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Comparative Analysis of Diffusion Metallization Coatings Applied on Steel Parts

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Abstract: In this paper the positive and negative aspects of diffusion metallization of steels were reviewed. It was shown that at high heating temperatures and prolonged exposure under these temperatures, steels show a tendency to enlarge austenitic grain. Overheating can occur at high exposure temperatures (T>1000°C), which can be rectified by repeated heating however if burning of the steel microstructure occurs, it cannot be corrected. Given these circumstances, when assigning diffusion metallization modes, it is necessary to consider the factor of overheating or burning of steel in the process of exposure to high temperatures. To avoid this phenomenon, it is recommended to use alternative low-temperature processes of diffusion saturation of steels. Nitriding, nitro-cementation, gas-thermal spraying of the surface of steels are shown as such examples. It was suggested that these processes in comparison with diffusion metallization are more promising and acceptable for the restoration of worn surfaces of steels in the manufacture of parts of specialized equipment. Given that the parts of specialized equipment work in extreme conditions, repeated high-temperature heating of these steels is not recommended.
To overcome the shortcomings of the diffusion metallization, the most frequently used coatings are applied by CVD, thermal spray, and cloth cladding techniques. As an alternative promising solution, the development of innovative methods of diffusion saturation, like an ion plantation of atoms on a relatively cold surface of the part could also be considered. It is shown that diffusion metallization is most acceptable for saturation of the surface of non-ferrous metals and alloys with the hardest and wear-resistant compounds.

Keywords: diffusion metallization, steel, austenite growth, overheating, burnout, chrome-boronizing, nitriding, nitro-cementation.

1. Introduction

During diffusion metallization of steels, the processes of saturation of them with chromium and aluminium were studied in most detail. Diffusion metallization is usually carried out in solid, liquid and gaseous media. The metallizer in solid metallization are ferroalloys, for example, ferrochrome, etc. with the addition of NH_4Cl and as a result of the reaction of the metallizer with HCl or Cl_2 compounds of $AlCl_3$, $CrCl_2$, $SiCl_4$ and similar are formed. These compounds dissociate in contact with the surface of the steel to form free atoms [1, 2].

Liquid diffusion metallization is carried out by immersing steel parts in a molten metal bath (for example, aluminium). Gas metallization is carried out in a gaseous media consisting of chlorides of various metals.

Majority of diffusion metallization of steels consist of repeated heating, and in most cases to very high temperatures. At the same time, the low rate of diffusion of saturated elemental metals compared to nitrogen and carbon prevents the widespread use of diffusion metallization on an industrial scale, since the process becomes expensive and is carried out at high temperatures (1000-1200°C) requiring long exposure times [1]. However, the diffusion-saturated surface (chrome-plated, aluminized or silicated) has a high heat resistance. This process can be justified only when carbon steel parts are subjected to aluminization, chrome plating or silication, intended to function at operating temperatures of the order of 1000-1100°C.

When proposing diffusion metallization, attention should be paid to the growth of the austenitic grain of steel when it is re-heated. For example, during the transformation of perlite in the microstructure of steel into austenite, many small austenitic grains are formed. Further heating or prolonged exposure after full transformation of perlite - austenite leads to the growth of austenitic grain. It is known that steels are hereditarily fine-grained and hereditarily coarse-grained [1-4]. The latter, therefore, are very prone to the growth of austenitic grain, and hereditary fine-grained steels do not have grain growth even when heated to temperatures of 950-1000°C, but above these temperatures the factors that inhibit grain growth are eliminated and it begins to grow rapidly.

In this article, we sought to consider the pros and cons of diffusion metallization in the context of assessing the formation of the final structure of steel after this treatment, since sometimes researchers do not give much importance to this issue, citing only changes to the final properties and surface dimensions of steel parts. However, it must be stressed out that the operability and service life of critical parts that have undergone diffusion metallization also depend on their final microstructural condition.

