Laser Fusing of Alloy Powders for Applying Hard Facing Layers onto a Mild Steel Substrate

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Abstract

The surface engineering practice of applying an alloy layer onto a substrate of cheaper metal can be carried out by the conventional welding techniques and new technologies. The present work investigates an experimental assessment of surfacing process using the laser beam for fusing nickel and cobalt based alloy powders for applying a hard layer onto a substrate of low carbon mild steel. The main experiment was performed using pulsed 550W Nd:YAG Laser. The fusing process was conducted by varying the main controllable factors of process parameters such as the power intensity and interaction time. The evaluation of the bonded layers was based upon the visual examination and the micro hardness tests, which were conducted on the surface layer and the cross section. By examining the cross sections under the optical and the scanning electron microscope, a further estimation of the experimental samples was obtained. The findings indicated that the layers applied by laser heating had a good mechanical integrity with the substrate metal. The main process parameters can be regulated according to the properties of the chosen alloy powders. The application of the investigated surfacing process might embrace a wide range of relatively small parts to be surfaced using a layer with special properties.

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Introduction

Surface engineering is a wide, enabling, progressive technology. Several available surface modification techniques and processes have been in existence for many decades. They range from the more traditional weld overlay surfacing and thermal spraying to the new technologies of laser and electron beam surface modification techniques. The surface of machine parts and components mostly needs to be modified to obtain special properties which are necessary for its service use such as high hardness, wear and corrosion resistance, fatigue strength or other required properties. 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. The coating thickness may range up to several millimetres and the deposit material is available in rods or powder. Some changes in the specification of base material might be necessary to accommodate the coating layer. These changes, on the other hand, should not impair the properties of the bulk material (1). The designer should control the properties of the system to ensure optimum performance. Several alternative available coatings and surface treatments can often provide acceptable solutions in a given situation. In the final selection of available applications, the designer must consider the cost as well as their practicability, taking into consideration the size and shape of modified components (2).

Common methods of Spraying and Welding processes for hardfacing may be carried out on a wide variety of surfaces, from small components with intricate shapes, to large flat or cylindrical areas. Selection of hard facing alloy and deposition process can be difficult because of the vast number of different combinations of wear types. Some applications require a degree of experimentation before choosing the hardfacing alloy and process. In view of the needs for energy and materials conservation, the hardfacing of worn or new parts and components must be considered not merely as reclamation process, but as a production process. By applying hard coatings to parts or components subjected to breakdown through wear, their working lifetime can be extended by up to five times (3). Most of the research efforts in this field were directed to improve surface hardness, produce an excellent bond between the selected coating and the substrate and to achieve a refined structure. Their results provide evidence of some dilution of the alloy by the base metal, which is usually mostly pronounced in the welding processes. Because of the manual application of these processes, a good knowledge of welding and operator skills is required.

A Relatively new field of rapidly growing surfacing technology is laser surface modification. Its techniques provide many unique characteristics that other conventional processes cannot offer. The role of high power industrial lasers in a range of surface treatment techniques is well known and embraces micro machining, heating, welding and surfacing capabilities. The examples include the use of controllable power laser beam in surface modification. Its benefits include: localized area of treatment, minimum thermal distortion of component, accurate and controlled depth and rapid energy transfer (4). Laser surface alloying process involves the melting of a thin alloy layer L onto a substrate S to yield an alloyed surface layer with desired composition and thickness by controlling the extent of mixing materials, laser power intensity and interaction time. The main characteristic of this process is the possibility of producing a surface layer having an almost required alloy composition with fine microstructures. Laser cladding process involves bonding of fused alloy powder to form a layer of different material onto a substrate with minimum melting of the substrate metal. Such mixture between the cladded layer and the substrate is confined to the interface. So, the properties of the new layer would not be affected by the dilution from the substrate. Quite often a defocused beam, typically 4-to10 mm diameter is used, and a cladded track of similar width is obtained. The laser beam melts both, the substrate and the cladded alloy simultaneously. Different methods are used to deposit the alloy layer onto the substrate before irradiation such as preplaced powder or sheet, thermal sprayed, electroplated or powder feed with inert gas. The thickness and width of a single track and quality of a cladded layer are affected by the beam intensity and size, traverse speed, interaction time and alloy powder properties. In some cases, the porosity is most likely to occur in the layer structure. However, the rate of dilution, porosity and thickness of clad layer are influenced by the regime that controls the laser beam (4).

