A Practical Assessment of Using Resistance Spot Heating for Applying Alloy Layers onto a Mild Steel Substrate

Musallam Toma[1]

Abstract

The present work investigates an experimental assessment of surfacing process using the heat from resistance spot welding for applying a hard nickel and cobalt based alloy layer onto a substrate of low carbon mild steel. The main experimental work was performed on a conventional spot welder with an adaptive controller. A special jig and two electrodes were designed to set the chosen specimens (ϕ20x3 mm) with the alloy powder under the electrodes pressure. The fusing process was conducted by varying the main controllable factors to select the required combination of parameters. To compare the results of the investigated Resistance Spot Surfacing process, additional experiments were performed using some common welding methods. The evaluation of the bonded layers was based upon the hardness tests and the examination of the cross sections under the optical and the scanning electron microscope. The findings indicated that the layers applied by resistance spot heating had a sustainable strength, good integrity with the substrate metal and short operation time.

[1]Dept. of Mechanical Engineering,Faculty of Mechanical and Electrical Engineering, Damascus University.

Introduction

Surface engineering is a wide, enabling, progressive technology. Several available surface modification techniques and processes for reducing wear have been in existence for many decades and range from the more traditional weld overlay surfacing to the new technologies of laser and electron beam surface modification techniques. The surface of engineering components and parts can be modified to obtain special properties necessary for its service use such as high hardness, corrosion and wear resistance. Surface modification of any component involves the design of a composite system (i.e. coating plus substrate), which is supposed to have a performance that cannot be achieved by the substrate alone. Some changes in specification of base material maybe necessary to accommodate the coating layer, but these changes should not impair the properties of the bulk material (1). The designer should control the properties of the system to ensure optimum performance. In the final selection of available applications the designer must consider the cost as well as their practicality, taking into account the size and shape of modified components (2). By applying hard faced coatings to parts or components subjected to breakdown through wear, their working lifetime can be extended by up to five times (3). The coating thickness may range up to several millimeters and the deposit material is available in rods or powder.

In surface engineering practice many *welding and spraying processes* are still the most commonly available methods of applying a layer of alloyed metal onto a softer and cheaper substrate to improve wear resistance of the base metal. These methods have been studied and reported in many published works (4,5,6,7). Most of research efforts were directed to improve surface hardness, produce an excellent bond between selected coating and the substrate, and achieve a refined structure. Their results provide evidence of some dilution of the alloy by the base metal, which is usually most pronounced in the welding processes. Because of the manual application of these processes, good knowledge and operator skills of welding is required.

The well-known electric resistance welding technique has different applications in joining metals. The spot welding process is the simplest and most widely used form of resistance welding in the mass production industries. The fundamentals of spot welding process are demonstrated in the AWS Welding Handbook (8). A variety of spot welding equipment is available to meet the various needs of production operations. The research studies in this field were mainly directed to achieve effective quality control of the nugget formation during the welding process of sheet metals (9,10,11,12). Most of these studies have revealed the main factors such as the acceptable values of electrode current, welding time, the conditions of contact sheets, pressure electrode force, hold time and its effect on tempering the nugget. Despite the wide diversity of its applications, resistance spot welding has not been yet proved the worth in surface processing.

Resistance cladding based on resistance seam and spot welding processes was investigated at The Welding Institute (TWI). The published article (13) includes brief principles of both processes. It is reported that the main benefits of these processes are: no inter-dilution of the substrate and coating, excellent mechanical integrity of the bonded materials, the ability to deposit genuine metal-ceramic composite coatings and the fastness of the cladding process comparing with many other processes. The use of the resistance spot welder for applying a fused metal alloy powder onto the surface of some parts and components appears to be attractive. This technique can be applicable with appropriate modification in its design and operation control for surfacing process. As with any technological process this technique must have special designed jigs and fixtures to set the parts, which need to be coated.

Since the resistance spot heating process would factually involve the fusing of a powder alloy and partially the substrate interface under the electrode pressure, it should be called the Resistance Spot Surfacing (RSS) process rather than Cladding process. How effective and practical would (RSS) be for applying a layer of alloy metal onto a substrate comparing it with some of the most common surfacing processes? More research studies need to be conducted in order to reveal the main control factors and their effects on the investigated process and to ascertain its availability and practicability in surfacing engineering. The purpose of this experimental research was:

- To investigate and assess the Resistance Spot Surfacing (RSS) process for applying a hard alloy layer onto a substrate of low carbon mild steel.
- To compare the obtained properties with some well known in practice methods such as Powder Spray Welding (PSW), Oxy-

acetylene Flame Welding (OFW), and Tungsten Inert Gas Arc Welding (TIG).

This investigation was supposed to give the practical conditions to be considered in any probable application of the suggested resistance spot surfacing process (RSS).

