CHAPTER 2

LITERATURE SURVEY

2.1 WELD HARDFACING

Weld hardfacing or fusion surfacing is a technique, primarily done to enhance the surface properties of substrate and hardfaced materials which generally exhibits better wear (D’Oliveira et al 2006), corrosion and oxidation resistance than the substrate (Balasubramanian et al 2008a). And also this process exhibits a good surface appearance without the presence of porosities of crackles (Manikandan and Varahamoorthi 2007). Nevertheless, this process is more economical than improving the desired properties of the entire component because hardfacing involves the application of a coating to a low cost base material. The desired coating properties, quality, performance and of reducing the consumption of hardfaced metal can be achieved by proper selection of the hardfacing material to be deposited and welding process (Leshchinskiy and Samotugin 2001, Davis 1993).

2.2 HARDFACING ALLOYS

Selection of hard alloys to process a coating should guarantee the protection of components exposed to severe abrasive and erosion wear. Those wear resistance characteristics of hardfacing alloys can be obtained primarily from their high volume fraction of hard carbides and also the toughness of the matrix (Kuo et al 2007).
Conventional hardfacing alloys are generally classified as steels or low alloy ferrous materials, iron or high alloy ferrous materials, cobalt base alloys, nickel base alloys, copper base alloys and tungsten carbide composites. Among hardfacing alloys, cobalt base hardfacing alloys play an important role in order to obtain wear (D’Oliveira et al 2008), oxidation and corrosion resistance (Burke et al 2005) as well as high hardness at elevated temperatures (Brooks 1990). The most popularly used Co-based hardfacing alloys are of the “Stellite” variety (Schwarz and Warlimont 1997), with a nominal composition of Co-28 Cr-4.3W-1.1C (wt %) (Aoh and Chen 2001). Those powders are mixtures of cobalt and other elements like nickel, chromium, tungsten, carbon and molybdenum. Moreover, the alloys have superior high temperature hardness, toughness and dimensional stability. Due to these advantages, they often used for overlaying.

D’Oliveira et al (2002a) investigated the high temperature behaviour of a Co-base alloy deposited on stainless steel substrate and reported that PTA deposits exhibited superior microstructural stability. Celik and Kaplan (2004) studied the effects of silicon on the wear behavior of Co-base alloys at elevated temperature and concluded that the addition of silicon to the stellite 6 alloy had increased the hardness of material and increased the wear resistance at low temperature, but decreased at high temperature. Aoh and Chen (2001) stated that the stellite 6 had a significant wear and corrosion resistance and especially it had a good weldability to different steels. They inferred that carbon present in the alloy had the greatest influence on the microstructure of stellite.

2.2.1 Hardfacing Alloys Selection

Hardfacing alloy selection is generally considered in terms of a compromise between wear and cost. Other important parameters generally to be considered for choosing an hardfacing alloy are
- Base metal
- Deposition process
- Corrosion and oxidation capacity required
- Service conditions
- Compatibility of the hardfacing alloy with the base metal
- Level of dilution and the overall cost.

### 2.2.2 Application of Hardfacing Alloys

Hardfacing alloys are extensively used for application where the surfaces are subjected to wear, oxidation, and corrosion under heavy load, and high pressures at elevated temperatures. Co-base and Ni-base alloys are mainly used for hardfacing application. The stellite 6 is widely used as a hardfacing material for components active in severe tribological environments e.g. valves, turbine blades, bearings and spindles because it has excellent abrasion resistance, corrosion resistance under high pressure condition and high hardness at high temperature (Benea et al 2005, Antony 1983). Moreover it contains chromium rich carbide which provides oxidation, corrosion resistance, high hardness and wear resistance as well as strength (Shin et al 2003).

### 2.3 SURVEY ON STUDIES OF WELD SURFACING

Survey of weld surfacing studies being carried out by various researchers is discussed briefly in this section.

Marimuthu and Murugan (2003) studied the main and interaction effects of PTA process parameters on dilution and bead geometry of stellite 6 hardfaced valve seat rings. The authors found that factorial technique could be

Jean et al (2005) developed Artificial Neural Network (ANN) model for studying the hardfacing surface roughness of cobalt (HMSP2548) and nickel base (HMSP1516) powder alloy material deposited by PTAW. The authors observed that hardfacing surface roughness was greatly improved by optimizing the coating conditions accurately predicted by ANN model.