The laser fusing processes of coating material injected into melted surfaces of substrate have been reported in published works (5,6). In these studies, the trials were carried out using hard carbide powders to obtain hard layers and to produce an integrally bonded layer. These laser processes offer minimum distortion and dilution, localised heating, controlled shape which require large equipment with careful set up and automatic operation. Thermal powder spray methods also have been used to preplace alloy powder onto a substrate for subsequent laser fusing (7). This process offers fast, clean and easily controlled method with minimum effect on the substrate. However, in industrial applications, these two subsequent processes mean increased labour cost. Because of the high capital cost for the laser and associated equipment. Only a small number of these applications is in production despite all the promising results demonstrated by the laser processing. It seems that a lot of developing work is still to be done by the laser system of manufactures to produce progressive and cost effective laser techniques. However, the reliable laser surfacing process could be widely available when it becomes more practical and economic.

The purpose of this investigation was to assess laser fusing of preplaced alloy powders as a viable method for hardfacing flat components of low carbon steel. The scope of the experimental work was limited to microhardness testing and metalloghraphic examination of the interface and alloy layer. This investigation was supposed to give the practical conditions to be considered in any probable application of the suggested laser fusing process.

Materials and method

Fundamentals and process description

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. The amplification action is activated in a solid-state laser by a high intensity arc lamp and in a gas laser by an electric discharge. This energy places a number of atoms in a higher energy level and, as they revert to normal level, photons are emitted. These photons, in turn, trigger additional photons. The light in a laser beam is in phase, highly collimated and generally of a single wavelength. This allows it to be easily focused to a spot with a diameter in the order of 10 to 1000μm, giving very high power densities at the work piece, Fig. 1.

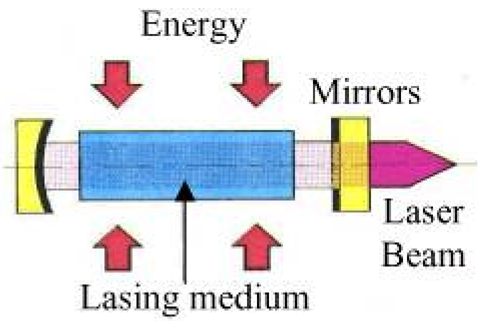


Fig. 1 Amplification action of laser beam

Lasers are used widely in materials processing. The main industrial lasers are CO2 and Nd:YAG lasers (yittrium-aluminum garnet doped with neodymium), with wavelength of 10.6 and 1.06µm respectively. The first uses mirrors for beam transmission, whereas the wavelength of Nd:YAG lasers allows it to be transmitted through a fiber optic. CO2 lasers have higher powers, up to 50kW, higher efficiencies and lower cost. The Nd:YAG laser however, is recently limited to 10kW, but the flexibility of the fiber optic delivery makes it an attractive option. Lasers with power densities in the order of 1-1000 kW/sq.mm produce a key holing action. This can be used to make narrow deep welds and cuts with very little heat input. In this present experimental work laser beam was used for fusing alloy powders to form a hard layer onto a substrate of low carbon mild steel.

