCrMoSi alloy coatings showed thicker eutectic lamellar Laves phase. Nevertheless microstructure changes were not significant enough to induce significant hardness changes.

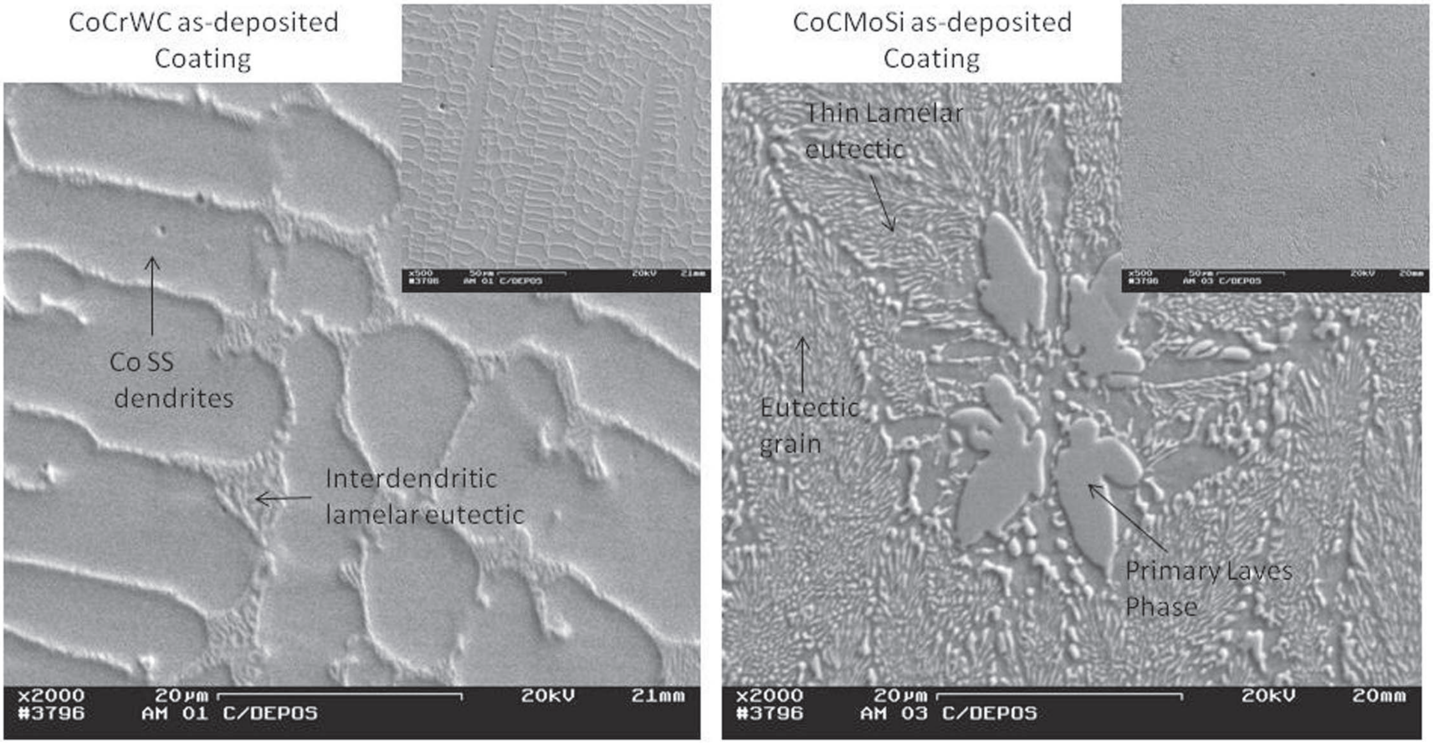
### 3.3. Wear Behavior

Further assessment of the response of each alloy to hardfacing was analyzed by the wear behavior of coatings. As describe in the literature the wear performance is a consequence of a complex set of variables involving testing parameters and the materials features. Aiming to identify the influence of PTA deposition on the response of each coating to abrasive sliding wear, coatings were tested before and after exposure at 600 °C for 7 days with a constant set of testing parameters.

The mass loss changes with sliding distance for two Co-based alloy coatings and the wear coefficients (mg/m) are shown in the Figure 7. Under the conditions tested a linear correlation between sliding distance and mass loss and a near constant wear rate were measured with increasing sliding distance.

