

Metallurgical characterization of a weld bead coating applied by PTA process on the D2 tool steel

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ABSTRACT

In this investigation, a nickel-base powder mixed with tungsten carbide particles was applied by Plasma Transferred Arc welding (PTA) on the surface of the D2 cold work tool steel to improve the surface quality and to extend its life time during applications. To obtain appropriate combination of hardfacing parameters and to run minimum number of experiments, the Design of Experiment (DOE) method was applied. Current, travel speed and preheat were considered as variable parameters. These parameters are important to reach a final layer with an appropriate bead geometry and accompanied with good metallurgical properties. All samples were prepared for metallurgical investigations and the effect of process parameters on the weld bead geometry was considered. For each run of experiment, weld bead geometry parameters including dilution, penetration and reinforcement were measured. Microstructures and the distribution of tungsten carbide particles after welding were analysed by Optical Microscopy and Scanning Electron Microscopy equipped with EDS microprobe. In addition, microhardness tests were performed to evaluate the mechanical properties of the weld bead layers. Finally, amongst all the experiments, the best sample with appropriate bead geometry and microstructure was selected.

Keywords: Design of Experiment, Hardfacing, Nickel-base powder, PTA process, Tool steel

1. Introduction

Surface hardening processes can improve tribological, wear and corrosion properties of industrial components which are working in harsh situations [1,2,3]. Amongst different welding processes, Plasma Transferred Arc (PTA) welding is relatively new method compare to other conventional welding processes such as GTAW and GMAW [2]. In PTA method, powder as filler material is carried from powder holder to the weld pool [4]. This method can produce layers with different thickness accompanied with strong metallurgical bond to the substrate. Also, it has high productivity and ability to automation for weld overlay applications [1,5]. In addition in PTA method welding efficiency and dilution can keep in minimum level, and by adjusting the feeding rate precise weld bead can be achieved [3,6]. The impact of process parameters in PTA process on microstructure and properties of the weld bead was investigated by researchers [7,8,9]. Boulithis et al.[7], investigated on the effect of PTA surface treatment on tool steel before and after applying heat treatment. Nouri et al.[10], worked on effect of welding parameters on properties of the hardface layer. Chatterjee et al. [11], worked on various layer deposits which can be achieved by changing the dilution with base metal, it mainly depends on heat input parameters such as current and travel speed. Also, adding nickel base powder on steels cause to improve corrosion resistance because of incremental behavior of the nickel. For improving the wear resistance properties mainly tungsten carbide (WC) was added to nickel matrix. After deposition of the mixed powder, nickel matrix play as an binder of hard particles to improve wear properties [12,13,14]. In addition different type of carbides can be added and applied on the base metal to improve surface properties [15].

Balamurugan et al. [16], investigated on optimization process of PTA for weld overlay of titanium carbide. It should be mention that, PTA process include many variable parameters such as current, feeding rate, travel speed and etc., which can have direct effect on surface quality [17,18]. Weld bead geometry play an important role in properties of the hardfaced layer. The selection of appropriate welding parameter is very important to reach suitable bead geometry [19]. Garcia Vazquez et al. [20], analyzed the weld bead geometry of nickel base powder deposited by PTA in metallurgical point of view. One researcher reported that there is relation between bead shape and quality of the layer [21].

Controlling and selecting appropriate parameters are very important to reach a layer with appropriate bead geometry. Consequently, based on different types of equipment, powders and other process parameters, should be combined with the aim to obtain an integral welding. Hardfacing manufactured using Design of Experiment (DoE) method, is useful to reach appropriate number of trials and conditions with minimum run of experiments [22].

The effect of feeding rate and travel speed of nickel base powder which applied on the low carbon steel was reported by Ming et al.[23] and Lim et al.[24]. Palani et al. [25,26], investigated on optimization of parameters for weld overlay of stainless steel on structural steel. Davis et al [16], tried to find appropriate dilution and weld bead geometry. Siva et al. [27], worked on optimization of the PTA process by using nickel base powder on stainless steel. In addition to many works, still there is lack of information to find optimum welding condition to reach appropriate weld bead geometry accompanied with high mechanical and metallurgical properties.