1-Laser head with focused beam

2-Covering plate with square hatch

3-Specimens A & B with preplaced alloy powder

4-Movable work table
X-cross direction
Y-Traverse (Feed) direction

5-Laser fusing in process
V-feed speed

6-Preplaced alloy powder
7-Track of fused alloy powder

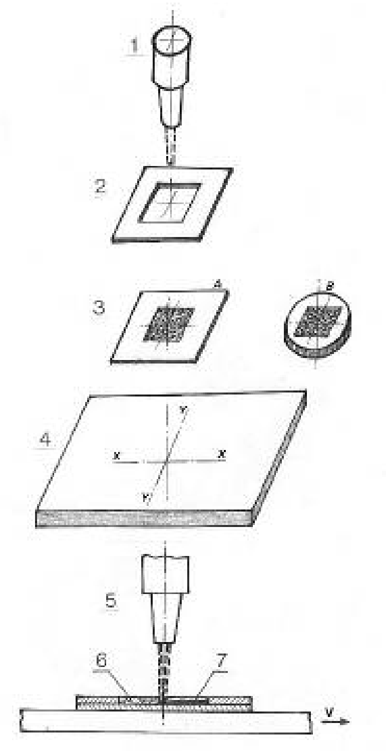


Fig. 2 Method of laser fusing

The method for laser fusing of alloy powder is shown schematically in Fig. 2, where a focused laser parallel beam is seen to melt alloy powder particles on the surface of steel specimen. Loose powder is preplaced within square hatch (14x14mm) made in covering plate thickness 1mm. By levelling the heaped powder we can define the thickness of bulk powder, which is set on the specimen surface. The specimen is held stationary on the movable worktable, which has a traversing movement along Y direction with a speed V. It also has periodically a cross movement in X direction with a constant pitch. So, the laser beam can scan the area (12x12mm) of square hatch automatically, fusing the preplaced layer of alloy powder onto the substrate and forming one layer of multi side-by-side track. Processing was done in a chamber under

slight stream of argon gas. The surfacing process was repeated to form multi-layered structure of required thickness (1,5-2mm).
The implemented equipment was a 550W Nd:YAG pulsed laser, which provides focused beam for direct fusion of chosen alloy powder. The laser beam was controlled to obtain variable process parameters and levels, which are shown in Table 1.

Table 1- Variable parameters of pulsed laser beam system and their levels

Energy per pulse	**E, (J/cycle)**	**10**	**15**	**20**
Frequency of pulsed laser	**F, (Hz)**	**15**	**20**	**25**
Average power of laser beam P=ExF	**P, (W)**	**150**	**300**	**500**
Traverse speed in Y direction	**V, (m/s)**	**1**	**1**	**2**
Focused spot laser diameter	**D, (mm)**	**0.5**		
Cross oscillating frequency	**(Hz)**	**50**		
Cross oscillating width	**(mm)**	**1.2**		
Cross pitch in X direction	**(mm)**	**1.2**		
Specific energy of laser beam Es=P/DV	**Es, (J/sq.mm)**	**From 300 to 1000**		

Choice of substrate metal and alloy powder

The substrate was low carbon (0.15% C) mild steel: with a plate form (50x50x1mm) of specimen A for the preliminary experiment to produce one alloy layer structure, and with a round flat form (20mm diameter x 3mm thickness) of specimen B to produce multi-layered overlapped alloy structure. The powders were selected from a list of commercially available self-fluxing nickel and cobalt base hardfacing alloys. The composition of the powder alloys and their deposit hardness are given in Table 2. The alloy powders provide good abrasion and wear resistance and are characterised by ease of application and the ability to dissolve oxides of iron, nickel or chromium and to form a hard smooth protective film, which prevents atmospheric oxidation.

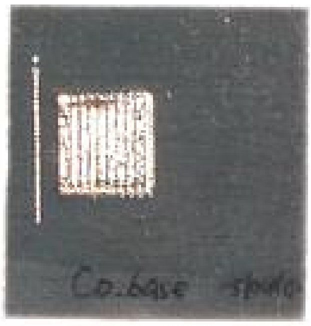
Table 2- Coating alloys used for surfacing process

Coating Alloys	Composition of main elements (%): Ni Cr Fe Si W Co B C Mn	Deposit Hardness (HVN)
Ni-base SF60	71 15 4.5 4.5 - 1 3 1 - With the addition of 100% WC tungsten carbide	710-790
Co-base SF20	13 19 2 3 16 42 3 1.5 0.5	740-790

