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Application of Concentrated Solar Power for elaborating wear resistant hardfacing surface layers

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The present study investigates the exploitation of Concentrated Solar Power (CSP) for the in-situ production of wear resistant carbide-based surface layers onto steel base metal. The use of alternative thermal sources, such as laser or solar, for remelting or cladding pre-deposited powder layers has been implemented in order to achieve continuous, non-porous coatings, well-adhered to the substrates. Compared to laser sources, concentrated solar energy is mainly characterized by its renewable nature and, in addition, by higher efficiency. For this purpose, "solar" experiments were carried out at the installations of *Plataforma Solar de Almería* (Spain). Carbide-based powders (TiC and WC) were pre-deposited onto carbon steel and subsequently exposed to concentrated solar irradiation for various dwell time values. The temperature field developed during solar exposure was recorded in real-time by the aid of an optical pyrometer that allowed monitoring the temperature evolution of the irradiated surface, as well as by the aid of a thermocouples' set placed at different loci within the base metal that allowed determining the progress of thermal fields within the steel. Microscopic observations of the obtained surface layers allowed the correlation between the treatment parameters and the microstructure achieved. Subsequently, preliminary sliding tests against an alumina ball and a cutting insert with a cBN-coated tip were performed using a pin-on-disc apparatus, in order to evaluate in-service performance and machinability of the elaborated hardfacings, respectively. Based on these experimental results, the proposed technique was compared to Flux Cored Arc Welding (FCAW), to which it exhibits many fundamental commonalities.

Keywords: Concentrated Solar Power, surface modification process, carbide-based hardfacing, microstructure, tribological performance

INTRODUCTION

"Cemented carbides" are two-phase, ceramic-metal (CerMet) materials, consisting of hard carbide particles such as WC, TiC, Cr_3C_2 etc. bound together by a metal binder phase. They are the primary materials of choice in harsh applications, like hard metal cutting, rock drilling, excavation [1], due to their high hardness and wear resistance under non-lubricated conditions. Besides their use as sintered monolithic wear resistant components, they are also applied as coatings of metallic parts operating under sliding, abrasion and erosion conditions in high temperature and corrosive atmospheres [2, 3]. The principal deposition technique to obtain such coatings, with thickness in the range of 200-400 μm, is High Velocity Oxy-Fuel thermal spraying, which, like all thermal spraying techniques, requires specially pre-treated feedstock powders having a suitable particle size distribution to be sprayable. In addition, the coatings obtained are prone to decarburization/ dissociation of the carbide particles during in-flight towards the substrate, due to the high temperatures developed.

In an effort to mitigate such high processing temperature problems, non- conventional thermal sources, such as laser, or alternative ones, like concentrated solar power (CSP) have been implemented. Compared to laser sources, concentrated solar energy is mainly characterized by its renewable nature and, in addition, by higher efficiency [4] and lower capital costs [5]. Previous works have already formed a solid background on the feasibility of creating metallic, oxide- or carbide-based coatings [6,7] onto metallic substrates via CSP. In particular with respect to carbide coatings, preliminary experiments on solar-aided surface alloying of steels, demonstrated that the obtained treated zones were thick, hard and free of pores and cracks [8,9].

The present study is part of an integrated research project targeted to investigate the feasibility of optimising the "solar surface treatment" process and obtaining carbide-based hardfacing layers with acceptable microstructure features and tribological performance. In this perspective, a first preliminary study by the present authors involved TiC-based surface layers as a case study [10]. The present work is a follow-up including in the one hand additional solar experiments with TiC powder to validate the first results. In the other hand, further experiments with WC-based powder were performed to demonstrate the feasibility of elaborating diverse carbide-based wear resistant surface layers by the proposed solar process.

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EXPERIMENTAL DETAILS

The surface treatments using concentrated solar irradiation were carried out at the installations of *Plataforma Solar de Almería, PSA* (Spain). A schematic illustrating the operation principle of such facilities is presented in Fig.1, while the plant of Almeria has been previously described [6-9]. The present study took place in the new horizontal SF40 solar furnace, specifically designed for high temperature materials treatment under controlled atmosphere. The facility is of 40 kW power and reaches a peak concentration exceeding 7000 suns. An extensive description of this particular installation has been recently published [11], providing technical details of the concentrator system, the flux regulation modes and flux measurements.