The aim of this study was to identify the important parameters to reach appropriate hardfaced layer of nickel base powder mixed with tungsten carbide on cold work tool steel (D2) by PTA process. Twenty weld

overlays with different parameters were applied on the surface, the characteristics of each layer was evaluated by means of optical microscopy, scanning electron microscopy attached with Energy dispersive spectroscopy (EDS), and microhardness, the existing of phases on layer was evaluated by X-ray diffraction analysis. Finally amongst all samples, the best sample was selected, based on metallurgical characteristics and weld bead geometry.

2. Materials and Experimental procedure

2.1. Materials.

In this experiment, Plasma transferred arc welding (PTA) process was used to apply nickel base powder on tool steel. The D2 tool steel in form of block in dimension of 130 × 50×12.5 mm was selected as a substrate. Table 1 indicated chemical composition of the base metal.

Table 1. Chemical compositions of base material

Material	Nominal Chemical Composition (wt%)							
	C	Si	Mn	Cr	Mo	V	P	S
D2 Steel Substrate	1.58	0.37	0.48	11.52	0.89	0.56	0.017	0.029

The suggested heat treatment was applied on the base metal to reach the required hardness and toughness. In this heat treatment, first sample preheated to 790°C for 1hour, then temperature increased to 1100°C and samples remain in that temperature around 35 minutes. After that blocks were quenched in oil bath, finally to reach appropriate toughness two steps equal tempering at 315°C for 2 hours were performed [28].

Before applying the layer, the surface of the substrates was grinded by emery papers to remove oxides and contamination. As a hardface filler material, nickel base powder reinforced with tungsten carbide particles was used. The powder is a mixture of spherical powder of nickel-chromium-silicon and agglomerated tungsten carbide, which contains 60% mono tungsten carbide plus 40% nickel matrix. Fig.1 indicates the morphology and of the powder which is used in this investigation. Also, Table 2 shows the chemical composition of the matrix and reinforced material.

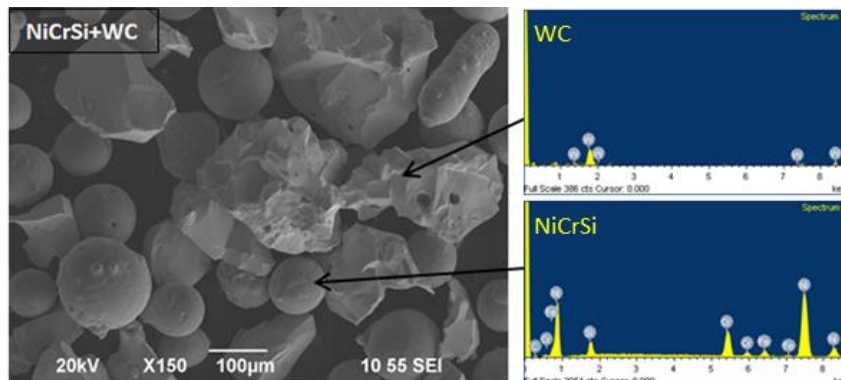


Fig.1. Morphology and chemical analysis of Ni base powder

Table 2. Chemical composition of the hardfacing powder.

Material	Nominal Chemical Composition (wt%)
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		C	Si	Cr	B	W	Ni
Hardfacing powder alloy	Matrix	0.6-0.8	3.9-4.9	14.0-16.0	3.0-3.4	-	Bal.
	Reinforcement	6.0-6.2	-	-	-	Bal.	-

2.2. Plasma hardfacing

In PTA process, there are many variables which have to be adjusted. In this investigation as will be explain in next section, current, preheat and travel speed were considered as variables. Other parameters were fixed based on values specified in Table 3. Plasma machine with trade mark of Castolin Eutectic Eutronic Gap 3001-DC was used for applying the hardface layer.