The purpose of this article is to evaluate the pros and cons of diffusion metallization of steel parts during the process of saturation of them with various elements at sufficiently high temperatures and extended exposure times.

2. Discussion

Above, it was mentioned that in terms of the tendency of austenitic grain to grow when steels are heated, they can be hereditarily fine and coarse-grained. Hereditary coarse-grained steels begin to rapidly increase the size of the grain even with slight heating. Technological process of hot deformation, chemical-heat treatment, as well as properties, including operational ones dependant on the tendency of steel grains to grow. Hereditary fine-grained steels have a greater head room of processing temperatures and hot processes can be completed at higher temperatures.

However, when heated to a sufficiently high temperature (1000-1050°C), hereditary fine-grained steel can develop even a larger grain of austenite than hereditary coarse-grained steel. Depending on the heating temperature for hot processing, steel can develop the following types of structure: without overheating (Figure. 1,a), overheating and burning . Overheating (Figure. 1, b) can be rectified by re-heating to a lower temperature. If heating occurs at even higher temperatures and steel (even fine-grained) is under the influence of high temperature in a slight oxidizing environment of the furnace for a long time, steels may burn out (Figure. 1.c.). Burning is accompanied by oxidation and partial melting of the grain boundaries and a stone-like fracture. This can be considered as an incorrigible defect.

The most reliable explanation of the nature of the fine-grained structure is given by the so-called “Barrier” theory. Aluminium introduced into liquid steel shortly before it is cast into moulds forms with dissolved in liquid steel nitrogen and oxygen particles of nitrides and oxides

(AlN, Al_2O_3). These compounds dissolve in liquid steel, and after it's crystallization and subsequent cooling, they are released in the form of the smallest sub-microscopic particles ("non-metallic dust"). The latter, formed mainly along the grain boundaries, prevents its growth [4, 5].

In our opinion, aluminum nitrides and oxides play the role of Type 1 modifiers during the primary crystallization of steel, which are active centres of crystallization, contributing to the formation of a fine-grained structure, hence the inheritance of fine-grained steel. When the steel is reheated, these inclusions, like dislocations, located along the grain boundaries play the role of barriers to their growth.

Despite this, starting from a certain temperature, even fine-grained steels experience intensive grain growth. As shown by studies [6-10], at sufficiently high temperatures, aluminium nitrides dissolve in the surface layers of the austenitic grain. At the same time the barriers that prevent the growth of austenite grain are eliminated and the grain begins to grow.

a) b) c)

Figure 1. *Microstructure of carbon steel depending on heating temperature (x100) ([3] p. 147) a-without overheating; b-overheated; c-burned*

Enlargement of the austenite grain in steel has almost no effect on the statistical characteristics of mechanical properties (hardness, tensile strength, yield strength), but greatly reduces the impact strength, especially at high hardness (tempering at low temperature). This phenomenon is affected by an increase in the threshold of low-temperature embrittlement with the enlargement of the grain.

The tendency of steel for grain growth depends on its composition and the degree of deoxidation. Steels deoxidized only with manganese or manganese with silicon are classified as hereditary coarse-grained. Steels deoxidized and modified additionally with aluminium, titanium, cerium and other elements in an amount of 0.05-0.1% belong to the group of hereditary-fine-grained.

The transition through the critical point A_1 is accompanied by a sharp decrease in grain size. With further heating, the grain of austenite in fine-grained steel does not grow to very high temperatures, after which it begins to grow rapidly. In coarse-grained steel, nothing prevents grain growth, which begins immediately after passing through a critical point. Hereditary fine-grained steel at a sufficiently high temperature can have a larger grain of austenite than hereditary coarse-grained steel, so there is still a real grain obtained in steel at a given heating temperature. The size of the actual austenite grain is determined by the heating temperature, the duration of aging and tendency of the particular steel to grow the grain.

It is known that fine-grained steels have higher mechanical properties, so the natural granularity of steels is assessed by points of a specially developed granularity scale (Russian Standard GOST 5639-82, No. 6-15).