The surface-modified base metal was a common carbon steel grade (DIN St 37-2), containing less than 0.17 wt. % C and exhibiting a liquidus temperature of ~1540 °C. Specimens of dimensions 70×35×15 mm^3 were polished and the surface to be irradiated was covered by the respective carbide powder to form a disk-like, 1 mm-thick layer, with a diameter of 3.5 cm, since the radiation spots have a diameter of 3.0 cm. Two series of solar campaigns were performed applying TiC and WC powders. During solar exposure, the temperature of the specimen surface was recorded in real-time by the aid of an optical pyrometer, in order to determine the operational conditions and correlate them to their effects on the material. In all cases, treatment was taking place within a quartz bell jar, under inert atmosphere with the aid of Ar gas flow.

The optimization of process parameters comprised post-treatment macroscopic and stereoscopic observations of the exposed surfaces, using a Leica MS 5 and a Nikon SMZ 1500 stereomicroscope, as well as microscopic observations of the relevant cross-sections, conducted using a Nikon Epiphot 300 inverted metallographic microscope. Vickers microhardness measurements on characteristic areas of the specimens' cross-sections were carried out using an Instron-Wolpert tester, applying a 0.3 kg load. The tribological performance of hardfacing layers, obtained under the optimum conditions, was estimated using a pin-on-disk apparatus (Centre Suiss d' Electronique et de Microtechnique, CSEM). Preliminary sliding friction tests were performed in dry air (25%RH, 20 °C), using as counterbodies a cutting insert with a cBN-coated tip and an Al_2O_3 ball (∅ 6), in order to estimate the machinability and the in-service performance of the obtained layers, respectively.

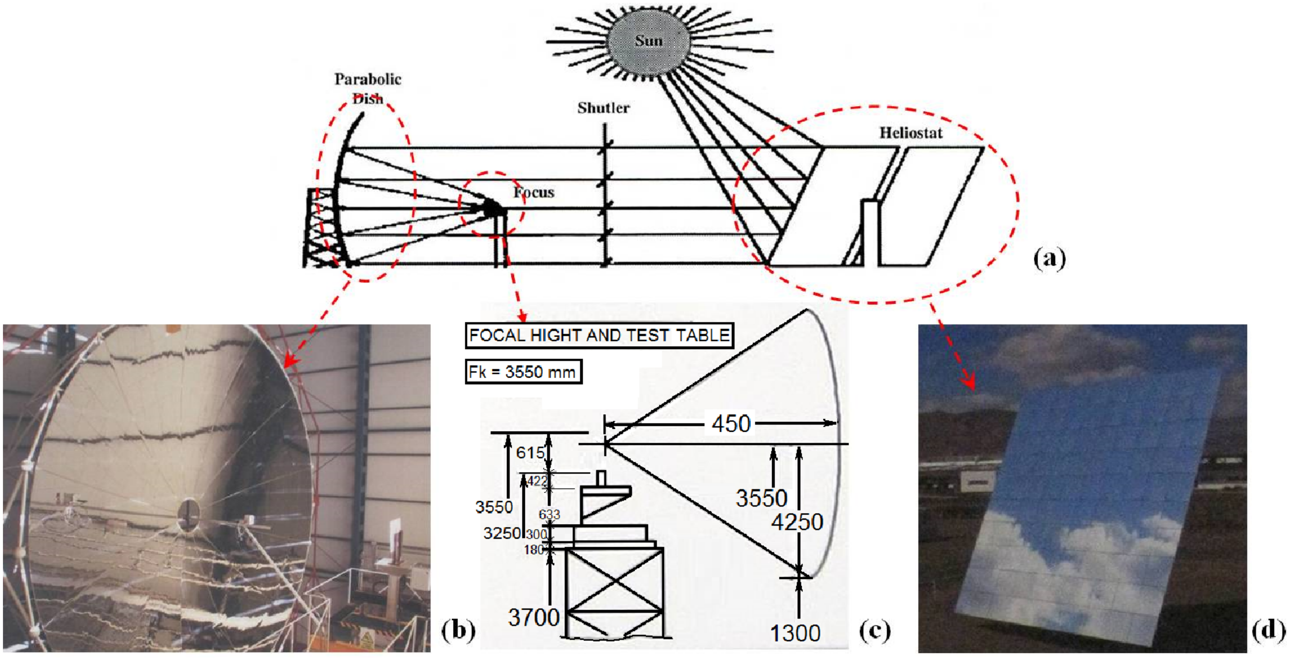

Fig.1. Solar furnace installation at *Plataforma Solar de Almeria, PSA* (Spain): (a) Schematic presentation of operation principle, (b) Actual stationary parabolic concentrator, (c) Schematic of arrangement ensuring a 3810 $kW.m^{-2}$ peak flux at the focal point, normalised to 1000 $W.m^{-2}$ insolation and (d) Photograph of heliostat consisting of 100 plane facets, each one of 1 m^2 reflecting surface