Materials and Method

Operating equipment

The investigated (RSS) process was conducted on a TECNA 3971 air operated pincer type portable welder with a TECNA TE100-10 adaptive controller. The equipment can provide a sufficient transformed electric power of 35-kVA as standard power at 50% duty cycle. The factual used power depends on the selected power rate (%), that can be monitored from 20% to maximum 99%, and the resultant electrical resistance in secondary electrode circuit which includes the resistance in the contact surfaces and bulk materials of the work components. The current time can be controlled from about 5 cycles (0.1s) to maximum 99 cycles for each fusing operation, which can be repeated after controlled intervals in automatic regime. The electrode pressure force can be limited by regulating the air pressure supply. The principle of the investigated process is shown schematically in Fig.1 where a substrate with alloy powder is set in a special copper jig under pressure force of two electrodes. It was necessary to make some changes in the operation control to accommodate the welder for applying a layer of fused alloy powder onto substrate. So, in order to achieve the full time and heating temperature required for complete fusing without preceding the melting point of substrate metal, a variation in the power rate and current time, which is interrupted by intervals, was carried out during the experimental trials. However, the resistance heating temperature, which arise in the centre of specimen, would be relatively higher than in the perimeter. That should be considered for a proper selection of main controllable parameters. The fusing and bonding processes occur by means of the heat resistance energy when a high current passes between the electrodes for a short controlled time as shown schematically in Fig.2.

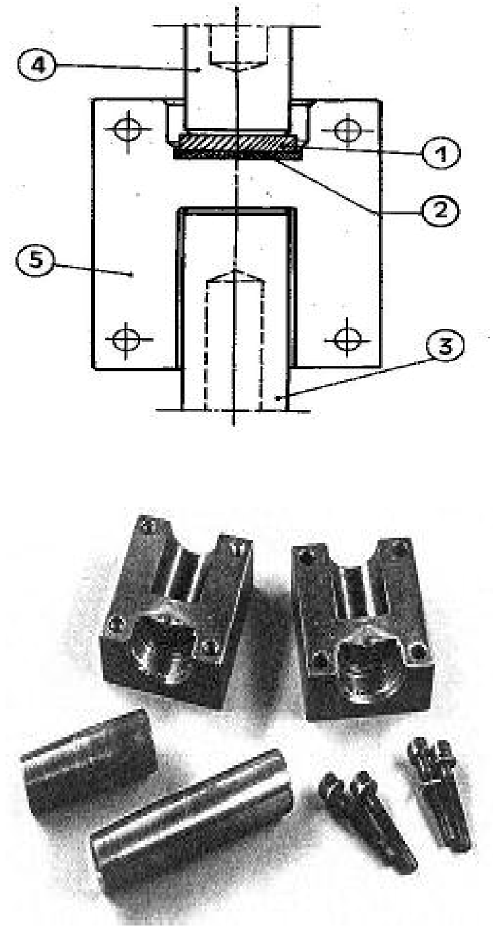


Fig.1 Principle of resistance spot surfacing (RSS).

1) Specimen of mild steel (substrate); 2) Alloy powder; 3) Lower fixed electrode; 4) Upper moving electrode; 5) Copper jig (two pieces).

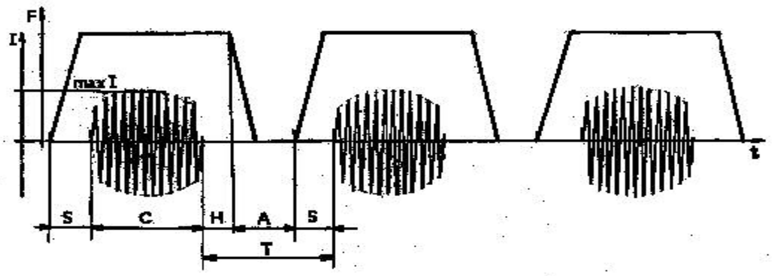


Fig.2 Scheme of three periods sequences for Resistance Spot Surfacing.
F- Electrode pressure force; I-Electrode current; S- Squeeze time; C- Current time;
H- Hold time; A- Interval of automatic regime; T- Period interval;

The design of the jig and electrodes depends on the shape of parts and components, which need surfacing. It should be important to consider the uniform of current path lines, which would pass through both electrodes and located specimen, obtaining minimum effect of any possible side shunt, that may pass uselessly out of the fused interfaces. In this investigation a jig with two electrodes was designed and made from a copper alloy.

Choice of substrate and alloy materials

The substrate was low carbon mild steel (0.15% C) with a round flat form (20mm diameter x 3mm thickness). The coating materials were selected from a list of commercially available nickel and cobalt base hard facing alloys with a lower melting point to provide good hardness and wear resistance. The alloy powders (Ni-based SF60 with the addition of 100% tungsten carbide WC, and Co-based SF20) were used for (RSS) and (PSW), while alloy rods (Ni-based Stellite 60, and Co-based Stellite 6) were used for (OFW) and (TIG). The composition of the coating alloys and their maximum expected deposition hardness are given in Table 1.

Table 1- Coating alloys used for surfacing processes

Coating Alloys	Composition of main elements (%):									Deposit Hardness (HVN)
	Ni	Cr	Fe	Si	W	Co	B	C	Mn	
Ni-base SF60	71	15	4.5	4.5	-	1	3	1	-	710-790
Co-base SF20	13	19	2	3	16	42	3	1.5	0.5	740-790
Ni-base Stellite60	74	16	2.5	2.5	-	1	3	1	-	690-700
Co-base Stellite 6	2	25-29	2	2.5	4.5	58-62	-	1	1	690-700

Experimental plan

In view of the investigating nature of this research, the experimental plan was designed to give sustained findings of the suggested surfacing method compared with other conventional known methods. The statement of the experimental topic was applying certain amount of hard alloy (2mm thickness) on mild steel specimens (20mm diameter x 3mm thickness) by resistance spot surfacing (RSS). It was necessary to carry out series of consequent preliminary experiments of the process with a selected combination of process parameters to define the main factors and their effective levels such as: the required power rate (%) and the resultant current; the sufficient current time, number of periods and intervals; the effect of pressure force and tip diameter of the electrodes; the conditions of contact surfaces and their effect on electrical resistance. The main target was to achieve a steady surfacing process with maximum surface quality. After the preliminary experiments had been carried out, the main factors with three narrow variable controllable levels were selected and justified as followed in Table 2.