Table 3. Constant parameters of the PTA process

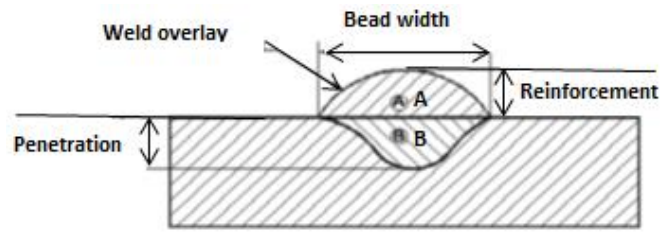
Parameter	Value
Voltage (V)	20
Nozzle diameter(mm)	3.2
Torch to work piece distance (mm)	10
Plasma gas Ar (l/min)	12
Shielding gas Ar+10%H ₂ (l/min)	3.5
Carrier gas (l/min)	3.5
Feeding rate (g/min)	29

2.3. Specifying the important parameters and developing the design matrix

In PTA process, there are many variable parameters which have effect on surface layer quality, but in this investigation based on suggested important parameters in literatures [] three factors of current (A), travel speed (S) and preheat (T), with five levels for each factor were considered. The reason for choosing pre heat as variable was because of susceptibility to crack initiation in tools steel during welding. D2 steel as a base metal with high carbon and high chromium percentage is sensitive to crack during welding [AWS]. Based on suggested statistic modelling for determination of appropriate parameters, surface response methodology with considering three factors with five levels was used. As a result, twenty runs should be performed. Details of mathematical modelling and measurement discussed elsewhere [29].

2.4. Sample preparation

After applying the layers, liquid penetration test was applied on all samples to observe existing surface defects. Finally, the overlay samples were cut from the cross section for metallography investigation. After normal surface preparation of the samples with consecutive emery papers and diamond polishing till 3µm, Nital 2% and solution of 30% HF and 70% HNO₃ reagent was used for etching the base metal and weld overlay part respectively. First the Olympus SZX A0 stereomicroscope equipped with Infinity Analyze software was used for measurement of each layer characterization (dilution, width and penetration). The schematic form of weld bead parameters is shown in Fig 2. For microstructure analysis microscope Leica MF4M (OLYMPUS PMG 3) was used.



$$\%Dilution = (B / (A + B)) * 100$$

Fig 2. Weld bead geometry measurement.

2.5. Microhardness testing

For the evaluation of mechanical properties, hardness test was performed on cross section of each joint. The vickers microhardness of the samples was measured through the base metal, heat affected zone and deposited layer. The *Future Tech* micro hardness machine was used to make about 30 measurements separated 0.2 mm each and using 1 kg load and 15 second loading time.

3. Results and discussion

3.1. Characteristic parameters of bead geometry.

In this study three responses were considered for each run, dilution, penetration and reinforcement. Based on response surface methodology with considering three levels and five factors, twenty runs were performed. The details of parameters and responses are listed in another work of the authors []. **Error! Reference source not found.** indicates variable parameters and factor levels that were used in this study.

Table 4. variable parameters in this investigation

Parameter	Notation	Factor levels				
		- 1.682	-1	0	+1	+1.682
Current(A)	I	86,36	100	120	140	153,63
Preheat (°C)	T	181,82	250	350	450	518,18
Travel speed (cm/min)	S	59,7	70	85	100	110,2

3.2. Effect of process parameters on bead geometry

Based on obtained data and for detail analysis of all twenty samples, special mathematical modeling is required but with more simplification, following results can be obtained. Fig. 3, indicated the effect of travel speed with penetration and dilution, as it is clear with increasing the travel speed, the penetration decrease and mainly with travel speed between 80 to 100 cm/min, minimum penetration is attainable. But increasing travel speed does not have specific effect on dilution. Because with increasing the travel speed, heat input decrease, consequently rate of diffusion on the surface decrease and penetration decrease. To observe the effect of current on dilution and penetration, based on information of Fig. 4, with increasing the current, the value of dilution steadily increase, it could be due to increasing the heat input in unit cell, as a result selecting appropriate parameter to reach optimum weld bead geometry is an important issue which should be considered [].