The specimens were tested applying normal loads (*N*) in the range of 1-10 N and for a linear velocity of 0.20 $m.s^{-1}$. After testing, the wear volume (*v*) was measured using a mechanical Taylor-Hobson stylus profilometer and the wear coefficient (*k*) was calculated, using the formula:

$$k = \frac{v}{N.s} \quad (1)$$

where (s) denotes the total sliding distance, in m

The tribological results for the solar-modified layers were compared to results concerning respective hardfacing deposits obtained by Flux Cored Arc Welding (FCAW) technique.

RESULTS AND DISCUSSION

Fundamental aspects on the proposed "solar" surface modification process were presented in a previous study [10], involving only TiC powder. This study was employed as a first test exploratory case aiming at identifying the crucial operational parameters leading to successful surface hardfaced layers. It was found therein that the crucial parameter inducing hardfacing was not the overall solar irradiation exposure time but the actual dwell time of the base metal at temperatures above its liquidus; thus this dwell time should be considered as the effective solar treatment duration. In fact, a linear relationship between the maximum hardfacing thickness and this time was observed.

The present study, involving a new campaign with TiC powder as well as a first-of-its-kind campaign with WC powder, corroborated further these observations. Fig.2 shows for each carbide, three representative in-situ measurements of the specimens' surface temperature via an optical pyrometer, demonstrating the temperature evolution as a function of the total exposure time. The relevant dwell times, in the particular experiments, for TiC span between 300-500 s and those for WC between 250-300 s. Both these intervals were within the optimum time ranges for hardfacing. Analytical details on the calculation of the surface treatment duration have been provided previously [10]. A dwell time below a critical threshold value was not sufficient to induce melting of the base metal up to a depth adequate to achieve incorporation of the carbide particles within the melting pool. On the other hand, excessive dwell above the liquidus temperature resulted in high porosity of the re-solidified metallic matrix.

A typical WC-hardfaced specimen obtained is presented in Fig.3a. It can be clearly distinguished that solar irradiation has affected only the area to be treated, leaving the rest of the specimen's volume intact. A visual result of solar surface modification is demonstrated in Fig.3b, showing achievement of immersion and entrapment of non-molten carbide particles within a surface pool of molten and re-solidified base metal.

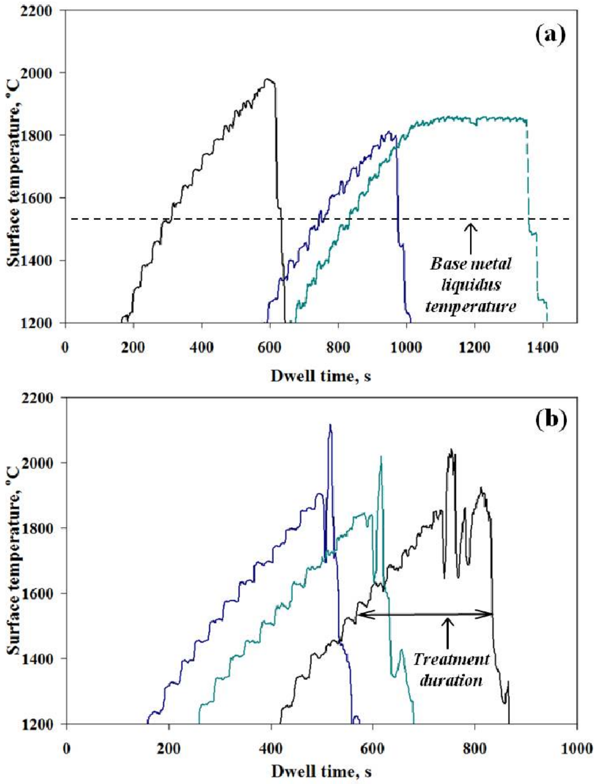

Fig.2. Surface temperature evolution during solar irradiation exposure of three different: (a) TiC- and (b) WC-covered specimens