Heating pre-euthectoid steel to a temperature significantly higher than A_3 (1100-1200ºC) and subsequent cooling lead to the formation of a structure consisting of large needles of excess ferrite that cut through large grains of perlite. In honour of the Austrian scientist A.B. Widmanstätt such a structure was called the Widmanstädter structure (Figure. 2). Heating steel to high temperatures, leading to the formation of a large actual grain and obtaining a Widmanstädter structure, is called steel overheating. The coarse grain structure can be corrected by repeated austenization to a temperature of 30 – 50^{0}C above the A_3 point.

An even higher temperature heating of steel causing formation of melted areas appearing along the grain boundaries and their oxidation results in steel burning. As noted above, when burned, the steel fracture surface becomes stone-like and it is impossible to correct it.

The temperature ranges of austenitic grain growth for both hereditary coarse-grained and fine-grained steels are presented in Figure. 2. Looking at these diagrams, one can see that for hereditarily coarse-grained steels, reheating is dangerous from the point of view of coarsening the austenite grain at temperatures above 900^{o}C, and for hereditarily fine-grained steels, a sharp enlargement of the austenite grain occurs at temperatures above 1000^{o}C.

Now let’s look at this problem in the view of reheating steel during diffusion metallization. For example, chrome plating - saturation of the surface of steel products with chromium provides increased resistance of steel parts to gas corrosion (scale resistance) at temperatures up to 800^{0}C, high corrosion resistance in environments such as water, sea water and nitric acid. Chrome plating of steels containing more than 0.3-0.4% C also increases hardness and wear resistance [11].

The layer obtained by chrome plating of steel containing 0.3% or more carbon consists of chromium carbides $(Cr, Fe)_7C_3$ or $(Cr, Fe)_{23}C_6$. Figure.3 shows the structure of the chrome layer obtained on steel with 0.45% C. The layer consists of chromium carbides $(Cr, Fe)\ _7C_3$.

Underneath the layer is a transition layer with a high carbon content (0.8%). Such layers are formed as a result of the diffusion of carbon from the inner layers to the surface towards the chromium. Carbon has a higher rate of diffusion than chromium, so not all carbon is consumed to form a carbide layer and for this reason there is a transition layer with a high carbon content under the carbide layer. The carbide layer has a high hardness. The hardness of the layer obtained by chrome plating of iron is 250 – 300 HV, and chrome plating of steel results in 1200 – 1300 HV [12].

a b

Figure 2. *Widmanstädter structure (a) schematic (b) micrograph*

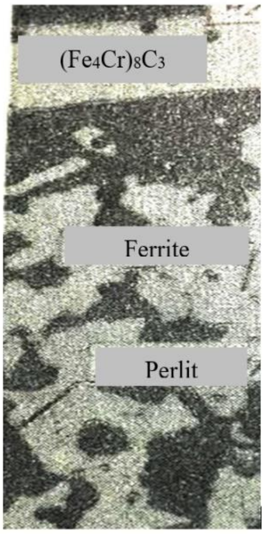

Figure 3. *Microstructure of chrome plated layers if steel x 200 ([4], p. 246)*

This is all plausible, and diffusion metallization has a positive effect on the structure and properties of steels in the situation when overheating is not allowed, and there is no burnout. However, it must stressed out that this is not always the case. In most cases, in order to increase the efficiency of diffusion and increase the working dimensions of worn parts, their diffusion saturation is carried out at very high temperatures and long exposure times.

For example, in some works [11-13] diffusion saturation of parts of special-purpose products was carried out by diffusion metallization. Mainly nitrogenized Russian steel grades 50PA, 30XH2MΦA, 38XH3MA, 30XHMΦA, 30XPA, 38XH3MΦA as per GOST 4543-71 were chosen as the object of the study. They were used to fabricate parts of special-purpose products. In the work [13] chrome-borating was carried out in a solid media using chromium powders X97 and boron carbide B_4C_3H. Diffusion saturation of parts was carried out at a temperature of 1100^0C for 4 hours. In the same work the authors only refer to the data on the phase composition of the saturated boron carbide layer.