Table 2- Main variable factors and their levels

Power rate	%	65	70	75
Current time x 3 periods	Cycles	80	90	99
Interval between periods	Cycles	125	145	165
Electrode pressure force	daN	125	140	155

The qualities of surfacing process and surface hardness were chosen as main responses for each sample. The qualities were defined in marks by evaluating coated area, distortion and faults in layer and substrate such as porosity and cracks. The surface hardness testing of the layer was conducted on a Rockwell test machine with C diamond cone under 150-daN load.

Experimental procedure

The main experiment was designed on the base of Tauguchi methodology according to the typical orthogonal array (L9- 4factorx3 levels) (14). This method involves the combination of controlled levels and reduces the number of required trials, which can be repeated to confirm the efficiency of the experiment. The data of the controllable factors for 9 trials, which were conducted twice, is shown in Table 3.

Table 3-The combination of controllable factors and their levels for resistance surfacing of nine trials with Ni – base powder alloy with the addition of WC.

Trials	Period Interval	Power Rate	Current Time	Electrode Force	Index of Specimens	Index of specimens
	T, (cycles)	P, (%)	C, (cycles)	F, (daN)	1-st. Experiment	2-nd. Experiment
1	165	65	80	155	1-Ni	A-Ni
2	165	70	90	140	2-Ni	B-Ni
3	165	75	99	125	3-Ni	C-Ni
4	145	65	99	140	4-Ni	D-Ni
5	145	70	80	125	5-Ni	E-Ni
6	145	75	90	155	6-Ni	F-Ni
7	125	65	90	125	7-Ni	G-NI
8	125	70	99	155	8-Ni	H-Ni
9	125	75	80	140	9-Ni	I-Ni

To minimize the electrical resistance of contact surfaces and to avoid possible expulsion in the contacts with electrode tips, the specimen surfaces should be fine ground. Only one face of each specimen, which was subjected to contact the electrode tip, was ground by a silicon carbide paper to fine grit 600. The other face was left rough for good adhesion with the alloy layer. The main process of resistance surfacing was implemented using Ni-base wear resistance alloy powder with the addition of WC.

The Co-base alloy powder was implemented with six samples and the trials narrowed to only two levels in order to assure the feasibility of the resistance surfacing process with other alloy powder. The data of these trials is shown in Table 4.

Table 4- the combination of controllable factors and their levels for resistance surfacing of six specimens with Co-base alloy powder.

Trials	Period Interval	Power Rate	Current Time	Electrode Force	Index of Specimens
	T, (cycles)	P, (%)	C, (cycles)	F, (daN)	
1	145	70	99	140	J-Co
2	125	75	90	140	K-Co
3	145	65	99	140	L-Co
4	125	65	90	125	M-Co
5	125	70	90	125	N-Co
6	145	75	99	125	P-Co

The other specimens required for comparison were surfaced by means of conventional common methods (PSW, OFW, and TIG). Every coated specimen was initially surface ground in order to carry out a Rockwell hardness test and visual examination. To complete the estimation of the surfacing process, some of the coated specimens were ground on a wheel-grinding machine to obtain (1-1.2 mm) layer thickness for surface hardness testing and visual examination, while the other specimens were sectioned and prepared for micro examination of the cross section.
The sectioned samples were mounted then polished gradually to a fine degree (<0.1μm) until the surface of the cross section was free from scratches. Etching was conducted with 2% nitric acid then the samples were treated with a methanol solution. The etched samples were examined under the optical microscope in order to observe the microstructures of the bonded layer with the substrate. The Vickers hardness testing was conducted on the cross section to measure the hardness in different points of the layer and substrate. For further evaluation of the surfacing processes, the mounted samples were prepared for Scanning Electron Microscopy (SEM) in order to define the chemical compositions of layer elements and their percentage. This microanalysis would give a proper estimation of the bonded layer dilution by the base metal.

Results and Discussion

Experimental parameters

A total of 42 specimens were prepared for surfacing by resistance heating. The preliminary experiments were conducted consequently from wide to narrow levels of variable factors. Then the selected combination of process parameters was defined for the main factors and their effective levels, which gave the required surface layer. General relationships between the rate of used power (P, %) and each of the current time (C, cycles) and the value of electrode current (I, kA) were obtained on the base of the experimental trials of the equipment. The data of process parameters are shown in Table 5. The mathematical formulas given in the table could define approximately the effective required levels of process parameters for applying a layer of Ni-base alloy onto a substrate of mild steel.

Table 5- Experimental parameters for surfacing by resistance spot heating.