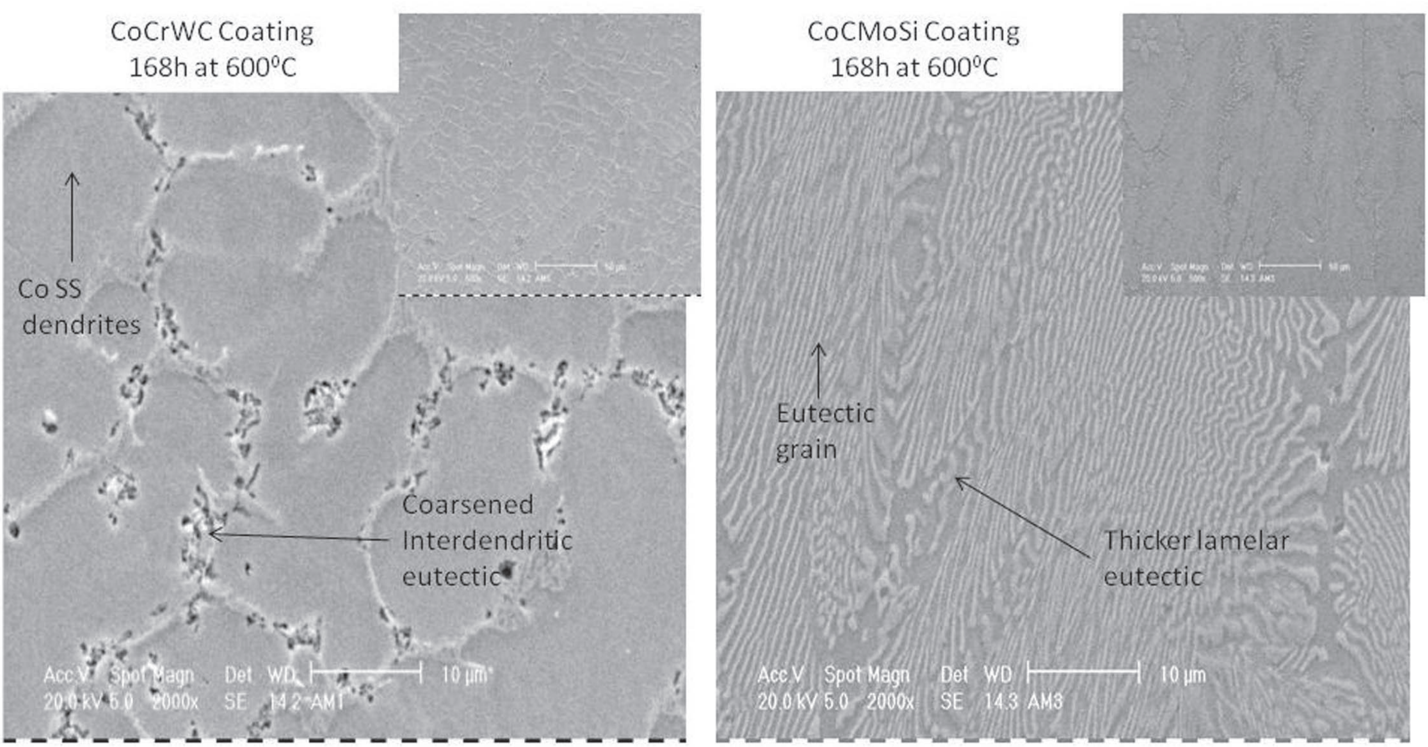
The chemical composition of each alloy had a role on the mass loss rate of the coatings, the CoCrWC coatings exhibiting a higher rate (0,3848 mg/m) than CoCrMoSi coatings (0,3506 mg/m). Differences can be associated with the higher measured hardness and the eutectic lamellar microstructure with a high volume fraction of hard intermetallic Laves phase [5, 6].

Both Co-based alloys coatings showed an increase on the mass loss following temperature exposure, and although the CoCrMoSi coating exhibited a lower wear rate changes induced by temperature were more significant on these coatings, a 22 % increase on the mass loss as opposed to a 15 % increment measured on CoCrWC coatings. The observed coarsening of the structure and of the carbides, in particular, can account for the reduced wear resistance of Stellite coatings and follows literature predictions on the stability of this alloy at high temperature. On the other hand, the hardness stability of CoCrMoSi coating after exposure for 7 days at 600 °C might suggest a stable wear