In our opinion, to avoid overheating of steel during diffusion metallization, it is necessary to limit the processing temperatures to 900-950^{o}C. However, in this case, the duration of saturation should be increased to 6-10 hours to obtain the necessary effect of saturation of the steel structure and required thickness of the diffusion layer. If production requirements dictate that only diffusion metallization of steel products be carried out, then the above temperature and exposure times should be adhered to, although this could be considered as economically unjustified or challenging. This will prevent overheating of steel and consequently supress the formation of coarse-grained austenite with the ensuing consequences.

It should be noted that the medium carbon alloy steels considered by the authors belong to the category of improved steels. In these steels, in addition to molybdenum, vanadium is added, which helps to obtain a fine-grained structure. Examples of steels alloyed with Cr, Ni, Mo and V are Russian grades 30XH3MΦA and 30XH2MΦA. Greater stability of supercooled austenite provides high calcination, which makes it possible to strengthen large parts with heat treatment. Even in very large sections (1000 - 1500 mm or more) in the core after hardening, bainite is formed, and after release - sorbite. These steels after hardening and tempering possess high strength, ductility and toughness and a low threshold of cold brittleness. This is facilitated by the high content of nickel. Molybdenum present in steel increases its heat resistance. These steels can be used at a temperature of 400-450^{0}C.

In addition, these steels belong to the category of nitrided steels. Nitriding greatly increases the hardness of the surface layer, its wear resistance, the limit of endurance and corrosion resistance in such environments as air, water, steam, etc. The hardness of the nitrided layer is noticeably higher than the hardness of the cemented layer and is preserved when heated to high temperatures (450 - 500^{0}C), while the hardness of the cemented layer, which has a martensitic structure, is preserved only up to 200 - 225^{0}C [14]. These benefits facilitated wide application of nitrided M50 steels in the main shaft bearings of the gas turbines used for civil aircraft propulsion by companies like General Electric.

Compared to diffusion metallization, nitriding is carried out at a very low temperature without damaging the original structure of the steel. Moreover, nitriding of steel is carried out after hardening and high-temperature tempering, i.e., steel before nitriding already has increased strength and toughness in the core of the specimen.

Recently, nitriding in a smouldering discharge (ion nitriding) has been used, which is carried out in a rarefied nitrogen-containing atmosphere (NH_3 or N) when connecting the processed parts to the negative electrode - the cathode. The anode is the installation container. Between the cathode (part) and the anode a smouldering discharge is excited and gas ions bombarding the cathode surface heat it to the saturation temperature. The process of ion nitriding is implemented in two stages: first is the cleaning of the surface by cathode spraying, second is saturation itself.

Cathode spraying is carried out for 5-60 minutes at a voltage of 1100 – 1400V and low pressure. In the process of cathode spraying the surface temperature of the part does not exceed 250^{0}C. Nitriding is carried out at a temperature of 470-580^{0}C and operating voltage of 400 - 1100 V, process duration of 1 - 24 hours.

Ion nitriding reduces the total duration of the process, allows to get a diffusion layer of controllable composition and structure, minor deformation of the part and has great efficiency.

Now let us return to the question of diffusion metallization of alloy steels intended for the manufacture of specialized equipment. In some studies diffusion saturation, i.e., chrome-borating of alloy steels was carried out at a sufficiently high temperature (1100^{0}C) and a long exposure (4 hours). At the same time, the microstructure of steels after high-temperature processing as well as their strength characteristics with the exception of microhardness were not presented in the work. However, a comparative analysis of steels was given without referring to their microstructure. So, for example, the following reasoning was given:

- in the steels 50PA and 30XH2MΦA there is a fine carbide under the layer. The structure of coatings in steels 38X3MA and 30XHMΦA is similar to the structure of 30XPA and 38XH3MΦA, while a boride mesh is not formed under the coating.
- coatings over steel 30XH2MΦA have a fine-grained structure.