Metallurgical processes involving metals' melting and re-solidification are frequently accompanied by the appearance of residual porosity and micro-cracking of the treated volume. A successful solar treatment should result in surface layers free of such microstructural defects as well as homogeneous distribution of the reinforcement particles within the base material in order for the surface layer to have uniform performance during application. An exemplary case of such a continuous, uniform surface layer obtained via solar irradiation is presented in Fig.4a, for TiC hardfacing. SEM observations at the neighbourhood of the solar-treated layer/ unmolten base metal interface (Fig.4b) demonstrated further the validity of the previous findings throughout the entire depth of the treated zone.

However, the specific type of the carbide, TiC or WC, had a significant influence on the micro-phenomena taking place during the effective solar treatment (dwell at temperatures above 1540 °C). TiC particles immersed within the ferrous pool seem not to be attacked by the liquid metal during treatment. As shown in Fig.5a, the carbide particles boundaries remained intact and totally unaffected by the surrounding metal. On the contrary, in the case of WC (Fig.5b), the contact of carbides with the liquid metal led to partial dissolution of the particles directed from the outer to their inner region. Thus, longer effective solar treatment duration and/ or smaller particles' size could result in total dissolution of WC particles within the metallic matrix.

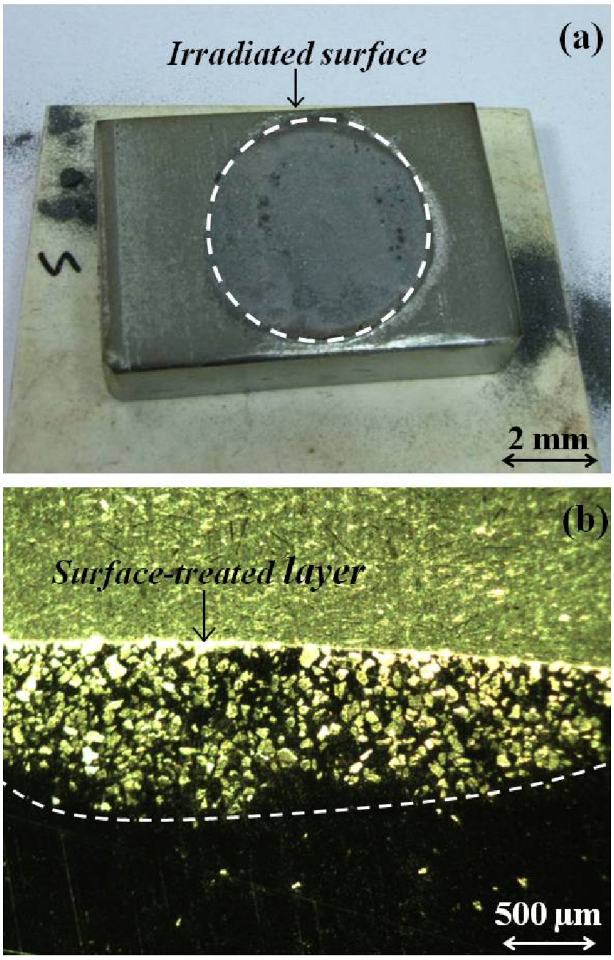

Fig.3. (a) Macrograph of a typical WC-covered specimen, exposed to solar irradiation and (b) Typical cross-section view of a successfully TiC-hardfaced specimen (stereo-graph)

Microhardness values obtained at selected areas of the hardfacing layers demonstrated different trends for the two carbides that could be of relevance with the microstructure observations above. These values ranged from 2500 up to 2900 HV0.3 in the case of TiC-harfaced layers and from 1000 up to 1500 HV0.3 in the case of WC ones. The magnitude and the span of these values could be attributed to:

- The relevant inter-carbide spacing, imposing constraints to the plastic deformation of the metal [12], in the case of intact TiC particles.
- The enrichment of the metallic matrix in carbon around the semi-dissolved particles, in the case of WC-hardfaced layers.