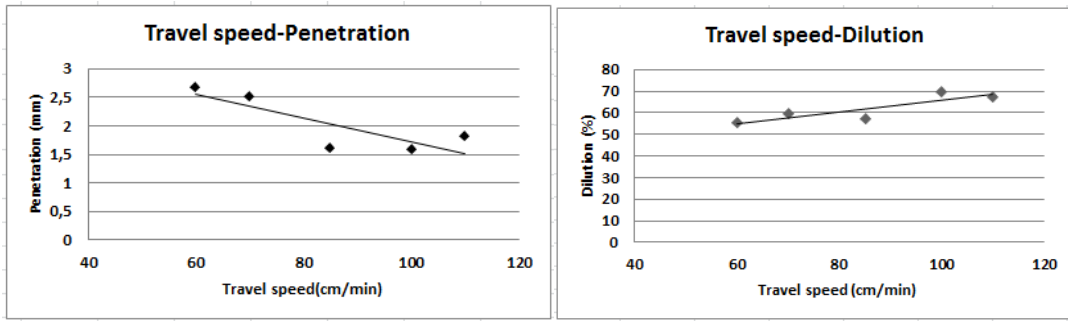


Fig. 3. Effect of travel speed on penetration and dilution

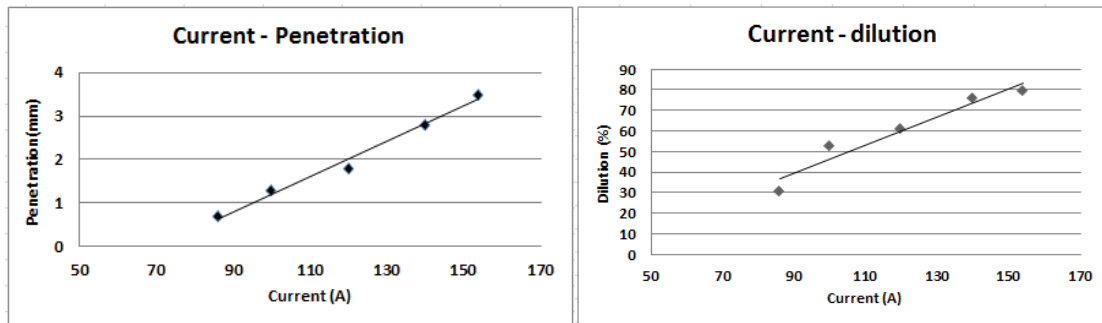


Fig. 4. Effect of current on penetration and dilution

3.3. Microstructure analysis

The cross section of one sample layer after preparation and measurement of weld bead parameters is indicated in Fig. 5(a). As it shown, the layer can be divided into three distinct parts of deposited layer, heat affected zone and base metal. The carbide microstructure in base metal and dendritic structure of deposited layer in all three zones is clear in Fig. 5(b).

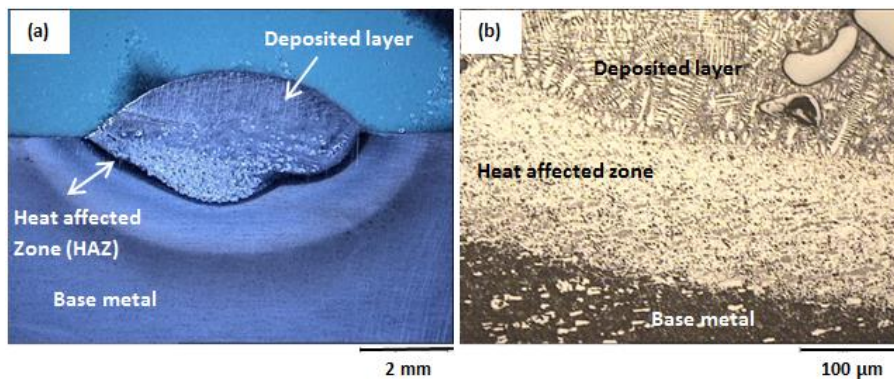


Fig. 5. (a) Macro structure of one hardfaced sample (b) microstructure of different zone

The characteristic parameters of each bead such as dilution, reinforcement, penetration calculated according to

Fig 2. This measurement was repeated for all twenty tested samples. Fig. 6 indicates the weld profile of some samples which showed relatively appropriate bead shape compare to all tests.