Such conclusions, which are not confirmed by microstructural analysis, do not give a clear picture of the quality of steels after high-temperature diffusion saturation. In such works, the main emphasis is placed on the increment of dimensions, i.e., on the restoration of the dimensions of worn parts of weaponry equipment. However, those microstructural changes in the steels after high-temperature processing with long exposure could lead to very undesirable phenomena such as deterioration of the structure and properties.

In addition, the process of diffusion chrome-borating of steels is incorrectly called diffusion metallization, since boron does not apply to metals. This process could more accurately be called diffusion saturation of steels with boron and chromium.

Currently diffusion metallisation has a strong presence in the surface treatment of some parts of specialized equipment, such as small arms, etc. Using existing technology, they are subjected to diffusion chrome plating, chromo-titanium plating and even chromo-boration in order to increase their durability under extreme operating conditions.

We believe that the restoration of expensive parts of specialized equipment is a promising area, but at the same time it is necessary to take into account all pros and cons of the chosen processing method. If the aim is to restore the worn dimensions of parts, then a lower-temperature and efficient process can be recommended, for example, nitrocarburization, which is carried out at temperatures of 840-860^{0}C. With a high carbon content in steel containing Cr, V, Mo, etc., carbonitrides are formed and located mainly along the grain boundaries in the form of a continuous or broken grid. The conversion of carbon and alloying elements into carbonitrides reduces the stability of austenite, which also leads to the formation of troostite in the layer.

The thickness of the nitro-cemented layer is usually 200-800 μm, but it should not exceed 1000 μm, since with a large thickness it forms a dark component and other defects that reduce the mechanical properties of steel [15].

As another alternative to diffusion saturation of steels, methods of gas-thermal spraying of various powders on the recoverable surfaces of parts can be recommended [16]. Gas-thermal spraying methods are widely used for coatings for various purposes. These protective coatings increase the corrosion resistance of products and reduce wear on working surfaces.

The main advantage of gas-thermal spraying methods is high productivity with satisfactory quality of coatings. With gas-flame spraying, mainly the surface of the repaired part is heated, and the core remains slightly heated. This is the main advantage of gas-flame spraying in the restoration of critical parts. Example of successful application of HVOF (High Velocity Oxygen Flame) technology to improve the wear resistance of API 610 pump wetted parts was demonstrated earlier [17]. Authors stressed that surface hardening treatments used in pump industry generally fall into two categories, diffusion and overlay coatings [18, 19]. First category does not see wide application in the pump industry due to relatively low thickness and microstructural heterogeneity. Diffusion coatings are generally applied using interstitial elements like carbon, nitrogen and boron interacting with the base metal in a special atmosphere at elevated temperatures. They have much stronger adherence to the base metal due to their intrusion into the parent metal lattice. Due to their high heterogeneity any machining operation following diffusion coating process can lead to complete or partial removal of the hardest outer layer. It was also generally accepted that diffusion coatings shouldn't be applied on stainless steel parts. Plain carbon steel and low alloy steel are the best candidates for application of diffusion coatings. Coating of stainless steel may result in removal of chromium from the solid solution due to precipitation of chromium carbide, hence leading to degradation of base material's corrosion resistance.

Application of diffusion coatings requires good understanding of the interaction between the base metal and coating as high thermal mobility of interstitial atoms of the coating can significantly reduce the surface mechanical properties of the base alloy. As it was mentioned earlier interstitial diffusion coatings are only used on low alloy or plain carbon steel. For substrates made of stainless or alloy steels it is general practice to use gas thermal spray processes.

Compared to diffusion metallization mentioned earlier, the above methods of saturating the surface of steels are more progressive and innovative technologies. However, if you compare them with each other, you can choose the gas-thermal coating method from the point of view of productivity and overall efficiency. Note that the gas-thermal method of saturating the surface of parts, compared to the above, is more flexible and easy to implement, and also has many varieties, such as flame spraying, detonation gas spraying, plasma spraying, etc.