Spot welder: TECNA 3971 with TE100-10 adaptive control; Copper jig and electrodes (Φ18 mm); Specimen: mild steel (Φ20x3 mm); Layer: Ni-base alloy powder with the addition of WC (thickness 2mm).										
Power rate	P, (%)	40	50	60	65	70	75	80	85	90
Max. Electrode current	I, (kA)	1.4 ±0.2	3.4 ±0.2	4.9 ±0.3	5.7 ±0.4	6.3 ±0.5	7.0 ±0.5	7.7 ±0.5	8.0 ±0.6	8.2 ±0.6
Current time of one period	C, (cycles)	160 ±5	130 ±5	110 ±5	100 ±5	90 ±5	85 ±5	80 ±5	75 ±5	70 ±5
Experimental Formulas:		$I \approx (1.9\sqrt{P} - 9.5) \pm 0,5$; $C \approx (6400/P) \pm 5$; I (kA), P (%), C (cycles).								

It is important to note that the required power rate for completely fusing the alloy powder ranged from 60% to 80% in reverse correspondence with the current time, which ranged from 110 to 80 cycles. While the higher power overheated the substrate and caused the appearance of distortion and expulsion in the fused interface the lower power gave insufficient heating for fusing the alloy powder.

Main response parameters

The trials were performed in a random test order for 18 specimens, which were surfaced using a Ni-base alloy with WC, and for 6 specimens, which were surfaced using a Co-base alloy. The experiments showed good fusion, and the layer was fully bonded with the substrate metal. A small amount of distortion was observed on the substrate surface as a result of the electrode pressure force at the highest temperature during the fusing process, which could be controlled. Agglomerated spots of fused powder were observed on the side of specimens when a high electrode current was monitored. Some evidence of an incomplete coated surface with the presence of porosity was observed on the layer when a low electrode current and short cycle time were monitored. Some of the surfaced samples with evidence of the surface features can be seen in Fig. 3. The data of the main experiment and the results of response parameters are given in Table 6 and Table 7 for the (RSS) process.

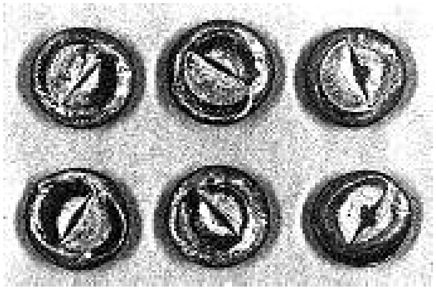


Fig.3 Samples being surfaced by resistance spot surfacing (RSS).

Table 6- Main parameters of experiments for resistance surfacing with Ni-base alloy powder with the addition of WC

Index of samples	Current	Quality & Hardness		Index of samples	Current	Quality & Hardness	
	I, (kA)	Q, marks	H, HRC		I, (kA)	Q, marks	H, HRC
1-Ni	5.4	73	43.3	A-Ni	5.5	74	44.7
2-Ni	5.8	80	42	B-Ni	6.2	70	42.3
3-Ni	7.0	77	44.7	C-Ni	6.8	73	45
4-Ni	5.7	78	47.3	D-Ni	5.7	76	49.3
5-Ni	6.0	79	46.7	E-Ni	6.6	78	45.7
6-Ni	7.1	77	48	F-Ni	7.0	78	50.7
7-Ni	5.6	79	47	G-Ni	5.6	79	48
8-Ni	6.9	81	47.3	H-Ni	6.5	76	46.3
9-Ni	7.5	79	41.7	I-Ni	7.1	79	41

Table 7- Main parameters of experiments for resistance surfacing with Co-Base alloy.

Index of samples	Current	Quality & Hardness	
	I, (kA)	Q, marks	H, HRC
J-Co	6.8	78	60.7
K-Co	7.3	70	61
L-Co	6.0	73	58.3
M-Co	6.2	67	56.3
N-Co	6.7	74	58
P-Co	7.2	69	59.1

Based upon the findings, a wide range was noticed in the values of the electrode current monitored during the subsequent periods of the fusing process for the same power rate. The reason for that is the high sensitive effect of the electrical resistance, which includes the contact and bulk resistance of the used alloy powder and the substrate metal at a variable elevated temperature of resistance heating. Consequently, differences in fusing behaviour would be noted for different alloy powders, which could be used in the resistance surfacing. Hence, each alloy powder, due to its properties and melting point, needs a definite range of required resultant electrode current and relatively the power rate and time of periods. For instance, the fusing process of the Co-base alloy powder required less power rate at the same time of periods, comparing with the Ni-base alloy powder with the addition of WC, which has a higher melting point. Any excess power rate would lead to agglomeration of the fused powder on the side of the substrate.

Nine average responses of quality marks and hardness HRC numbers were obtained for two sets of the main experiments with the Ni-Base alloy with the addition of WC. The responses were used to calculate the effect of four controllable variable parameters. From the analysis of these effects it could be indicated that the response increases or decreases while the magnitude indicates the value of the effect. The four main effects are shown graphically in Fig. 4.