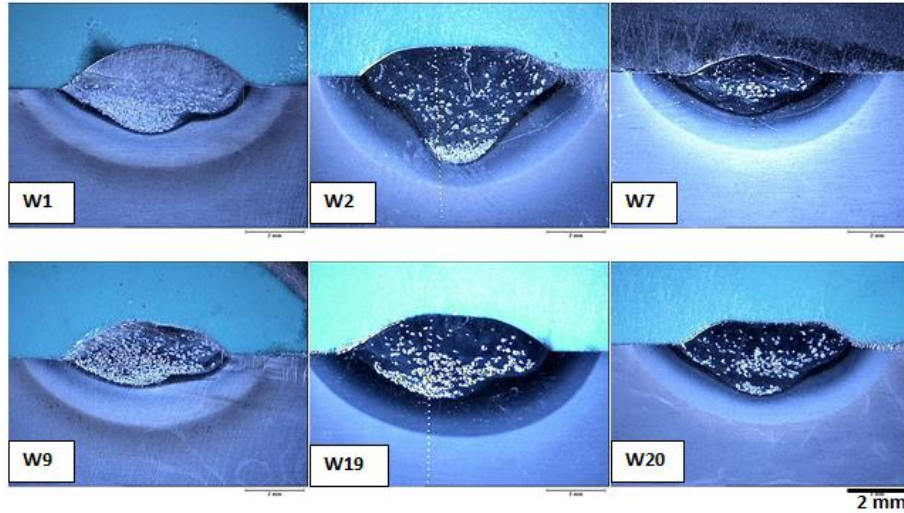


Fig. 6. Weld bead shape of some prepared samples

The microstructure of base metal D2 steel is shown in Fig 7. The optical microscopy of the steel shows martensitic microstructure which contains carbide distribution with different sizes. Large carbides are mainly M_7C_3 , which form during solidification because of existing higher amount of alloying elements. This carbide which mainly are Cr_7C_3 , dispersed in the microstructure during hot working. Finer carbides are secondary one, which precipitated out from the austenite phase [30]. EDX analysis of the carbides, in another work of the authors [], indicated that, in addition to Chromium carbide, there is Vanadium carbide which distributed in the matrix. Vanadium form very hard and thermally stable VC or V_2C carbides as isolated particles, which cause to improve wear resistance.

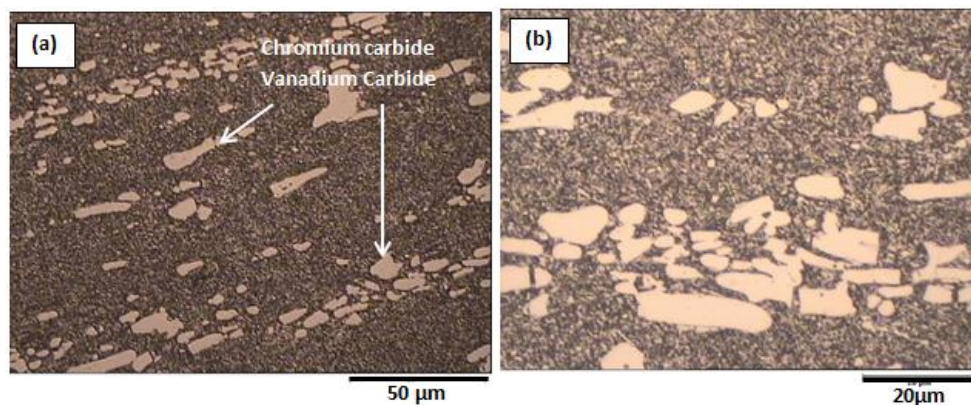


Fig 7. Microstructure of Base metal D2 steel (a) and (b) optical microscopy in different magnification

Fig. 8, indicated the microstructure of HAZ which can be divided in two parts of close to weld zone with larger grain size and close to base metal with smaller grain size. In addition near the interface a lamellar eutectic phase is visible. This area is transition zone between substrate and deposited layer. During

solidification, silicon easily dissolved to Nickel solution in the deposited layer. In this area eutectic reaction occurs and lamellar eutectic is form.