Unlike diffusion coatings application of overlay coatings requires external source of heat and powder. Major processes are vapour deposition, plasma and thermal flame sprays, cladding and electroplating. The key advantages of these technologies compared to diffusion coatings are that no distortion of substrate material and no phase transformation are apparent. Generally, these coatings can be applied to thicknesses of up to 1.0 mm. However, majority of thermal spray techniques are line-of-sight processes and are not suitable for difficult to access areas like pump impeller or diffuser passageways [18-20]. Chemical vapour deposition (CVD) and cladding can overcome this limitation. Successful application of chemical vapour deposition (CVD) boriding to impeller passage was reported elsewhere [21].

Application of thermal spray coatings as a means of enhancing pump internal wear resistance capability underwent several evolutionary milestones over the past decades [22-24]. One of the limiting factors in the wide application of these coatings in the early stages of their development was inadequate bonding between coating and base metal. The density of the early generation coatings was insufficient and in combination with weak bonding could often result in premature failures due to physical detachment, delamination, or cracks. With development of high velocity oxy-fuel coatings (HVOF) these problems were gradually eliminated. In HVOF process the coating powder is heated and blasted onto the coated part by means of a thermal spray gun (Figure 4). Powder particles are heated by high temperature flame and travel with supersonic velocities as shown in Figure 5. Temperatures in the combustion flame can reach 3000°C.

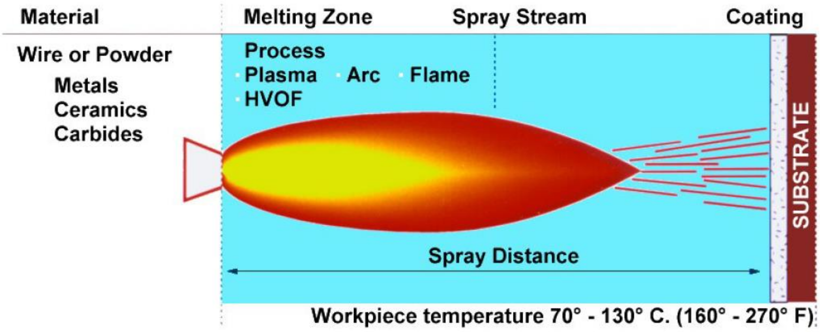

Figure 4. *Schematic of the thermal spray coating system © Sulzer Pumps (UK) Ltd. All Rights Reserved. Used With Permission.*

Application of HVOF coatings could be of first choice when the substrate parts are not suitable from material's compatibility point of view and when the ticker coatings are required. They offer ability to operate in the most extreme, i.e. high pressure, erosion, corrosion, abrasion environments. Despite their long life, reliability, and reduced downtime which made their application across various industries from landing gears of civil aircraft to pumps and valves used in oil and gas industry, one major limitation is that the process is line of sight and can't be a solution for parts with complex geometries.

Experience has shown that tungsten carbide and chromium oxide based cermets demonstrate good combination of wear resistance and durability when applied by plasma spray or HVOF to centrifugal pump impeller areas subjected to erosion and wear [20]. Field experience conducted on centrifugal pumps with HVOF coated components (Diamalloy 2004 or its equivalent) demonstrated good performance in abrasive or adhesive wear conditions. As such a radially split double suction pump suffering from a premature wear due to abrasive catalyst fines in a refinery service was successfully upgraded increasing its service life from 2 months to 18 months [21]. These successful reports of dramatic improvements of service life made application of HVOF coated parts as a standard for high-energy water injection pumps used in offshore oil and gas industry.

As alternatives to the diffusion saturated surface of worn parts, numerous other methods can be cited. However, we believe that the examples given are sufficient for a sober understanding of the approaches to restoring the parts of specialized equipment.