The graphs indicate that the difference in selected variable levels of the main factors leads to a varied range of response. The quality marks of layer surface ranges from 74 to 79 with the average of 77. The hardness numbers varies from 41 to 49 HRC with the average of 46 HRC. The findings define the most effective levels of main factors for resistance surfacing for the given conditions as following:

Power rate 65 – 70%; Current time 90 – 99 cycles x 3 periods; Interval time 125 – 145 cycles; Electrode force 125 – 140 daN;

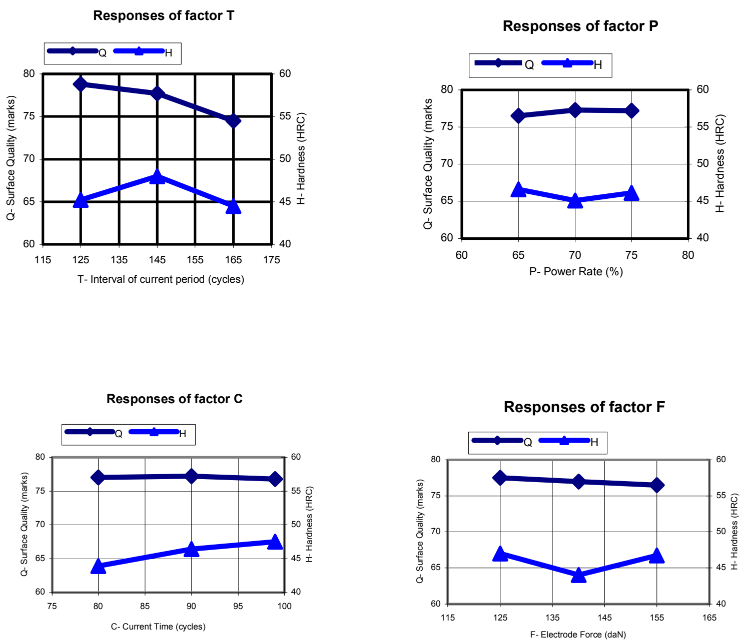


Fig.4 Graphics of response to the main controllable factors.

It is necessary to note that there is no direct correlation between two responses of the hardness and the surface quality, which was chosen for estimating the samples being surfaced.

Comparison between the results of surfacing methods

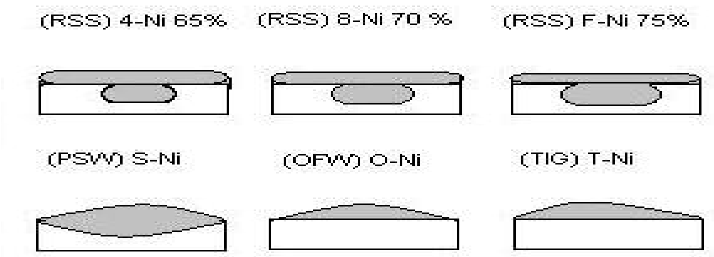
To compare the response parameters of surfacing process, a set of 12 specimens was coated with Ni-base and Co-base alloy layers by the other common surfacing methods (OFW, PSW, and TIG). All the coated samples were also partially ground and prepared for evaluation by hardness testing and visual examination. The quality marks and hardness numbers HRC are demonstrated in Table 8. It is seen that there are no wide differences between the results. The Rockwell hardness test showed no cracks in all the applied layers. The most important finding was that the coating applied by (RSS) had a sustainable strength and good mechanical integrity with the substrate metal. Besides, the (RSS) process was relatively very short in operation time.

Table 8- Main parameters of experiments for common surfacing methods

Surfacing methods	Index of samples	Quality Q, marks	Hardness H, HRC
PSW	S1 – Ni	73	42
	S2 - Ni	71	42.3
	S1 – Co	77	45.7
	S2 - Co	78	46.3
OFW	O1 – Ni	84	48.3
	O2– Ni	85	53
	O1– Co	71	42
	O2– Co	72	42.7
TIG	T1– Ni	84	46.3
	T2– Ni	83	52.7
	T1– Co	82	58
	T2– Co	81	57.7

A set of ten surfaced samples by means of different methods were ground on a grinding wheel machine to obtain 1–1.2 mm thickness of the hard layer for conducting further Rockwell hardness tests and visual observation of the layer. A further set of ten surfaced samples using different methods were sectioned and mounted in plastic forms. Then the cross sections were prepared for optical microscopy and Scanning Electron Microscopy (SEM) and Vickers hardness testing.

The cross sections prepared for micro examination and (SEM) have different forms of alloy layers and interface bands. These forms are shown schematically in Fig.5. Observation of the cross-sectioned samples surfaced by RSS showed an area in the middle of the substrate, which was similar to the nugget that is usually formed in sheet metal spot welding. Its size correlated consistently with the used power rate and current time. It seems to be an alloying rather than a dilution process. The base metal appears to have been alloyed by the fused alloy powder under the pressure of electrodes. This is associated with a high temperature arising in the middle area of the specimens where the most intensive current path takes place.



(RSS) 8 – Ni 70% **(RSS) F – Ni 75%**

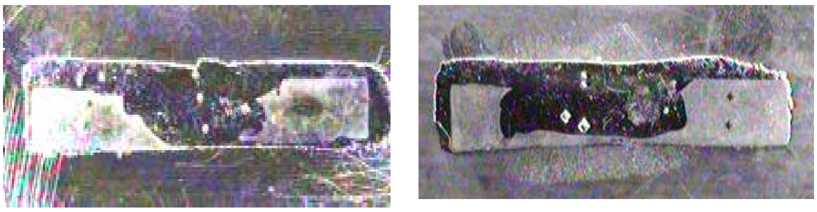


Fig.5 Formation of the layers and the interface bands

Hardness testing results and probes microanalysis

Table 9 summarizes the results of the hardness test that took place on the ground-coated surface and cross section of the samples.