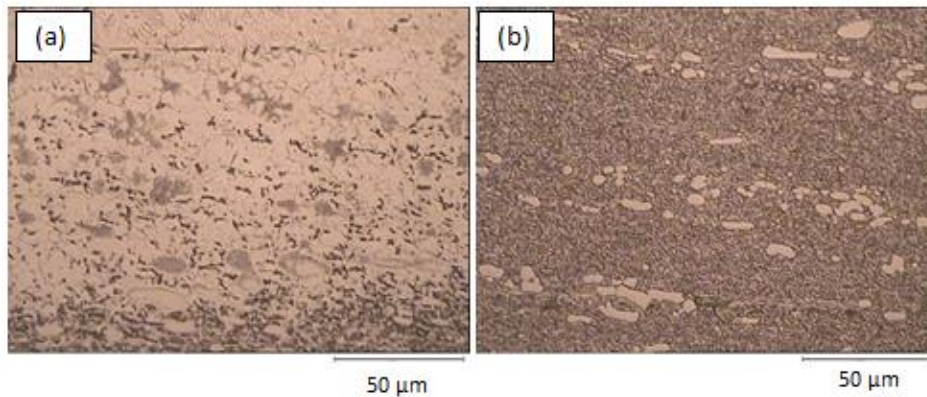


Fig. 8. Microstructure of heat affected zone (a) close to fusion zone (b) far from fusion zone

The microstructure of nickel base coating (Fig. 9) indicated hypereutectic dendritic structure. It exist primary face center cubic Ni-FCC dendrites which are NiCrFe rich and the interdendritic region which concentrated carbide former elements. Partition of iron-carbon result on the participation in austenite solid solution and interdendritic region [31].

For all cases the interface between layer and base metal was sound and crack free. Based on analysis, the existing phase is identified as γ -nickel dendrite and FeNi+Ni₂B eutectic. Also the tungsten carbide particles distributed in the layer, mainly in form of blocky W₂C particles. It should be mention that the temperature of the plasma is not high enough to melt the carbides. Near the substrate microstructure consists of very fine dendritic carbides indicative of rapid solidification. The microstructure of weld bead included tungsten carbide particles which distributed in dendritic nickel matrix. Also, volume fraction of carbides, close to the top surface is less than the area near to the base metal.

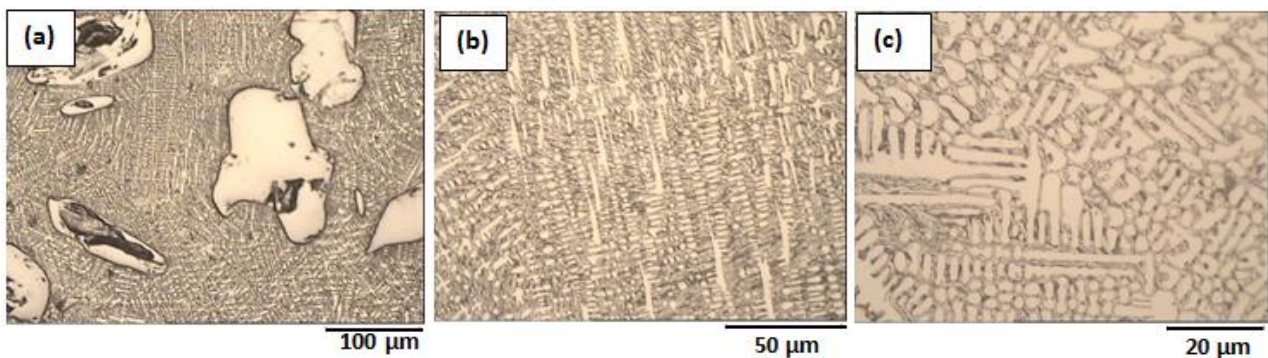


Fig. 9. Microstructure of Nickel base overlay (a) WC particles in matrix (b) denderites in different magnifications

3.4. Hardness Profile

The macro hardness value of the base metal was measured around 48 HRC, which obtained by medium of five indentations. Also, for investigation of hardness through the surface layer, the Vickers micro hardness was performed. The hardness value of hardface layer through the cross section for different samples are vary, which is because of different distribution of tungsten carbides in the weld pool. The main reason of high hardness in layer is because of existing combination of nickel with tungsten carbide particles. The

composition of the layer is tungsten carbide particle, Ni base solid solution which strength by Si, Cr and hard phases such as Ni₃B. Fig.10, indicated the hardness profile of some random samples from all tests.

The hardness of the outer surface is not maximum, because as explained before mainly tungsten carbide accumulated in the bottom part of the layer, subsurface zone which is due to higher density of the particles compare to matrix. Just in sample W9 the distribution of the WC particles were more homogeneous, consequently indicate maximum hardness value near the top surface around 800HV1, but in sample W19, the hardness value are more constant in surface layer (550 HV), just an increase near the base metal is visible which is due to accumulation of WC particles. Based on hardness data in heat affected zone, for all the samples decrease trend from weld overlay zone to the base metal was observed, which is necessary to homogenize the hardness value between two different parts. The hardness of matrix is roughly equal to base metal, just in area of existing WC particles, the hardness dramatically increase.