Experimental plan and procedure

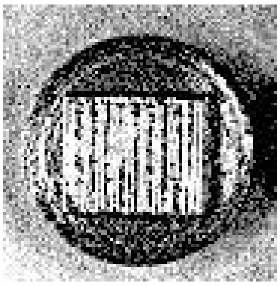
The preliminary experiment aimed to choose the optimum settings of controllable level parameters which were narrowed down by the findings heading to obtain a good bonded multi-tracked layer on the substrate of plate form (specimens A). The trials started initially in order to produce a single bead or track on the substrate with a steady laser beam for every setting. Then, the main experiment was conducted to obtain a good multi-layered structure of required thickness onto the round flat substrate (specimens B). 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 energy E of pulsed laser beam, its frequency F and traverse speed V. The main resultant factor was the specific energy Es, which had a wide range and depended mainly on the melting point of the alloy powder and the thickness of produced layer. Specimens were laser processed under selected parameters to fuse completely the coating alloy with minimum heating or melting the substrate. The main process of surfacing was implemented using nickel base wear resistance alloy powder with the addition of tungsten carbide, but the cobalt base alloy powder was implemented to assure the feasibility of the laser surfacing process with other alloy powders.

The possibility of forming pores due to irregular packing and levelling of bulk powder onto the substrate can then be minimized by controlling the fusion process, and the resultant layer surface can also be smoother. This will again be in favour of building up the next layer on the top of it to achieve the required coating thickness of 1.5-2mm. The shape of the alloy layers being applied onto the specimen A (with multi-tracked layer) and B (with multi-layered coating) is shown in Fig. 3.



Specimen **A -Co**

Specimen **A -Ni**



Specimen **B -Co**

Specimen **B -Ni**

Fig. 3 Shape of alloy layer being applied onto specimen B

Every coated specimen B was a surface ground on a wheel-grinding machine to obtain (1-1.2 mm) layer thickness in order to remove the roughness of the last multi-tracked layer and to carry out the hardness test and visual examination. To complete the estimation of the surfacing process, some of the coated specimens were sectioned and prepared for micro examination of the cross section.

The sectioned samples were mounted in special forms, and 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 test 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

Response Parameters

With the processing variables available for experimentation, a wide range of structures and properties is possible. So the selected combination of process parameters was defined for the main factors and their effective levels, which gave the required surface coating with a good bonded multi-tracked layer upon the square specimens A without any pores and cracks. This could be observed initially by visual examination. An evidence of the surface roughness is usually the most pronounced in the laser fusing of overlapped passes. The data of the preliminary experiment and the results are given in Table 3 for Co-base alloy layer and in Table 4 for Ni-base alloy layer. It is important to note that, to obtain good bonded layer, the required specific energy of laser beam was in the range from 400 to 600 W/sq.mm for cobalt base alloy, and from 600 to 1000 W/sq.mm for nickel base alloy. The reason for this difference is the addition of tungsten carbide WC, which has a high melting point. Hence, each alloy powder, due to its properties and melting point, needs a different range of required specific energy of laser beam for fusing process. The insufficient specific energy led to the formation of pores, while the higher specific energy caused agglomeration of fused powder and over heated the substrate.

Table 3- Data of preliminary experiment of laser fusing a Co-base alloy powder for applying multi-tracked layer with square specimens A

Index of samples	Energy per pulse, E(J/cycle)	Frequency of pulsed laser, F (Hz)	Average power of laser beam, P (W)	Traverse speed in Y direction, V (m/s)	Specific energy of laser beam, Es (J/sq.mm)	Quality of layer
Co-1	10	20	200	2	200	Evidence of pores
Co-2	15	20	300	2	300	
Co-3	10	20	200	1	400	Good bonded layer
Co-4	10	25	250	1	500	
Co-5	15	20	300	1	600	
Co-6	20	20	400	1	800	Agglome ration

Table 4- Data of preliminary experiment of laser fusing a Ni-base alloy powder for applying multi-tracked layer with square specimens A

Index of samples	Energy per pulse, E (J/cycle)	Frequency of pulsed laser, F (Hz)	Average power of laser beam, P (W)	Traverse speed in Y direction, V (m/s)	Specific energy of laser beam, Es (J/sq.mm)	Quality of layer
Ni-1	15	20	300	2	300	Evidence of pores
Ni -2	20	20	400	2	400	
Ni -3	20	25	500	2	500	
Ni -4	15	20	350	1	600	Good bonded layer
Ni -5	20	20	400	1	800	
Ni -6	20	25	500	1	1000	

The main experiment with round specimens B was conducted within the selected combination of process parameters to achieve multi-layered coating. After grinding the samples, a Rockwell hardness test conducted with the C diamond cone under a load of 150 daN showed some cracks in the applied layers. The reason for that can be the high degree of brittleness that takes place with high cooling rate while the laser fusing is on process. So the hardness test was conducted on a Vickers hardness machine under the load of 10 daN. The data of the main experiment and the results are given in Table 5 and the graphs of the relationship between surface hardness and specific energy demonstrated in Fig.4 for Co-base and Ni-base alloy layers.