The effect of pulsed current on dilution, the solidification structure and coating hardness of high carbon cobalt based alloy which was deposited on carbon and stainless steel substrate using PTA coating process was studied by D’Oliveira et al (2006). They deduced that the use of pulsed current produced finer and more homogeneous solidification structure, lower dilution and higher hardness. The characteristic behavior of cobalt base alloy and tungsten carbide composite coating by laser cladding was reported by Xu et al (2006a) and Chen and Chang (2006). Qingyu et al (2007) addressed the microstructural aspects and wear behavior of cobalt based coatings deposited on low carbon steel substrate using PTA process. Praburaj and Varahamoorthi (2007) investigated the dilution of different welding processes like Shielded Metal Arc Welding (SMAW), GTAW, GMAW, SAW and PTA and reported that a lower dilution range could be obtained by PTA hardfacing process. The effect of the pulsed GMAW variables on the bead geometry and dilution in cladding X65 pipeline steel with stainless steel was investigated by Nouri et al (2007). They used the full factorial technique to develop mathematical models.
to predict the relationship between welding variables and dilution and weld bead geometry.


Siva et al (2009) highlighted the development of a mathematical model correlating various process parameters to weld bead geometry in PTA hardfacing of Colmonoy 5, a Nickel based alloy over Stainless steel 316 L plates. Selection of welding process to hardface boiler grade steels based on quantitative and qualitative factors was investigated by Balasubramanian et al (2008a) and concluded that PTAW process was found to be the best method to hardface boiler grade steels. Takano et al (2010) reported the effect of process variables on the characteristics of stellite 6 deposit on low carbon steel substrates produced by PTA hardfacing process.
2.4 PLASMA TRANSFERRED ARC WELDING

PTAW is an extension of the GTAW process where both utilize a gas shielded arc produced by a non-consumable tungsten cathode. It is similar to GTAW, however, plasma arc offers a higher arc density by virtue of the collimated nature of the plasma beam. The most important aspect is the directional stability of the beam. The stiff plasma beam is not deflected by external magnetic or electric fields like GTAW beam. Consequently, high current densities and higher energy concentrations can be produced with higher arc temperatures.

PTAW is preferred for hardfacing application over other conventional welding processes because transferred arc melts the whole amount of powder and only a thin film of treated component surface as a result of minimum dilution produced between the deposit and substrate. In general, the use of a plasma transferred arc in hardfacing offers several advantages over conventional welding processes (Budinski 1988, D’Oliveira 2008, Siva et al 2008, Mitelea et al 2008):

- Higher deposition rate (upto 25kg/hr);
- Low dilution (generally less than 10%);
- Lower level of distortion;
- High reproducibility;
- Extremely high wear resistance;
- Provides very strong fusion bond between the substrate and coating material;
- Reliable process parameter control;
• Easy to mechanize and to automate;

• Processing thicker coatings (1.2 to 2.5 mm or higher) besides the controlled solidification rate;

• Allows large variety of material to be used for surfacing.

2.4.1 Application of PTA hardfacing

PTA hardfacing finds extensive use in applications such as (Richard 1990, Siva et al 2008)

• Valve industries

• Aircrafts

• Missile components

• Pressure vessels

• Agriculture machines

• Railways

• Hydraulic machineries

• Mining industries

• Earth-moving equipments

• Chemical, nuclear and thermal power plants etc.

2.5 BEAD GEOMETRY

Bead geometry which includes bead width, height of reinforcement and depth of penetration, as shown in Figure 2.1, is an important physical property of a weldment. Control of weld bead shape is essential as the
mechanical properties of welds are affected by the weld bead shape (Connor 1991). Bead geometry variables such as bead penetration, bead width, reinforcement and dilution are affected by welding current, welding voltage, wire feed rate, welding speed, nozzle-to-plate distance, gas flow rate and work piece thickness (Harris and Smith 1983, Gupta and Parmer 1989, Anderson et al 1990, Murugan et al 1993, Yang et al 1993, Chan et al 1999, Kim et al 2002, Nagesh and Datta 2002, Kim et al 2003a). Therefore, it is clear that precise selection of the process parameters is necessary.

Nagesh and Datta (2002) worked on SMAW and reported that the bead width and height decreased with increase in arc travel rate and increase in arc length resulted in an increase in bead width and decrease in bead height. Marimuthu and Murugan (2003) observed that the penetration and dilution of PTA hardfaced specimens increased with increase in welding current, whereas reinforcement, bead width and total area decreased with increase in travel speed.