Table 9- Hardness testing results and approximate degrees of dilution

Index of samples	Surfacing methods	Surface hardness after grinding HRC	Average hardness of the cross section for:			Approx. degree of dilution %
			Layer HVN/ HRC	Core HVN/ HRC	Base metal HVN	
3-Ni	RSS	43	-	-	-	-
4-Ni		-	472/47	502/49	192	7-(49)*
8-Ni		-	446/45	484/48	216	(50)*
D-Ni		47.3	-	-	-	-
F-Ni		-	545/52	454/46	199	2-(45)*
H-Ni		44	-	-	-	-
J-Co		59.7	-	-	-	-
L-Co		-	630/57	639/57	214	(53)*
S1-Ni	PSW	-	463/46	-	171	19
S2-Ni		42	-	-	-	-
S1-Co		-	505/49	482/48	199	(40)*
S2-Co		45	-	-	-	-
O1-Ni	OFW	-	570/53	-	152	0
O2-Ni		51	-	-	-	-
O1-Co		-	405/41	-	175	7
O2-Co		41	-	-	-	-
T1-Ni	TIG	-	563/53	-	174	0
T2-Ni		50.4	-	-	-	-
T1-Co		-	626/57	622/56	201	(68)*
T2-Co		56	-	-	-	-

(*) Dilution in the core of the area where there was most distortion.

The degrees of dilution were defined approximately by the results of Table 10, which presents the microanalyses of the elements composition in the layers. The surface hardness measured after surface grinding decreased only by 2-5% compared with the hardness measured on the initial surface layer. Despite the high degree of dilution in the core (45-53%), the samples being surfaced by RSS with Co-base alloy have an average hardness of approximately 57 HRC, which is almost equal to the deposit hardness reported in the properties of alloy surfacing powder. The samples with Ni-base alloy show a lesser average hardness of approximately 46-49 HRC. The reason for that difference from the reported value of the deposit hardness is the need for higher input heat required to fuse completely the Ni-base alloy powder with the addition of WC. It is known that tungsten carbide granules have a higher melting point (2867°C) than Ni-base alloy powder (964-1003°C). But, in this case, the use of higher input heats or power rate would affect the mild steel substrate since a higher electrode current could pass through it. Therefore, the power rate was limited at 75% in the conducted trials. Eventually, the WC granules dispersed in the matrix of fused Ni-base alloy and mixed with the molten interface metal, particularly in the middle of the substrate. Consequently, the deposit hardness of the applied layer was not as would have been expected and was affected by a high degree of dilution (45-50%) from the base metal.

Table 10- Electron probe microanalysis of the layer and interface substance.

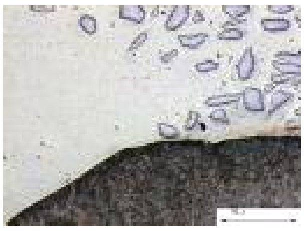
Index of sample	Place of micro analysis	Chemical composition of main elements, %					
		Ni	Cr	Si	Fe	W	Co
4-Ni	Layer	40.8	5.3	12.9	8.7	32.3	≈0
	Core	15.5	1.7	8.7	49.2	24.9	≈0
8-Ni	Core	16.6	1.7	8.4	49.8	22.6	0.9
F-Ni	Layer	49.1	5.2	13.5	3.4	28.8	≈0
	Core	17.2	1.7	9.1	45.1	26.9	≈0
L-Co	Core	5.5	10	3.6	53	7.6	20.3
S1-Ni	Layer	27.4	2.7	11.7	21.4	36.7	0.1
S1-Co	Core	7.2	12.5	4.7	40.6	9.7	25.3
O1-Ni	Layer	77.2	17	2.2	2.7	0	0.9
O1-Co	Layer	0.9	23.9	2.6	9.5	4.5	58.6
T1-Ni	Layer	78.2	15.3	2.4	3.3	0	0.8
T1-Co	Core	0.4	7.7	1.1	67.9	2.7	20.2

The deposit hardness obtained by other methods (OFW, PSW and TIG) ranged from 42 to 53 HRC for Ni-based alloy layers and from 42 to 58 HRC for CO-based alloy layers. The results depended mainly on the operator skills, the heating and cooling regime of surfacing process, and the quality of the equipment and its control. It was necessary to consider that the fusion of the substrate metal might take place and lead to some

dilution when performing thicker layers by most of the surfacing processes such as OFW, PSW and TIG.
By means of the Scanning Electron Microscopy (SEM) the probe microanalysis was conducted to define the composition of main elements included mainly in the surface layer of each sample and additionally in the area where there was some detection of most substrate distortion. The samples being surfaced by RSS showed a wide range of dilution from about 5% in the surface layer to 50% in the middle area of the substrates distortion. The other methods of surfacing showed a lower dilution from about 0 to 45%.

Metallographic examination

The results of metallographic examination (Fig.6-9) demonstrate that the alloy layers are well bonded onto the substrate. In Ni-based alloy layer, which contains the addition of tungsten carbide (Fig.6a, c), it is seen that the WC granules remained not fused and dispersed in the Ni-based matrix out of the central core. The reason for that is the insufficient resistance heating temperature in this region. While in the core, it raised to a maximum value that was sufficient to fuse the WC granules and some base metal increasing the degree of dilution.



a) F - Ni Interface

b) L - Co Interface

c) F - Ni Layer

d) F - Ni Substrate

e) L - Co Layer

f) L - Co Substrate

Fig.6 Microstructures of the samples surfaced by RSS.