Table 5- Data of main experiment and surface hardness of Co and Ni-base alloy layers applied onto steel substrate with round specimens B

Index of samples	Specific energy of laser beam, Es (J/sq.mm)	Vickers surface hardness (HV10) (HVN)
La-Co 1	400	470
La-Co 2	500	620
La-Co 3	600	658
La-Ni 1	600	525
La-Ni 2	800	790
La-Ni 3	1000	836

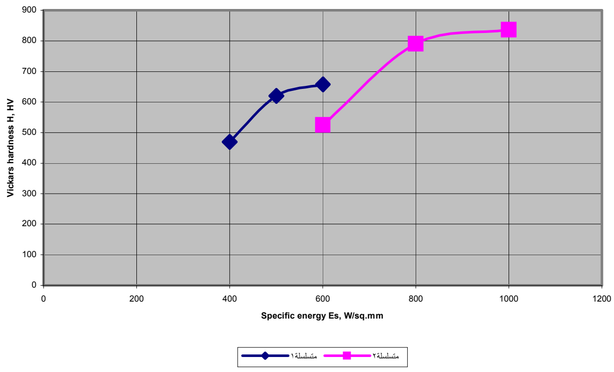


Fig.4 Graphs of the relationship between Surface Hardness H and Specific Energy Es

As it is seen, the surface hardness is correlated directly with the specific energy. The surface hardness of the Ni-base alloy layer has reached the value of deposit hardness that is reported for the selected alloy powder, but the hard layer is usually liable to crack under impact force. The surface hardness of the Co-base alloy layer is considerable, but lower than the reported deposit hardness. So it has higher ductility. Hard surfacing alloys are designed to provide maximum resistance to specific wear factors or combinations of wear factors. The performance of these alloys is in direct relation to the amount of carbide forming elements present in combination with carbon. The carbon reacts with the carbide forming elements, like chromium, tungsten, etc., creating hard carbides from which the deposit layer derives its wear resistance. As the ratio of these carbides increases, abrasion resistance increases and toughness or ductility decreases. In that case, the subsequent heat treatment process can modify the microstructure to achieve the required hardness, strength, ductility, and wear resistance, etc.

Evaluation of the cross section

Table 6 demonstrates the results of Vickers hardness test that carried out on the cross section. The dilution degrees shown in this table were defined approximately by the results of Table 7, which presents the microanalyses of the composition of the elements in the layers.

Table 6- Vickers hardness test on cross section of some samples B

Index of samples	In the layer (HVN)	In the substrate (HVN)	Aprox. Dilution degree, %
La-Co 2	620	201	0
La-Ni 2	790	198	7-15

Table 7- Electron probe microanalysis of the layer and interface substance

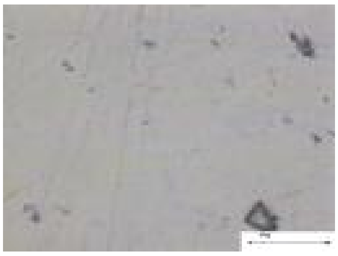
Index of Sample	Place of micro analysis	Chemical composition of main elements, %					
		Ni	Cr	Si	Fe	W	Co
La-Ni 2	Layer a	37.6	3	12.2	9.3	37.6	0.3
	Layer b	32.4	2.9	12.1	16.6	35.9	0.1
La-Co2	Layer	11.4	19.8	7.5	1.7	17	42.6