The influence of arc power and mode of metal transfer on bead width, penetration and reinforcement in hybrid welding process was presented.
by El Rayes et al (2004) and concluded that with increase in the arc power increased the bead width, whereas it reduced the reinforcement. Benyounis et al (2005) investigated the effect of laser power, welding speed and focal point position on penetration, width of welded zone and width of heat affected zone using RSM. They found that welding speed had a negative effect while laser power had a positive effect on the weld bead parameters.

Kannan and Murugan (2006) reported that bead width, penetration, reinforcement and dilution increased with the increase in welding current in Flux Cored Arc (FCA) cladding process. However, they found that increase in travel speed resulted in decrease of bead width and height of reinforcement. Palani and Murugan (2006a) stated that bead width, penetration and reinforcement increased with increase in welding current, whereas those values decreased with the increase in travel speed in 317L Flux Cored stainless steel cladding deposited on IS:2062 structural steel substrate by FCAW. Nouri et al (2007) observed that bead width, height of reinforcement and depth of penetration increased with increase in wire feed rate in pulsed GMA cladding process. Also, they found that bead width, height of reinforcement and depth of penetration decreased with increase in travel speed. Dhas and Kumanan (2007) highlighted that the bead width increased with increase in welding current, arc voltage and welding speed, whereas it decreased with increase in electrode stick out in SAW process.

Siva et al (2009) found that penetration, dilution and total area increased with increase in welding current and decreased with increase in travel speed in PTA hardfacing process. Thao and Kim (2009) studied the effect of process parameters such as welding voltage, arc current, welding speed, contact tip to work distance and welding angle on bead geometry of lap joint in GMAW process. They concluded that the increase in welding voltage increased the weld bead width and decreased the weld bead height. Also, the
increase in arc current resulted in increased bead width and height of reinforcement, while increase in welding speed decreased the bead width and height of reinforcement. It was stated by Faruk et al (2010) that the depth of penetration increased initially with increase in welding current and then decreased and also with increase in welding current decreased the bead height in case of electric arc welding process. Tewari et al (2010) investigated the relationship between the process parameters on depth of penetration and resulted that the depth of penetration increased with increase in heat input and decreased with increase in welding speed.

2.6 DILUTION

The composition and properties of weld hardfacing are strongly influenced by dilution obtained. Dilution, defined as the ratio of the substrate melted area to the total melted area, is within 5-10 % for PTA surfacing process. It is generally measured by the percentage of base material, or previously deposited weld material in the weld bead. Control of dilution is important in hardfacing, where low dilution is typically desirable by limiting penetration and base metal melting (Funk and Rieber 1985). When the dilution is high, the surface properties are not enhanced to the expected level because of the presence of higher amount of base metal. When the dilution is low, the final deposit composition will be closer to that of the filler material, and the wear and corrosion resistance of the weld hardfacing will also be maintained. To obtain desired strength and wear resistance, it is essential to have a complete control over the relevant process parameters to minimize dilution on which the quality of a weldment is based.

Chandel (1987) reported that dilution increased with increase in welding current, welding speed and electrode extension in SAW process. Wu and Redman (1994) stated that different hardfacing methods resulted in different dilution levels with the base metal and that changed the chemistry
and hence properties. The dilution decreased with increase in heat input keeping the arc voltage constant was reported by Hunt et al (1994). Deuis et al (1998) told that with the increase of welding current and plasma gas flow rate resulted in increase in dilution whereas, it decreased with increase in powder feed rate. Gunaraj and Murugan (2000a) reported that percentage of dilution increased with the increase in welding voltage and wire feed rate and decreased with increase in welding speed and nozzle to plate distance for SAW process. Thiruchitrambalam and Pandey (2004) found that the higher percentage dilution could be obtained by plasma enhanced SMAW than SMAW process at similar welding conditions. The effect of pulse current on dilution of high carbon cobalt alloy deposited by PTA on carbon and stainless steel substrate was studied by D’Oliveira et al (2006). Results showed that the use of pulsed current led to lower dilution. Kannan and Murugan (2006) reported that the percentage of dilution increased with increase in welding current and welding speed, whereas, it decreased with increase in nozzle to plate distance and welding speed in FCA cladding process. Palani and Murugan (2006a) studied the effect of welding current, welding speed and nozzle to plate distance on the dilution in FCA cladding process. They concluded that the percentage of dilution increased with increase in welding current. The percentage of dilution increased to a maximum value with increase in welding speed and nozzle to plate distance and then decreased with further increase in welding speed and nozzle to plate distance. Nouri et al (2007) found that percentage dilution increased with increase in wire feed rate and welding speed in pulsed GMA cladding process.