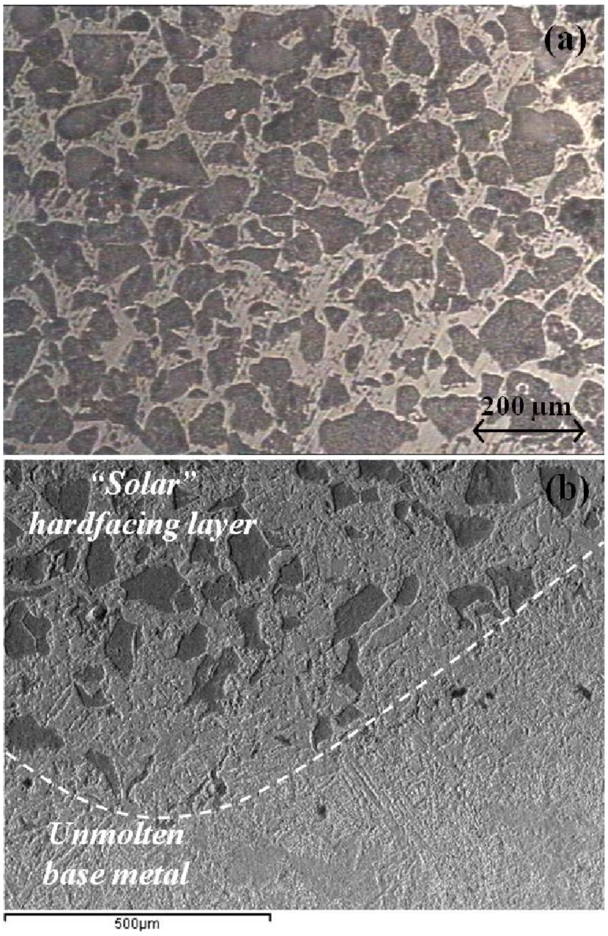

Fig.4. Cross-section of a microstructural-defects-free TiC-hardfaced layer: (a) Optical micrograph demonstrating the homogeneous distribution of carbide particles within the metallic matrix and (b) SEM photograph of the hardfacing / base metal interface

Preliminary dry sliding tests demonstrated the suitability of the solar hardfaced layers obtained for severe tribological applications, where high wear resistance is a requirement.

The evolution of the wear coefficient was estimated by interupted testing up to 200.000 sliding revolutions. Steady-state wear of the treated layers was achieved above 20.000 sliding revolutions; thereafter, the wear coefficient values remained practically constant. As shown in Table 1, both TiC- and WC-hardfaced layers exhibited comparable machinability and in-service performance with respective hardfacing deposits obtained by conventional FCAW technique.

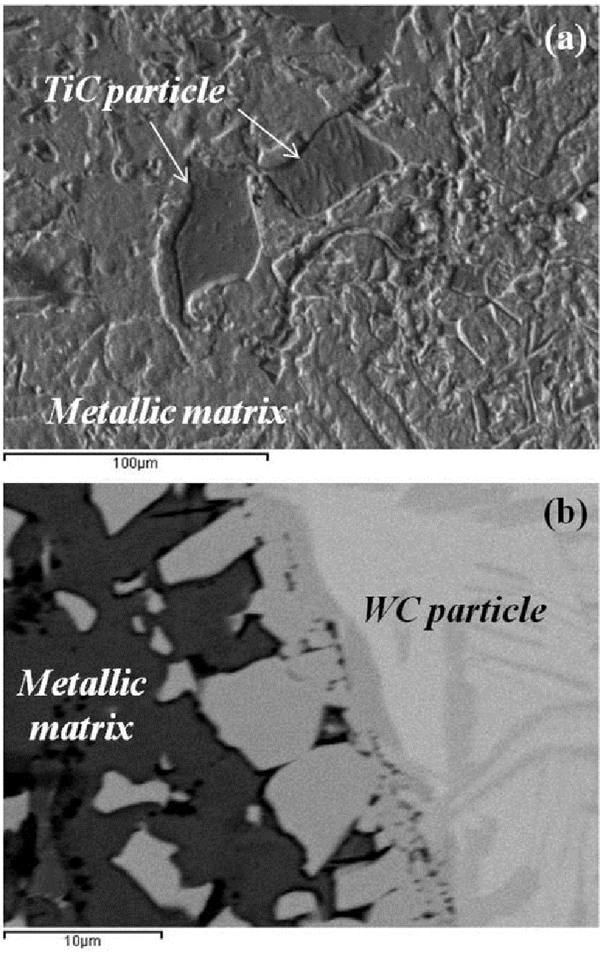

Fig.5. SEM micrographs of: (a) Non-dissolved TiC particles and (b) Partially dissolved WC particles, within the ferrous metallic matrix