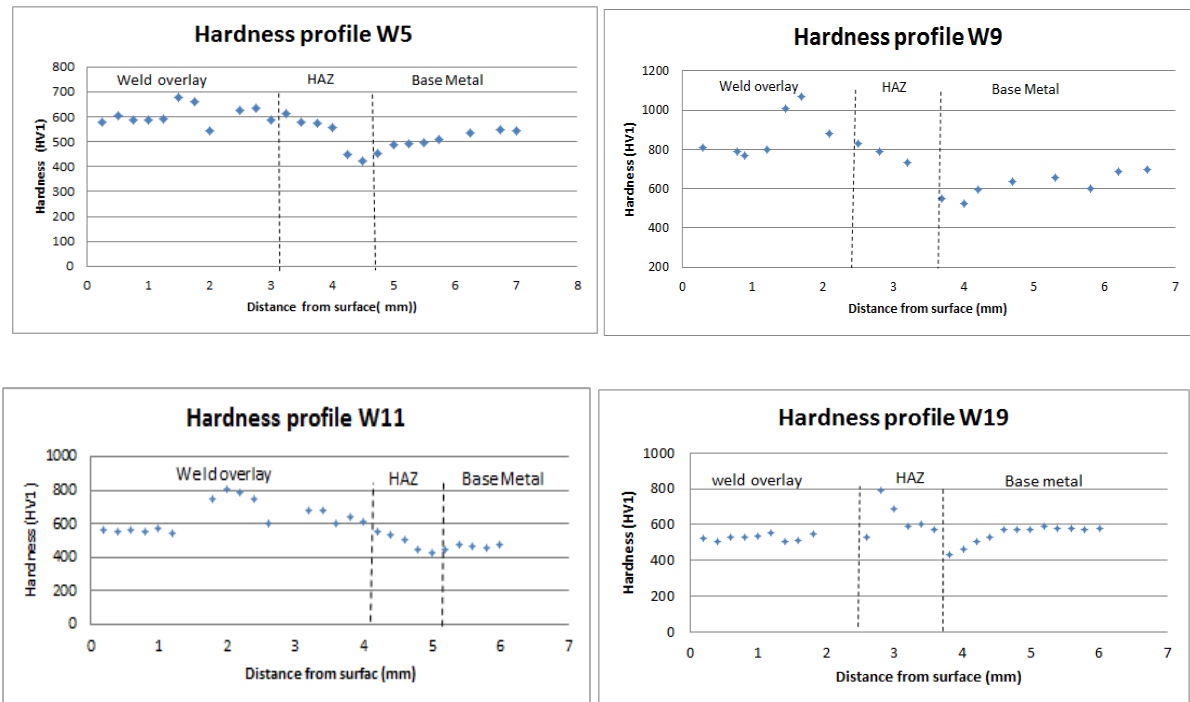


Fig.10. Hardness profile in different samples

3.5.SEM and EDS analysis

The EDX analysis was performed on different position of the deposited layer which indicated in Fig. 11 and Table 1 . As it is clear, in addition to large tungsten carbide particles, there are different types of blocky and Ni-Cr-Si-W-C particles and elongated W rich particles accompanied with small concentration of tungsten solid solutions which distributed near and far from WC particles and soft matrix. The diffusion of carbon to the matrix is faster than other carbide former elements. Complex and brittle carbide of M₃W₃C and M₆C can be form in matrix because of low carbon concentration in matrix alloys and rapid cooling of the melt, when WC exist as a reinforce material [32].

