Hardfacing of duplex stainless steel using melting and diffusion processes

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Abstract. Duplex stainless steel (DSS) is a material with high potential successes in many new applications such as rail car manufacturing, automotive and chemical industries. Although DSS is widely used in various industries, this material has faced wear and hardness problems which obstruct a wider capability of this material and causes problems in current application. Therefore, development of surface modification has been introduced to produce hard protective layer or coating on DSS. The main aim of this work is to brief review on hard surface layer formation on DSS using melting and diffusion processes. Melting technique using tungsten inert gas (TIG) torch and diffusion technique using gas nitriding are the effective process to meet this requirement. The processing route plays a significant role in developing the hard surface layer for any application with effective cost and environmental factors. The good understanding and careful selection of processing route to form products are very important factors to decide the suitable techniques for surface engineering treatment. In this paper, an attempt is also made to consolidate the important research works done on melting and diffusion techniques of DSS in the past. The advantages and disadvantages between melting and diffusion technique are presented for better understanding on the feasibility of hard surface formation on DSS. Finally, it can be concluded that this work will open an avenue for further research on the application of suitable process for hard surface formation on DSS.

1. Introduction

Duplex stainless steels have gained increasing interest in recent years for a number of applications in various industrial sectors of petrochemical process plant, marine engineering and automotive industries. These materials offer unique combination of high mechanical properties and corrosion resistance [1]. Although DSS is widely used in various industries, this material has faced wear and hardness problem in many applications [2]. Surface modification is a technique to improve the performance of engineering surface properties that has been developed for many years. This modification can be done by changing the surface microstructure without affecting the bulk properties of the material [3]. Previous works have approached many techniques to meet this requirement such as melting through TIG torch [4-8] and diffusion through gaseous thermochemical nitriding [9-14].

Surface melting by incorporation of ceramic particles can produce composite layer dispersed with ceramic particles which enhance the surface hardness [3]. In this process, the alloy powder in form of hard ceramic particles with desirable composition is homogeneously deposited onto the surface of the
substrate material. The heat sources such as laser, electron beams or TIG torch were used to melt the alloy powder and substrate material [4]. A coated surface obtained by TIG torch has the potential to produce a dense coating with good metallurgical bonding to the base material. The commonly used hard carbide particles to produce ceramic composite coatings with this melting process are; WC [5], TiC [6] and SiC [7]. Dyuti et al. [15] have found that the composite layer can be produced on carbon steel by melting via preplacement of Ti and Al powder mixtures in nitrogen environment under a TIG torch with energy inputs between 540-675 J mm\(^{-1}\). The clad layer that formed with dendrite microstructure consists of Ti-Al nitrides which distributed homogeneously throughout the melt pool. The hardness of the composite layer depend on dendrite population and maximum hardness was 900 Hv.

In the case of gaseous thermochemical nitriding (also known as diffusion process), the hardening of the surface layer on duplex stainless steel is due to incorporation of nitrogen in the austenite lattice, forming expanded austenite. Expanded austenite without nitrides is obtained when high amounts of nitrogen dissolved in stainless steel at temperature below 450 °C [2]. The growth of expanded austenite has been studied by previous researchers using various surface treatments such as nitriding [9,10] carburizing [10] and hybrid process with integration of nitriding and carburizing [16]. Fewell et al. [17] had explored that the expanded austenite is the crystalline structure and not mixed phase with some grains having different lattice parameters.

Most of the findings have showed that surface modifications via melting and thermochemical diffusion techniques are proven methods to improve surface coating of many substrate materials in terms of surface hardness, tribological and corrosion resistance. Several research works found in literatures focusing on melting using different alloying powders and substrate materials via TIG torch [3-7] and laser cladding [18-21]. No attempt was made on the incorporation of SiC particulates hardfacing on DSS by TIG torch melting technique in the earlier works. Moreover, the comparative study between melting and diffusion processes also is not available in the literature. In this paper, an attempt has been made to review, consolidate and highlight the results obtained by various researchers on hard layer formation through melting and diffusion for understanding the importance of opening the research avenue in order to employ this techniques effectively and efficiently for DSS.

2. Processing route for hard surface layer

2.1. Melting Process

Tungsten inert gas welding (TIG) is one of the cleanest and most important melting technique for welding stainless steels. This technique is using a non-consumable tungsten electrode, shielded by inert gas, is used to strike an electric arc with the base metal, providing necessary heat to melt the workpiece [22]. Normally, the inert gases such as argon, helium or nitrogen are used as shielding gas for this welding. The common application of this process is rail car manufacturing, automotive and chemical industries. One of the most advantages of melting technique is the elimination of interfacial incompatibility of the material based on their nucleation and growth from the parent matrix phase. The disadvantage of this technique is the residual stress during welding may cause distortion to the material.