Lakshminarayanan et al (2008) predicted the dilution of PTA hardfacing of stellite on carbon steel. They concluded that the percentage of dilution increased with increase in welding current and travel speed and decreased with increase in stand off distance and oscillation frequency. Ravi Bharath et al (2008) worked on PTA technique reported that dilution level
increased with increase in current, plasma gas flow rate and powder gas flow rate. Also, they concluded that the dilution was higher at higher preheat conditions. The percentage of dilution increased with increase in PTA current, whereas, it decreased with increase in travel speed, powder feed rate, torch oscillation frequency and stand off distance was reported by Balasubramanian et al (2008b), Siva et al (2009), Balasubramanian et al (2009). Takano et al (2010) concluded that the higher dilution could be obtained by increasing the intensity of processing current and plasma gas flow rate.

2.7 DESIGN OF EXPERIMENTS (DOE)

Designing of experiments provides a clear route for understanding the influence of input variables of a system on the output responses. It is very essential to achieve the most reliable results with minimal wastage of time and money in order to avoid the trial and error method in conjunction with a small number of repetitive experiments for getting the original results.

Building a experimental design means, carefully choosing a small number of experiments that are to be performed under controlled conditions. There are four interrelated steps in building a design:

1. An objective of the investigation to be defined.
2. The variables and their levels of variation to be controlled during the experiment.
3. The variables will be measured to describe the outcome of the experimental runs (response variables).
4. The design variables having a reasonable cost have to be selected with the available standard experimental designs.
There are various statistical techniques available for experimental design, which are well suited for engineering design. Adler et al (1975) observed that statistically designed experiments provided plans for conducting experiments to collect data from which valid statistical analysis of results could be carried over. Davis (1978), Myers and Montgomery (1995) presented the various techniques available from the statistical theory of experimental design, which were well suited to engineering investigations. Regarding DOE method, often used statistical techniques are

- Box-Behnken Design
- Box-Wilson Design

Both are central composite, rotatable type useful for evaluating the linear and quadratic effect and a two factor interaction. Their advantages are very efficient in terms of number of experiments and the provided information.

2.8 MATHEMATICAL MODELING

To get the desired weld quality in PTA hardfacing, it is essential to know the interrelationships between the process parameters and bead geometry as a welding quality. But, it is not easy to study these relationships because many kinds of nonlinear process parameters are involved. For this reason, experimental models can be developed to solve this problem. One of the experimental models was a regression modeling technique that was utilized to establish the empirical models for various arc welding processes using RSM. The use of multiple regression analysis method to solve the correlation between the welding process parameters and weld bead shape has increased. The following section highlights on some more studies conducted using mathematical modeling:
Raveendra and Parmer (1987) built mathematical models using fractional factorial technique to predict the weld bead geometry and shape relations. Gupta and Parmer (1989) used fractional factorial technique to develop mathematical models to predict the weld bead geometry and shape relationships for the SAW of microalloyed steel. The development of mathematical models using the five level factorial technique to predict the weld bead geometry for depositing 316L stainless steel onto structural steel IS 2062 in single wire surfacing using the SAW process was studied by Murugan et al (1993). The effect of process parameters on the bead shape in a narrow gap GTAW using statistical experimental design and linear regression modeling was studied by Starling et al (1995). Murugan and Parmer (1997) developed mathematical models using RSM to study the effects of SAW parameters on the clad geometry. Gunaraj and Murugan (1999) highlighted the use of RSM to develop mathematical models relating input parameters to weld bead geometry in SAW of pipes.

Gunaraj and Murugan (2000a, b) developed mathematical models using the five level factorial technique for prediction and optimization of weld bead for the SAW process. A comparison of back-bead prediction of the GMAW process using multiple regression analysis and ANN analysis was carried out by Lee and Um (2000). Koleva (2001) developed regression models to investigate the influence of Electron Beam Welding (EBW) parameters on the welding depth and width. Li et al (2001) established a static model for Al metal matrix composites in diffusion welding using ANN.