The features observed in the layers of laser fusing showed that in these layers the minimum degree of dilution and the high hardness were associated with a high brittleness. The deposit hardness of Co-based layer was about 615-620 HVN (56HRC) and the clad layer was not affected by any dilution. While the deposit hardness of the Ni-base alloy layer was raised almost to the maximum reported value of 790-800 HVN (64-65 HRC), because a higher input energy of the laser beam was implemented in carrying out the trial. The granules of WC were fused completely in the matrix layer and increased the hardness. For that reason the clad layer was partially affected by a dilution degree of 7-15%. However, the high hardness obtained was associated with some presence of porosity and cracks. These features can be explained by considering the method of overlaying single tracks. To refine the main structure of multitrack layers a convenient heat treatment should be selected, so the strength in the core of the applied layers would improve, but that option needs more investigation. In some cases the layers were quite brittle, and could not bear a contact load and repeated type of impact, so the hardness tests were carried out using a Vickers Pyramid Hardness testing machine with optical microscopy. By means of the Scanning Electron Microscopy (SEM) the probe microanalysis was conducted to define the composition of the main elements included mainly in the surface layer of each sample, Table 7.

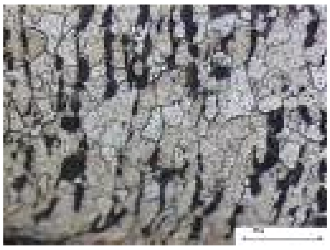
Metallographic Examination

The results of metallographic examination of the cross sections are shown in Fig. 5. The microstructures (a, c, e) exhibit a fine nickel and cobalt-based matrix alloyed with the main component metals (Ni, Co, Cr, Fe and W) and precipitation of hard metallic borides and carbides, which imparted most of the matrix hardness.

The observed structures show more cracks and porosity in some samples and the impression of Vickers diamond pyramid (Fig.5c). The presence of micro cracks in the structure of applied layer displays the brittleness of some samples that have been exposed to a high contact load of hardness testing. It can be seen (Fig.5a) that almost all the tungsten carbide granules became melted by the laser beam energy in the nickel base alloy layer and provided most of the matrix hardness which was raised almost to the maximum reported value of deposit hardness of 790 HVN. The substrate metal (Fig.5b, d, f) have not been affected by heat distortion and retained its coarse structure, therefore its hardness number remained without any changes between 198-201 HVN.

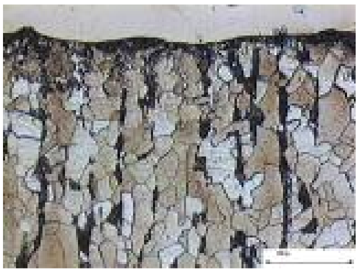


a) La – Ni2 Layer

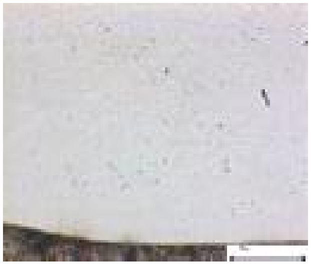


b) La – Ni2 Substrate

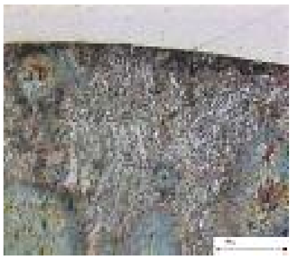
c) La – Co1 Layer



d) La – Co1 Substrate



e) La – Co2 Layer



f) La – Co2 Substrate

Fig 5 Microstructures of the samples surfaced by laser fusing process

Conclusions

1- Laser beam fusing process can be implemented to form high hard alloy layers of 1-2 mm thickness upon a substrate of cheaper metal as mild steel.

2- The main factor in laser surfacing process of applying a multi-tracked layer is the specific energy of laser beam, which depends on the properties of utilized alloy powders that need to fuse upon the substrate. This specific energy for laser fusing process with Co-based alloy powder was 400-600 W/sq. mm, and with Ni-based alloy powder with the addition of WC was 600-1000 W/sq. mm.

3- The interface between the substrate and the new layer was heated sufficiently to form a strong fusion bond and the fused area was precisely located and successive passes were accurately overlapped.

4- The application of the investigated laser fusing process might embrace a wide range of relatively small machine parts to be surfaced by an alloy layer of special properties.

5- Because of the multi-layered structure of coating applied by laser fusing and the possibility of forming pores, the coating should not be subjected to line or point-to-point contact or sever sharp and repeated type of impact.

6- The alloy layers of any thickness are responding to convenient heat treatment in order to improve its mechanical properties.

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