Table 1. Comparison of the steady-state wear coefficient ($mm^3.N^{-1}.m^{-1}$) between "solar" and FCAW TiC- and WC-hardfaced surface layers, tested under the highest load (10 N)

Surface layer	Sliding against cBN-coated pin	Sliding against Al_2O_3 ball
"Solar" TiC	5.11×10^{-5}	4.64×10^{-6}
FCAW TiC	2.11×10^{-5}	7.64×10^{-6}
"Solar" WC	7.83×10^{-6}	4.35×10^{-7}
FCAW WC	7.90×10^{-7}	6.96×10^{-7}

For comparison purposes, Fig.6 depicts the dependence of wear coefficient on the normal load applied for ball-on-disk experiments performed on the base metal of this study (red curve), as well as on a ferrous alloy typically used for hard tribological applications (blue curve). Both alloys exhibited wear coefficient values in the range of $1.12\text{-}2.09\times10^{-4}$ $mm.N^{-1}.m^{-1}$, when tested under the most severe conditions (10 N), whilst the relevant values for TiC- and WC-hardfaced layers were respectively 2 and 3 orders of magnitude lower (Table 1, last column).

A typical top-view of a wear track of the solar WC-hardfaced layers obtained is presented in Fig.7. Polishing and ploughing wear mechanisms of the metallic matrix that led to revealing of the carbide particles were clearly seen.

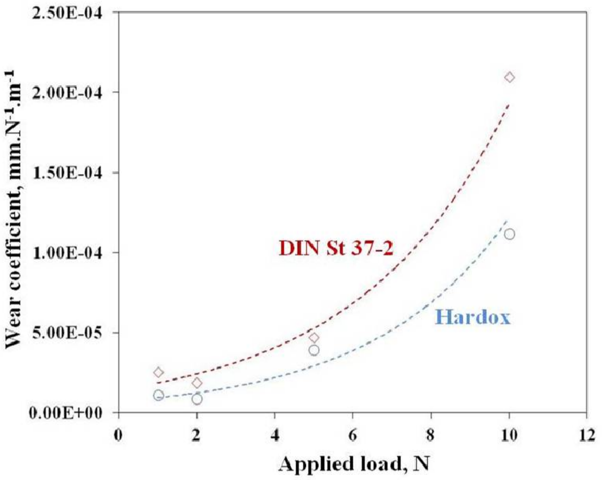

Fig.6. Wear coefficient evolution as a function of the normal load applied for the un-treated base metal employed in the present study (red curve) and for a typical wear resistant steel (blue curve)

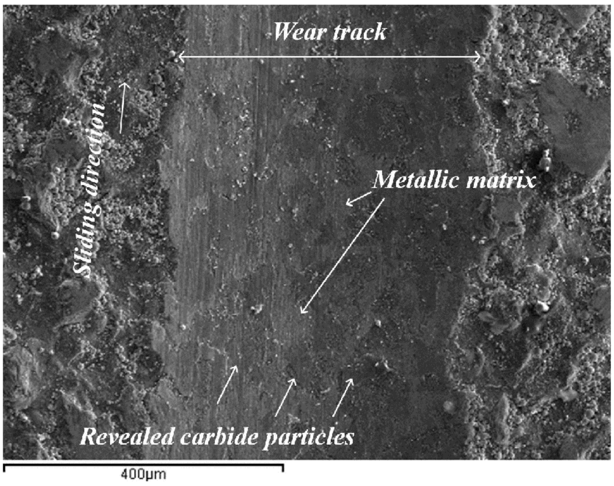

Fig.7. SEM top-view micrograph of the worn surface of WC-hardfaced specimen

CONCLUSION

Concentrated Solar Power (CSP) was exploited for the in-situ production of TiC- and WC- wear resistant surface layers onto steel base metal. The solar process parameters were optimised using as criterion the elaboration of layers without mictostructural defects. The kind of the carbide particles affected the micro-phenomena taking place during the melting stage of the process and consequently the microstructural features and the microhardness values of the obtained surface layers. The in-service tribological behaviour of both carbide layers was found superior to that of the base metal and comparable to that of relevant hardface deposits elaborated by Flux Cored Arc Welding (FCAW) technique.

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