Owing to the presence of boron and carbon in the alloy, precipitation of hard metallic carbides and borides were formed with the main metals (Cr, Fe and W) and provided most of the matrix hardness. Consequently, the measured Vickers hardness numbers in the Ni-based layer (420-670 HVN) were not what should have been expected and ranged widely below that reported in the properties deposit hardness of 710-790 HVN.

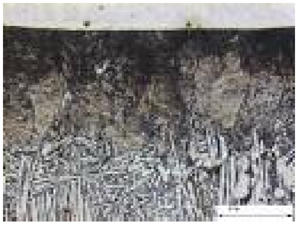
The photomicrographs of Co-based layers (Fig.6 b, e, f) display a fine microstructure of Co-based matrix alloyed with the main metals (Ni, Cr and W) and precipitation of hard metallic carbides and borides with the metals (Cr, Co, Fe and W) that provided most of the matrix hardness. The measured Vickers hardness numbers of the Co-based layers (630-670 HVN) were below the maximum reported in the properties deposit hardness of 740-790 HVN because of the high degree of dilution observed in the layer. It is seen from the microstructures of the substrate (Fig.6 d, f) that the base metal was exposed to a high red temperature. As the resistance heating process lasts only for a short time with a fast cooling rate, the substrate might be normalized. The original coarse structure of the rolled mild steel was recrystallized into a dendrite structure. Hence, the hardness number of the substrate remained in the range 190-215 HVN.

The photomicrographs shown in Fig.7 are for the samples surfaced by Flame Powder Spray Welding (PSW), where the same alloy powders were implemented in the surfacing process. The microstructure appears to have been exposed to a high temperature for a longer period than the other samples. In an attempt to fuse completely the sprayed nickel base alloy powder with the tungsten carbide granules, the surface layer and interface became more heat affected for a longer time. That is obvious from the presence of micro cracks and heat distortion shown in the interface. It is seen that the tungsten carbide granules were almost fused, but the hardness did not reach the expected value.

a) S1 - Ni Layer

b) S1 - Ni Substrate

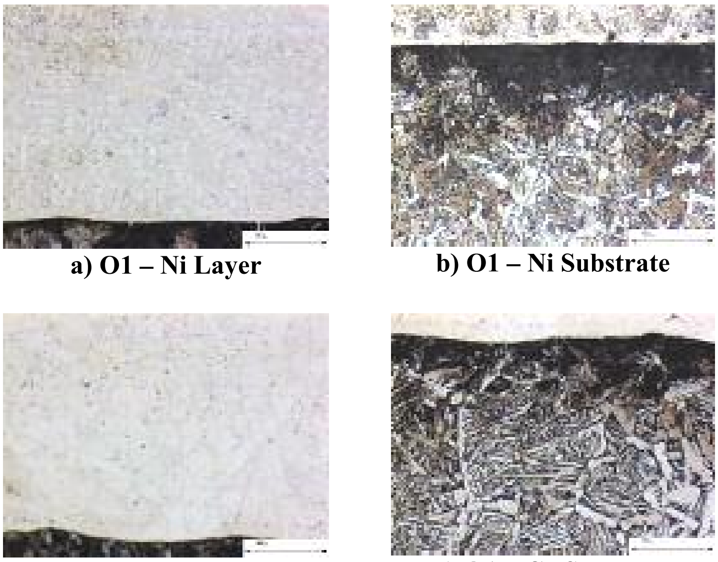
c) SI - Co Layer



d) S1 - Co Substrate

Fig.7 Microstructures of the samples surfaced by PSW.

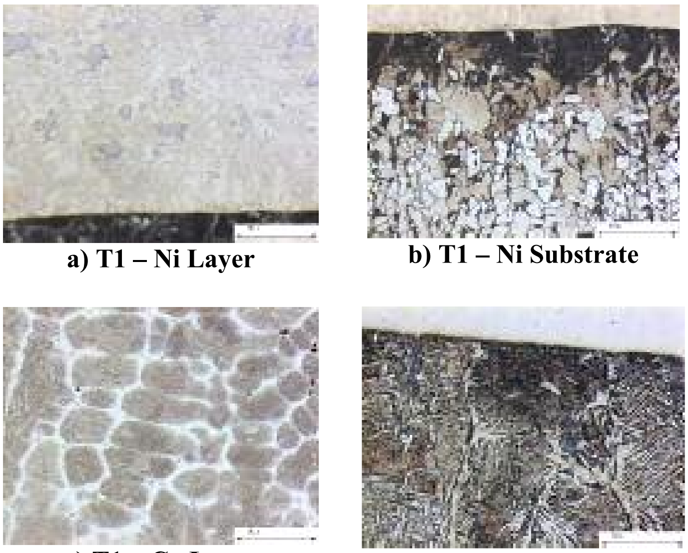
The photomicrographs shown in Fig. 8-9 are for the samples surfaced by Oxy-acetylene Flame Welding (OFW) and Tungsten Inert Gas Arc Welding (TIG). The deposit materials are nickel and cobalt based alloy rods. The microstructure of the nickel base alloy shows a well-bonded layer and good matrix with a fine dendrite forma of solidification. The structure of the cobalt base layer can be seen to be less coarse in the samples surfaced by (OFW) and coarser in the samples surfaced by (TIG) with a higher degree of dilution (40-68%).



a) O1 – Ni Layer
b) O1 – Ni Substrate
c) O1 – Co Layer
d) O1 – Co Substrate

Fig.8 Microstructures of the samples surfaced by OFW.