Many research works have been done on characterization of TIG welded mild steel and low alloy steel joints in the past. Buytoz [7] analyzed the microstructural properties of SiC particulates hardfacing on carbon steel with varying SiC between 30-45 µm. From the study, it can be observed that the microstructure of coating surface consists of primary dendrites and eutectic mixture of carbides and austenite. The microhardness of the surface layer was significantly improved to as high as 1135 Hv as compared to 220 Hv of the substrate material.

Maleque et al. [8] investigated the wear behaviour of TiC coated AISI 4340 (low alloy steel) produced by TIG surface melting. TiC coating layer was synthesized by preplacing a 1 mg/mm\(^2\) of 40 µm TiC powder on the surface of the steel. The maximum hardness achieved until 996 Hv and wear resistance increased two times higher than untreated alloy. The surface hardening and excellent wear resistance
of treated alloy due to formation of dendrite precipitation. Another finding by Mridha et al. [23] has investigated the incorporation of TiC particulates on low alloy steel surfaces via TIG technique. In the study, the crack free composite layer of 0.5 mm to 1.0 mm thickness was developed. Figure 1(a) shows the cross sectional view of the track with heat input 1680 J/mm by preplacing a 1.0 mg/mm2 addition of TiC gave a hemispherical shape melt with the hardness of the resolidified layer improves between 750 to over 1100 Hv compared to base hardness of 300 Hv.

Figure 1. Melt cross section (a) 1680 J/mm, 1.0 mg/mm2 [23] and (b) Micrographs showing dendrite distribution at deeper melt depth [3].

Mridha et al. [3] investigated the influence of processing conditions powder content and energy input on the hardness and surface clad quality of plain carbon steel using a TIG torch with varying titanium powder addition and figure 1(b) shows the dendrites observed at the middle of the melt zone. The maximum surface hardness of around 2000 Hv was developed in most of the tracks and this corresponds to high concentration of TiN dendrites within the modified layer. In addition, Mridha et al. [15] explored the melting of multipass surface tracks in AISI 4340 low alloy steel incorporating titanium carbide powders. It was found that the first track, containing more unmelted and partially melted TiC particulates, developed a maximum hardness of 1000 Hv. It has been observed, that the overall hardness developed in the multipass tracks was 2.5-3.5 times that of the steel substrate hardness of 300 Hv.

Adeleke et al. [24] studied the surface alloying of CP-Ti using preplaced Fe-C-Si powder by TIG technique. The surface modified Cp-Ti alloy exhibited hardness values ranging from 600 Hv to 800 Hv which was 3 to 3.5 times higher than base metal hardness. The higher hardness observed at particular areas are attributed to high population and big sizes of dendritic microstructures of TiC.

2.2. Thermochemical diffusion process

This process is mainly applied to steels and consists of enriching the surface of the material to be treated with certain metalloids. The gaseous compound containing the carbon, nitrogen or boron are supplied and deposited to the surface of material via diffusion mechanism. Generally, the treatment is heated to a temperature ranging from 500 to 1000 ºC to diffuse on the surface of material. Steels that have undergone this treatment are characterized by good resistance to wear, abrasion and fatigue [25]. The main advantages of this technique is the hardening of the entire surface of the treated specimen. However, the process must be controlled and ensure the process temperature is not too high to avoid the reduction of corrosion resistance.

Several researchers have explored the opportunity to perform this technique in the past. Haruman et al. [26] investigated the low temperature fluidized bed nitriding of austenitic stainless steel. The nitriding performed in temperature range between 400 ºC and 500 ºC for various treatment times. The results showed the hard layer surface after diffusion process as shown in figure 2. The microhardness of the layer also increased up to 1200 Hv.
Christiansen et al. [9,10] demonstrated that nitriding and carburizing of DSS are feasible to produce hard surface layer due to formation of expanded austenite. The nitriding was performed in a mixture of NH3 and H2. Expanded austenite without nitride/carbides was obtained when high amount of atomic nitrogen/carbon are dissolved in DSS at temperature below 450°C for nitrogen and 550°C for carbon. The hardness of hard layer increased until 1200 Hv compared to 400 Hv of substrate material.