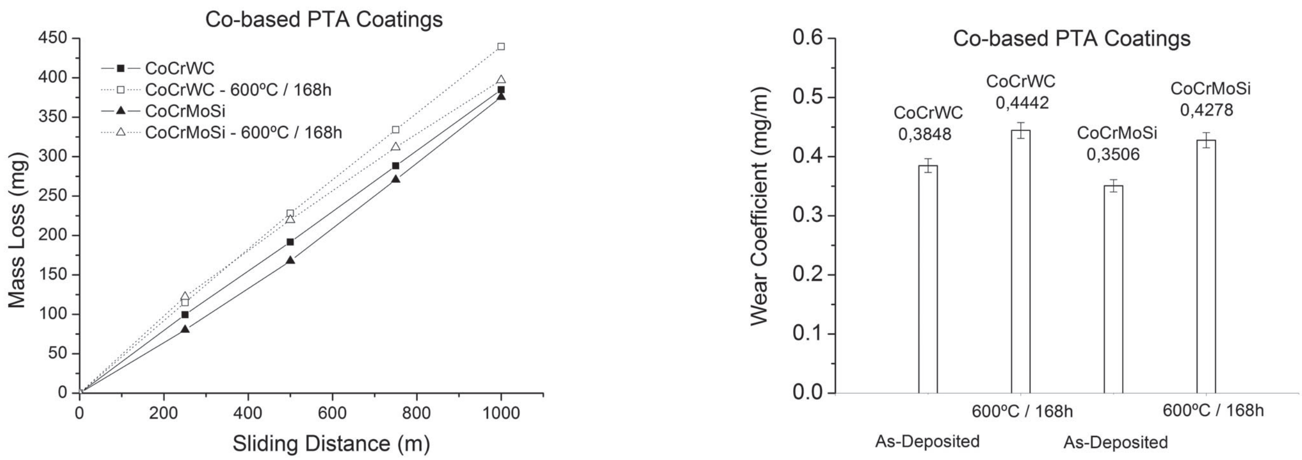

(a) (b)

Figure 5. Cross-section microstructures of as-deposited Co-based PTA coatings: (a) CoCrWC and (b) CoCrMoSi. Inserts in each micrograph show a general view of the microstructure.




(a) (b)

Figure 6. Cross-section microstructures of Co-based PTA coatings after long-term exposure at 600ºC. Inserts in each micrograph show a general view of the microstructure.




(a) (b)

Figure 7. Wear curves for both alloy systems tested (a) and the wear coefficient with the error bars as the standard deviation (b).

resistance. However, microstructure observations revealed that the lamellar structure coarsened when exposed at 600 °C reducing the reinforcement effect of the eutectic Laves phase. The reduced stability of the microstructure of both alloys can be associated with the fast solidification rate imposed by PTA deposition and with eventual chemical composition fluctuations due to the diffusion of the elements from the stainless steel AISI 316L substrate.

Concerning the industrial applications where the major technological challenge is found and hardfacing with CoCrMoSi alloy (Tribaloy T400) might be used to protect components, this study confirmed that weldability is not a major difficulty for, when compared to the CoCrWC (Stellite 6) alloy. Therefore material selection for the protection of equipment should be carried out considering the imposed demands on parts. If wear is the major demand the CoCrMoSi alloy coatings showed an enhanced performance compared to Stellite 6. However, if operation temperature is an issue, the degradation it induces on the CoCrMoSi microstructure might create a challenge. On the other hand, under specific corrosion conditions, such as molten metal corrosion as observed in galvanizing plants, previous results have shown the large areas of Laves phases contribute to a superior performance [7, 8]. Hot dip galvanizing facilities represent one of the most challenging service conditions that result on the accelerated degradation of parts. It has been associated with wear, temperature and reactivity of mechanical components in contact with molten alloy. Die cast processes must stop periodically for maintenance because of die material degradation and also galvanizing lines designed to produce 55AlZn coatings stop weekly for Co-based bearings replacement. Material used for sink roll bearings is exposed to 600 ºC temperature and operates for not more than 7 days (168 h) [3 - 6]. These hostile environments require parts to perform at elevated temperature, under abrasive wear and molten metal attack. Under this service conditions and according to the evaluation carried out, further optimization of the deposition parameters should be performed to evaluated the stability of Laves phases.

## 4. Final Remarks

This study analyzed the weldability of the Co-based alloy CoCrMoSi - Tribaloy T400, processed by plasma transferred arc hardfacing and included a correlation with the CoCrWC - Stellite 6 known for its good weldability. Weldability was assessed by the soundness of coatings and further characterization included the effect of temperature on their microstructure and wear performance. The main contributions can be summarized as follows:

- The Co-based alloys showed a good weldability when processed by plasma transferred arc on an AISI 316L stainless steel plate. Sound coatings with low dilution were obtained.
- Exposure at 600 $^0$C for 7 days did not altered the phases identified in each coating but caused coarsening of the structure though it only affected the hardness of the CoCrWC coatings.
- The effects of hardfacing on each alloy assessed by sliding abrasive wear behavior showed that in the as-deposited condition the chemical composition determined the better wear resistance of the CoCrMoSi coatings. However, dilution effects and the fast solidification rate imposed by PTA hardfacing made the effects of the 7 days exposure at 600 $^0$C more pronounced on the degradation of the wear behavior of CoCrMoSi coatings.
- Although this study confirmed the good weldability of both Co-based alloys studied it also adverts to the higher impact of dilution and solidification rate on the temperature stability of CoCrMoSi coatings.

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