The mathematical models developed by Gunaraj and Murugan (2002), using RSM to study the effect of SAW parameters on Heat Affected Zone (HAZ) characteristics. Kim et al (2002) used GA and RSM to determine the optimal welding conditions in GMAW process. Allen et al (2002) proposed a model based on Central Composite Design (CCD) to study the
effect of robotic GMA welding process parameters on weld bead geometry. Kim et al (2003a) studied the interrelationship between robotic Co₂ arc welding parameters and bead penetration by developing mathematical models using factorial technique. Kim et al (2003b) employed factorial design to correlate the robotic GMAW process parameters to weld bead geometry for optimization purposes. Park et al (2003) employed the bead-on-plate technique to develop a mathematical model to predict the magnitude of bead geometry in terms of welding process parameters.


2.9 CHARACTERIZATION OF STELLITE 6 PTA HARDFACED GATE VALVES

The mechanical, metallurgical and tribological properties of PTA stellite 6 hardfaced gate valves are characterized by macrohardness, microhardness, Microstructure, wear rate and residual stress. The following sections highlight the above mentioned properties of stellite 6 hardfaced gate valve.

2.9.1 Macrohardness

Macrohardness is an important mechanical property used for the quality control of hardfaced overlay because it is the basic identification to find the abrasive wear resistance of hardfaced overlay. It can be quickly measured and considered to be non-destructive tests when the marks or indentations produced by the test are in low stress areas. It mainly depends on the volume fraction of carbides present in hardfaced overlay (Schneider 1998). An increase in the volume fraction of carbides leads to a corresponding increase in the macroscopic hardness and for the wear resistance of the cobalt
based alloy as reported by Atamert (1988). Details on macrohardness of stellite 6 alloy deposited by PTA and other conventional welding processes collected from available literature are presented below.

Chan et al (1996) reported that the top surface bulk hardness of the PTA stellite 6 layer increased with increasing welding current and it varied from 40-52 HRC. It was due to increase in carbide volume fraction of PTA stellite 6 layer with increasing overlaying current. Nelson et al (1995) measured bulk hardness of PTA deposited stellite 6 overlays using vickers hardness testing machine with a 30 kg load. The average hardness was around 347 HV, calculated on a minimum of six points on the PTA deposited stellite 6 overlay. The hardness in the laser stellite clads varied between 500 and 570 HV as reported by Schneider (1998). The deposit hardness of stellite 6 alloy by Oxy-Acetylene (OA) hardfacing process was specified to be between 39 and 47 HRC (Lemaire and Le Calvar 2001). The average surface hardness of stellite 6 clad layer deposited by PTA process was 43.8 HRC (Aoh and Chen 2001).

2.9.2 Microhardness Survey

Microhardness is a measure of the overlay’s resistance to localised plastic deformation. The microhardness of stellites typically varies between 350 HV and 600 HV (Frenk and Kurz 1994). It is strongly dependent on the dilution (Abbas and West 1991, De Mol van Otterloo and De Hosson 1997, Schneider 1998), microstructure and in particular on amount of carbides generated (Hirose and Kobayashl 1995, Vite et al 2005) and the size of the dendrites (Frenk and Kurz 1994, Kuo et al 2007). An increase in dilution causes decrease in hardness of the deposited layer. The decrease in scale of microstructure resulted in increase in microhardness of the deposited layer (Atamert 1988, Persson 2003). An increasing level of carbon in stellites will form more complex carbides such as $M_7C_3$ and $M_{23}C_6$, which are responsible
for increasing the hardness of the deposited layer (Schneider 1998, Persson 2005).

It was reported that the microhardness of cobalt base hard-facing alloy deposited by MMA, TIG and laser surfacing processes increased in the same order corresponding to that of freezing rates, scale of microstructure and level of dilution involved in those processes (Atamert and Bhadeshia 1989). Jeng et al (1991) studied the distribution patterns of the microhardness in the stellite 6 laser clad specimens with 20%, 30% and 50% overlapping. The highest hardness arrived at the Heat Affected Zone (HAZ) of the stellite 6 clad layers with 50% overlapping, was due to the formation of martensite at the HAZ.