Nagatsuka et al. [27] investigated plasma nitriding treatment on DSS with temperature of 356 °C and 383 °C. Based on the result, the expanded austenite observed on treated specimens and produced hardened surface until 1000 Hv and good wear resistance.

2.3. Laser cladding

Laser cladding is the fusion of a different metal to a substrate surface, with a minimum of melting of the substrate. Surface coating by laser is a method that has been developed over the last two decades. The lasers minimal and easily controllable energy delivery makes it possible to alloy, impregnate, clad and harden components that are exposed to wear and corrosion. This process is employed which require a high productivity combined with flexibility without compromising on quality. A high and uniform quality with a low heat input makes this process suitable for a wide range of applications in which minimum distortion is desired. The disadvantages of this cladding technique is slow and expensive [28].

Laser surface alloying of Al with Fe is studied by Tomida et al. [21]. It is found that the hardness of laser alloyed layer increases until 1000 Hv with increasing of Fe Content. However, cracking occurred in the alloyed layer with higher hardness than 600 Hv because the brittle lump-like Fe2Al5 compound was produced on the surface. The wear resistance of the alloyed layer improved with increasing the hardness due to the formation of the fine Fe rich intermetallic compounds.

2.4. Ion Implantation

This treatment introduces energetic ions into the surface of austenitic stainless steel. Ion induces two types of change to the surface of the solid; structural alterations (creation of disorder) and chemical alterations (modification of the chemical composition of the surface). These changes provides significant result of physical, mechanical and chemical of the surface material of austenitic stainless steel [25]. The advantages of this process is can be easily and precise control of the dose and depth profile. The disadvantages of this process is damage recovery because ion implantation may causes damage to the crystal structure of the target which is often unwanted.

Fernandes et al. [29] investigated the mechanical properties of nitrogen rich surface layers on austenitic stainless steel treated by plasma immersion ion implantation. Based on the analysis, the harder surface formed due to the higher nitrogen concentration obtained by this technique. The wear rate of the treated samples also increased with nitrided layer with up to 500 nm of thickness.

Figure 2. SEM micorgraphs of 500 ºC of nitrided austenitic stainless steel: (a) 1 hour, (b) 3 hour (c) 6 hour [26].
3. Advantages and disadvantages of melting and diffusion techniques

Table 1 shows the matrix of the advantages and disadvantages of melting and diffusion processes on materials of the surface modification. It is important to understand of the process and to choose the best method in the application.

**Table 1.** Advantages and disadvantages matrix of melting and diffusion route of the process [30-34].

| Melting route | Diffusion route |
|---------------|-----------------|
| Advantages    | Disadvantages   | Advantages    | Disadvantages   |
| Inert gas such as argon, helium and nitrogen | Expensive | Ammonia or methane gas | The usage of ammonia gas is toxic and harmful |
| Short processing time, flexibility in operation and processing precision | Operator must be very close to weld specimen during the process | Allow effective hardening of the entire surface | Long processing time to produce hard surface layer |
| Reduced distortion due to concentrated heat source | Heat source may contribute to residual stress | Relatively low processing temperature | Temperature control is important to avoid the reduction of corrosion resistance properties. |
| Ability to create composite hard surface layer | The process requires binders and additives | Hard nitride layer is easy to produce | Difficult to produce high purity material |
| Eliminate interfacial incompatibility based on their nucleation and growth from the parent matrix phase | The process require solid lubricant particles to withstand wear resistance at high temperature | The surface layer has excellent wear properties at room and high temperature | Require more time to develop hard layer |
| No spark or sputter | Care should be taken to protect skin and eyes due to arc rays is very bright | The treatment process is controlled properly in the tube furnace | Difficult to control the extraction of hazardous gas and require expensive setup for proper ventilation |
| The process and clad specimens are clean | Specimen cleaning must be taken care before cladding | The native oxide film on the surface is removed before treatment | The specimen needs to be soaked in concentrated hydrochloric acid |

4. Concluding remarks

Hard facing development on duplex stainless steel using melting and diffusion processes are highlighted with the merits and demerits. It is clear that both processes are applicable to produce hard layer with better wear resistance properties. In summary, it can be concluded that many of the research works carried out on TIG torch melting technique and diffusion of thermochemical nitriding for other steels but very limited information is available in literature on DSS. In spite of considerable research on both treatments, no study has been conducted to compare and assess the characteristics features in terms of simplicity, microstructure and properties performance on DSS. Future study on the hard surface formation of DSS is expected to have the significant effect on surface hardness and wear resistance. Therefore, future work should be conducted to compare and assess the characterization of surface coated materials between these two processes.
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