This criticism of diffusion saturation refers mainly to steels, the structure and properties of which are subject to undesirable changes. This criticism cannot be attributed to non-ferrous metals and alloys. Working and decorative surfaces of non-ferrous metals and alloys can be subjected to diffusion metallization very successfully. At the same time, on a soft metal base, you can get a fairly hard and wear-resistant surface of the parts, as well as give them a good aesthetic appearance. One of the examples of diffusion metallization of non-ferrous metals is chrome plating of the surface of parts of fuel pumps, etc., made of copper and its alloys. Such coatings work very successfully under combination of conditions such as temperature, abrasives and cavitation.

Some promising results were obtained with application of infiltration brazed tungsten carbide cladding (IBTCC) for Fluidised Catalytic Cracker Unit (FCCU) recycle pumps [25]. These pumps usually operate in the environment of excessive hard particles of catalyst fines in the pumped medium. Originally developed for extreme wear applications with difficult geometries such as down hole drilling tools and coal fired power plants IBTCC seems to have superior performance for internal and "line of sight" applications for centrifugal pumps. Hard diffusion coatings (boronizing) and CVD were the only available techniques for coating of the internal areas however they are inferior to IBTCC as these films are very thin and can easily be punctured by large abrasive particles. Unlike hard diffusion coatings IBTCC combines a strong metallurgical bond and a dense, uniform distribution of tungsten carbide particles throughout the coating (Figure 6). It was reported that after 13 months in service, an IBTCC cycle oil pump showed no significant signs of internal erosion.

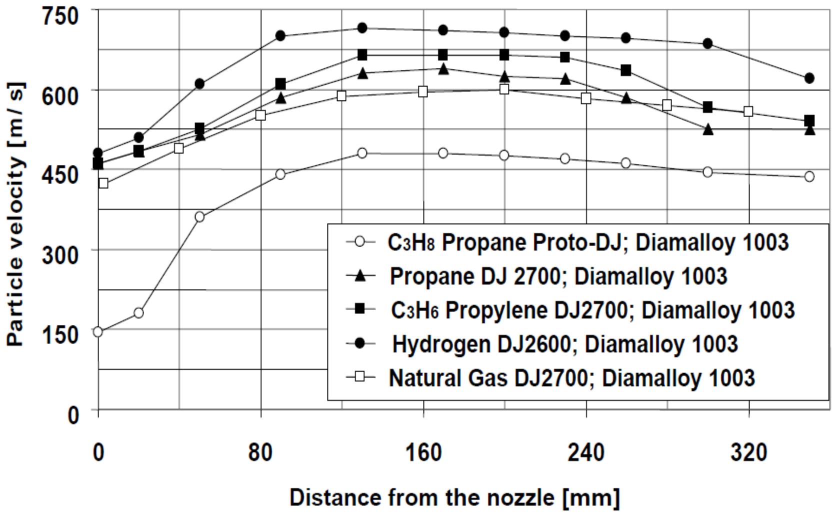

Figure 5. *Relationship between fuel gas and particle velocity © Sulzer Pumps (UK) Ltd. All Rights Reserved. Used With Permission.*