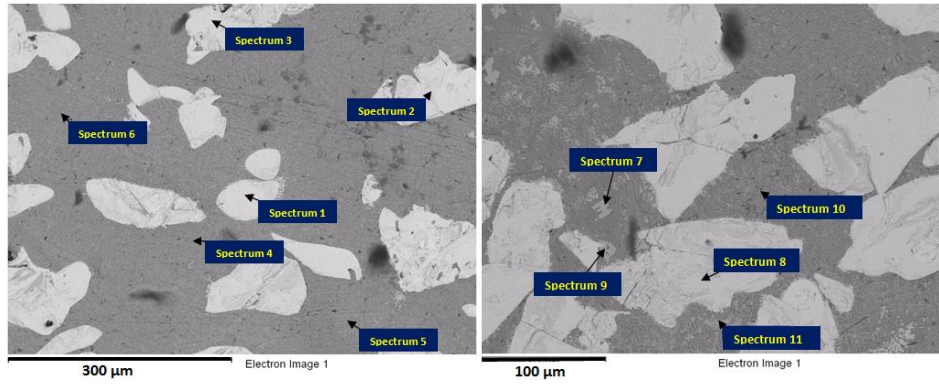


Fig. 11. Position of EDX analysis in different points of the microstructure

Table 5. chemical analysis of the spectrums which indicated in figure

	C	W	Si	V	Cr	Fe	Ni
Spectrum 1	7.26	92.74	-	-	-	-	-
Spectrum 2	7.08	92.92	-	-	-	-	-
Spectrum 3	7.24	92.76	-	-	-	-	-
Spectrum 4	5.04	20.71	0.23	0.39	12.71	45.72	13.15
Spectrum 5	9.49	22.89	-	0.65	17.57	38.60	9.76
Spectrum 6	5	16.31	0.77	0.35	10.70	44.34	20.38
Spectrum 7	5.01	50.86	3.15	0.37	13.7	9.21	17.7
Spectrum 8	5.81	81.56	-	0.36	5.50	3.96	2.82
Spectrum 9	8.90	15.05	1.55	0.31	18.90	31.30	24
Spectrum 10	2.78	15.24	2.56	-	5.61	37.33	36.48
Spectrum 11	7.82	90.83	-	-	-	-	-

As it is clear from Table 5, Tungsten in addition to exist in WC particle, is distribute in all part of the matrix in range between 15 to 50%. It was reported that WC/W₂C decarburized during spraying and W and C dissolved into Ni and NiCr. There is generally less W dissolve in NiCr than there is in Ni, this could be due to presence of Cr which stop diffusion of W into Ni and it is in agreement to the phase diagram of the alloys. Normally, the dissolution of WC in the matrix is not more than 5%. The matrix is composed of nickel dendrite and lamellar eutectic in interdendritic region. Also β-W₂C, quadrilateral precipitates such as η1-M₆C with some Cr and Ni (Cr,Ni)₃W₃C and thin plate carbide was reported as α-W₂C could be distributed in the matrix [32].

3.6. Finding the sample with optimum characteristics

Based on experimental data, sample W9 with the following parameters and responses which specified in Table 6 indicated the best results amongst all 20 samples.

Table 6. Parameters and results of optimum experimental sample

Sample name.	Current (A)	Travel speed (cm/min)	Preheat (°C)	Dilution (%)	Penetration (mm)	Reinforcement (mm)
W9	86.36	85	350	30.52	0.69	1.43

But, it is relatively difficult to perform the welding process to reach suitable bead geometry with using different sets of process variable. Based on what suggested in literatures [5, 26], to reach appropriate weld layer geometry, the reinforcement should be maximum, in addition penetration and dilution should be in minimum value. It is very important to select appropriate process parameters to obtain optimal weld bead geometry [10, 33].

4. Conclusions

After applying nickel base powder reinforced with tungsten carbide on D2 tool steel by PTA process with different parameters, the following conclusions can be drawn:

- Experimental investigation, showed that design of experiments is an effective method to find appropriate weld bead geometry in PTA process.
- Based on the result, current is the main parameter which has an effect on weld bead geometry, after that travel speed is important and the preheat is the last important controlling factor. Mainly with increasing the current, penetration and dilution increase, but reinforcement decrease.
- With increasing the travel speed, dilution increase, penetration and reinforcement decrease.
- Based on the obtained data the optimum parameter for hardfacing was found as current=86 A, travel speed=85 cm/min and 350°C preheat.
- The distribution of WC particles in the weld pool was not homogeneous and mainly accumulated in lower part of the weld pool close to the base metal which could be due to higher density of the particles.
- Due to existing WC in the weld overlay, the hardness increase and it cause to improve the surface properties in industrial applications.

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