The microhardness was found to be increased from 540-580 HV for the Stellite 6 laser clad to about 1390 HV for the matrix region of the composite by the inclusion of about 19 wt. % SiC in the cladding mixture. The composite clads showed substantially higher matrix hardness than the Stellite 6 clads. This hardness increase was attributed essentially to the solution of SiC in the liquid and the consequent increase in the proportion of carbides formed on solidification (Abbas and West 1991). The highest hardness in the laser stellite clad (800 HV) was achieved with a dilution of 15%, which was higher than the typical hardness of the applied powder (500-550 HV), provided the dilution was limited to less than 5 % (Schneider 1998).

The hardness of stellite 6 and stellite 6 mixed with Cr$_3$C$_2$ deposited by PTA hard-facing process was studied by Aoh and Chen (2001). The average hardness of stellite 6 and stellite 6 mixed with Cr$_3$C$_2$ were 43.8 and 57.8 HRC respectively. This slight rise in hardness of the stellite 6 mixed with Cr$_3$C$_2$ hardfaced layer was attributed to the presence of finer polygonal carbide phases to coarser carbide islands in the microstructure. D’Oliveira et al (2002b) studied microhardness of the five consecutive layers of Stellite 6
deposited onto a 304L stainless steel plate by laser cladding, with a 500 g load. They concluded that a decrease in average microhardness of stellite 6 layers resulted with higher dilution levels (De Mol Van Otterloo and De Hosson 1997) and the coarsening of the microstructure. The values of microhardness up to approximately 1000 HV were observed on top surface of the stellite 6 laser cladding (Jendrzejewski et al 2002). The microhardness of laser cladded stellite 6 was higher (510 HV) than that of PTA cladding (470 HV), which might be due to the morphology of carbides formed with different cooling rates involved in both cladding process as suggested by D’Oliveira (2002a).

Shin et al (2003) noted that the addition of Mo increased the hardness of the stellite 6 alloy from 41 HRC to 51 HRC, which was attributed to the change in microstructure of stellite 6 alloy with Mo addition. Celik and Kaplan (2004) concluded that the addition of silicon to the composition of stellite 6 alloy increased the hardness of the material.

The hardness of stellite 6 laser cladding was approximately 550 HV which was more than that obtained by other conventional welding processes (Persson 2005). The observed microhardness in the stellite alloy deposited on ASTM A-36 steel by SMAW process, was 757.4 HV (Vite et al 2005). Smolenska (2006) reported that the hardness of cobalt based laser and PTA cladding increased with increase in carbide volume fraction of cobalt based alloy. Xu et al (2006b) studied the microhardness distribution of laser and TIG stellite 6 clad layer. It was observed that in laser cladding, the maximum hardness obtained at fusion line was 670 HV which was due to less dilution. The reduction of hardness in TIG cladding was due to large heat input, low temperature gradient resulting in increase in dilution of substrate. Xu et al (2006a) investigated the hardness of powder mixture of Co-based alloy (Stellite 6) and tungsten carbide (WC) that was deposited on the mild steel
plate using 2.4 kW CO$_2$ laser. It was found that a gradual increase in the hardness from the substrate towards clad surface due to the variation of microstructure. They further discussed that in hypoeutectic structures, the hardness of the clad layer increased due to the increase in the hard complex carbides such as Cr$_{23}$C$_6$, Co$_3$W$_3$C and WC present in the eutectic structure. The use of pulsed current on high carbon cobalt alloy deposited by PTAW on carbon and stainless steel substrates resulted on higher hardness which was attributed to fine, more homogeneous solidification structure and lower dilution present in the claddings (D’Oliveira et al 2006).

Zhu et al (2007) reported that hardness of stellite 6 alloy deposited by PTA cladding on Ni76Cr19AlTi was more than 390 HV, which was due to the presence of Cr$_7$C$_3$ and W$_2$C carbides. Hardness of stellite 6 PTA clad valve seats was around 42 HRC, observed by Chang et al (2008). Smolenska (2008) studied the hardness of the cobalt based alloy deposited on steel substrate by laser and PTA cladding at different conditions such as as-clad, after cyclic oxidation and after corrosion in exhaust gases. They found that cladding deposited by laser and PTAW process at as-clad condition exhibited almost similar hardness on top surfaces. This increase in hardness was attributed to the increase of carbide volume fraction present in the matrix. The increase of hardness was observed for both laser and PTA clad after oxidation condition. The high hardness was observed in PTA cladding than that of laser cladding after corrosion in exhaust gases.