An evidence of heat distortion was observed while examining the appearance of the interface. The reason for this feature can be the high heat concentration being used in the surfacing process. This feature would ascertain the factor of operator skills on the quality of the surfacing. This factor is absent in the investigated surfacing process by resistance heating (RSS).



a) T1 – Ni Layer b) T1 – Ni Substrate

c) T1 – Co Layer c) T1 – Co Layer

Fig.9 Microstructures of the samples surfaced by TIG.

Conclusions

1. The investigated resistance spot surfacing process was short in operation time and demonstrated good mechanical properties of the bonded alloy layer with the mild steel substrate.
2. The surfacing process by resistance spot heating exhibited a high sensitive effect of the electrical resistance, which includes the contact and bulk resistance of the alloy powder and the substrate metal at elevated temperature. Therefore the suggested surfacing process should require an accurate and advanced process control with minimal operators skills.
3. The wide range of hardness numbers between the samples being surfaced by different methods correlated with the degree of dilution from the base metal and the heating regime of surfacing process. The samples being surfaced with nickel base alloy had an average hardness of 46 HRC and with cobalt base

alloy had an average hardness of 59 HRC. Dilution varied from 2-7%in the surface layer to 45-53% in the core of the surfaced sample.
4. By proper process control of the power rate and the period of resistance surfacing, both the deposit hardness and dilution degree can be regulated in a desirable range according to the properties of the chosen alloy powders for resistance surfacing.
5. The average rate of required current density for applying an alloy layer of 1.5-1.8 mm thickness onto a mild steel substrate was 18-22 A/sq.mm.

The application of the investigated resistance spot surfacing process might embrace a wide range of relatively small machine parts to be surfaced by a layer with special properties. Each part would require a specially designed jig and electrodes, taking into account the main path of the electrode current, where the higher resistance heating is taking place.

References

1. D.S.RICKERBY and A. MATTHEWS: in ‘ Advanced Surface Coatings: A Handbook of Surface Engineering ‘, 1-13; 1991,Glasgow, London, Blackie & Son, UK.
2. W. H. ROBERTS: ‘ Surface engineering and tribology in general engineering ‘: in ‘Surface engineering and heat treatment: past, present, and future’, (ed. P.H.Morton), 12-42; 1991,London, The Institute of Metals.
3. D. WOMERSLEY: ‘ Hardfacing: not merely a reclamation process ‘. Surface Engineering, 1995, 11, (1), 43-46.
4. D. WOMERSLEY: ‘ Practical assessment of spraying and welding processes for the hardfacing of grey cast iron ‘. Surface Engineering, 1991, **7**, (1), 61-66.
5. D. WOMERSLEY: ‘ Thermal spraying and powder spray welding processes for the hardfacing of grey cast iron ‘. Materials and Design, 1990, 11, (3), 153-155.
6. J.R.DAVIS, DAVIS & Associates: ‘Hardfacing, weld cladding, and dissimilar metal joining’: in ‘ASM Handbook, Welding, Brazing, and Soldering’; 1993, vol. 6, 789-829.
7. K.M. KULKARNI, and V. ANAND: ‘Metal powders used for hardfacing’: in ‘ASM Metals Handbook, Powder Metallurgy ‘; 1984, 9^{th} ed., vol. 7,823-836.
8. A.F. MANZ, MANZ & Associates:’ Spot, seam, and projection welding’; in:’ AWS Welding Handbook, Welding Processes ‘; 1991,8th ed., vol. 2, 533-539.
9. Z. HAN, J.E. INDACOCHEA, C. H.CHEN, and S. BHAT:’ Weld nugget development and integrity in resistance spot welding of high strength cold rolled sheet steels’. Welding Journal Research Supplement, Jul. 1993, **72**, 209-216.
10. J. G.KAISER, G. J. DUNN and T. W. EAGAR: ‘ The effect of electrical resistance on nugget formation during spot welding ‘. Welding Journal Research Supplement, June 1982, 167-174.
11. J.H. BROOMHEAD, and P.H. DONY: ‘ Resistance spot welding quality assurance ‘. Welding and Metal Fabrication, Feb. 1990, 58**,** (6), 309-314.

12. W.L. CHUKO, and J.E. GOULD:' Development of appropriate resistance spot welding practice for transformation - hardened steels '. Welding Journal Research Supplement, Jan. 2002, 1-7.
13. T. WAYNE, and N. DAVE:' Friction – friend or foe? Metal deposition by friction and resistance techniques '. Engineering Designer, Jan./Feb. 1993, 19, (1), 4-8.
14. A. BENDELL:' Introduction to Taguchi Methodology'; in: Taguchi Methods, Proceeding of the 1988 European Conference, (ed. T. BENDELL), 1-14: 1989, Elsevier Applied Science, London and New York.

Received, 24 February, 2004.