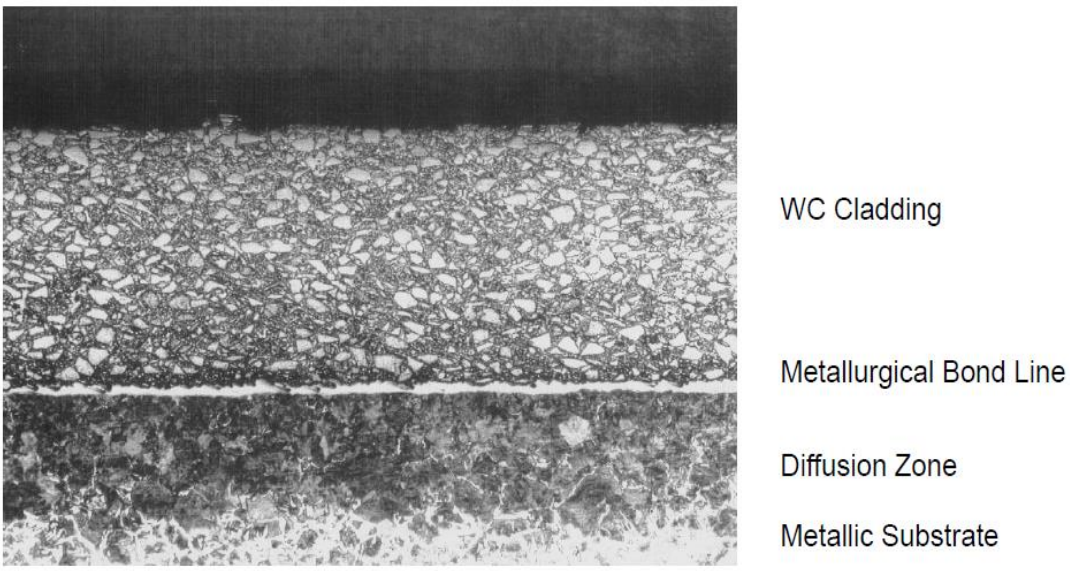

Figure 6. *IBTCC coating distribution [25]*

Another advantage of Infiltration Brazed Tungsten Carbide films compared to CVD films is that fact that they can be applied to a wide range of steels - Carbon and Stainless Steels or even Nickel Alloys. They offer thickness of up to 1.0mm with unform carbide distribution, no oxide contamination and minimal porosity. Therefore, this technology helps to overcome the "line of sight" limitations of the HVOF process and obtain superior quality films.

As it can be seen, the development of innovative technologies for diffusion metallization can be very promising. As such an example, an ion plantation of metal atoms on a relatively cold surface of parts can be recommended. In this process the substrate surface is embedded with ions accelerated to high velocities by electric field. Although this process has been little studied and currently has little practical application, we believe that in the near future ion plantation of various metals will take stronger place among the methods of saturating the surface of parts. Main advantage of ion implantation is good coating adherence, equal or superior to diffusion coatings. One of the key disadvantages of this process is relatively low thickness of the film in the order of 12-13 μm which limits its application as a standalone process, and it is used mostly in conjunction with other surface hardening techniques.

Thus, it can be noted that when restoring parts from steels, it is necessary to take into account the thermal nature of the effect of the chosen method on the structural state and characteristics of the metal, which leaves serious negative traces after the processing process. Therefore, it is this key circumstance that should play a major role when choosing a method for restoring critical parts.

3. Conclusions

There is an increasing demand to restore and bolster the functional properties of the worn parts of specialized equipment used in challenging operating environment. The application of various surface restoration and improvement techniques are nearly endless as they are successfully used for civil aircraft landing gears, pumps in oil and gas, refining and petrochemical industries, pulp and paper industry, gas turbines and weaponry. Although high-temperature diffusion saturation was often used as a first process of choice during original manufacturing, use of these processes to restore worn parts of specialized equipment has many limitations and seems to be impractical.

There are many alternative low-temperature methods of surface saturation that are successfully implemented in the industry and demonstrated proven track records. Field experience has demonstrated that abrasive wear of pump components can be significantly reduced by combination of HVOF, CVD coatings and infiltration brazed tungsten carbide cladding. Each if these processes have own limitations, however recent research has demonstrated that infiltration brazed carbide claddings can overcome some shortcomings of the HVOF which is limited to simple geometry parts due to "line of sight process". Unlike CVD hard diffusion coatings which are considered as a viable technique for difficult to access areas, infiltration brazed carbide claddings combine a strong metallurgical bond and a dense and uniform distribution of tungsten carbide particles throughout the coating. This results in superior microstructure, offering notable increase in the abrasion and cavitation resistance.

When selecting a method of diffusion saturation of the surface of critical steel parts, it is necessary to take into consideration the effect of thermal regime of the process on the substrate microstructure. Even hereditary fine-grained steels are very sensitive to the growth of austenite at high temperatures and long exposure time with the ensuing consequences.

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