2.9.3 Microstructural Analysis

Stellite alloy is a range of cobalt-chromium alloys, hardened by a combination of carbide formation and solid solution strengthening of the matrix, the former of which being the most important mechanism. The carbide former elements commonly found in the commercial Co-alloys are niobium, tantalum, molybdenum, tungsten, chromium, zirconium and
titanium. Chromium also plays an important role in the oxidation resistance of these alloys and to provide strength to the cobalt matrix by the formation of $M_7C_3$ and $M_{23}C_6$ carbides as well as to enhance the resistance against corrosion. Tungsten and molybdenum have large atomic sizes and give additional strength to the matrix. They also form hard brittle carbides. Nickel is added to increase the ductility. Depending on the carbon content and the heat treatment, various carbides formed in these alloys are $MC$, $M_3C_2$, $M_{23}C_6$ and $M_7C_3$. The predominant carbide found in Stellites is of the chromium rich $M_7C_3$ ($M=\text{metal}$) type. The composition of $M_7C_3$ ($\text{Cr}_{0.85}\text{Co}_{0.14}\text{W}_{0.01})C_3$ depends on alloy composition and cooling conditions (Guyard et al 1981, McGinn et al 1984). These carbides are responsible for the hardness of the deposit and for the wear resistance. In low carbon stellite alloys, other carbides such as $M_6C$ and $M_{23}C_6$ are abundant (De Mol Van Otterloo and De Hosson 1997).

The microstructure of the laser clad stellite 6 material was studied by Jeng et al (1991). They reported that cellular structures appeared in the lower part of the cladding layer and equiaxial structures surrounded by dendritic structures were observed in the area near the surface. Aoh and Chen (2001) studied the microstructure of stellite 6 and stellite 6 with the addition of $\text{Cr}_3\text{C}_2$ PTA clad layers. The microstructure of the Stellite 6 PTA clad layer showed a typical dendritic microstructure. Equiaxed dendrite was generally observed near the surface of the clad layer, while in the centre of the clad layer, the dendritic structure was found to be more columnar. The microstructure of Stellite 6 with $\text{Cr}_3\text{C}_2$ clad layer consisted of uniformly distributed and some needle-like chromium carbide phases and eutectoid matrix with very fine carbide precipitates.

Lemaire and Le Calvar (2001) commented that the microstructure of OA stellite 6 hardfaced layer consisted of dendrites formed from solid
solution surrounded by eutectic carbides (M$_7$C$_3$ type). They further reported that the OA hardfacing process provided a coarser microstructure than that of PTAW. The laser clad stellite 6 layer consisting of fine dendritic structure with a minor presence of impurities was reported by Jendrzejewskia et al (2002) and Persson (2003). As-deposited stellite 6 microstructures can be described as a Co rich matrix with a network of carbides in the interdendritic regions (Sullivan et al 1970, Davis 1993). D’Oliveira et al (2002a) studied the microstructure of stellite 6 alloy deposited on stainless steel AISI 304 plate by PTAW and laser cladding. They reported that in the case of laser cladding, a planar region was followed by a cellular and a dendritic structure. The slower cooling rates of PTAW (Lugscheider and Oberlander 1992) process eliminated the cellular region, therefore near the interface a planar region was followed by a dendritic structure. The typical microstructure of the Stellite 6 alloy consisted of $\gamma$-Co (Co-rich matrix) dendrites with a Face Centered Cubic (FCC) crystal structure surrounded by lamellar mixture of the Co-rich phase and carbide phase resulting from the eutectic reaction into interdendrite during solidification (Shin et al 2003).

Microstructure of PTA cladded stellite 6 alloy was reported by Kim et al (2003c) and Song and Kim (1997). It was shown that stellite 6 alloy consisted of cobalt dendrites surrounded by a network of eutectic lamellar composed of FCC cobalt and eutectic M$_7$C$_3$ carbides. Vite et al (2005) concluded that stellite alloy consisted of thick dendritic structure rich in cobalt matrix and interdendritic structure rich in chromium carbides. A solidification structure was observed in the cobalt based alloy deposited by pulsed current plasma transferred arc with dendrites of a Co-rich matrix and a carbide interdendritic region (D’Oliveira et al 2006). The microstructure of stellite 6 alloy deposited on Ni76Cr19AlTi exhausting valve using PTA cladding had typical dendritic structure with major carbides of Cr$_7$C$_3$ and W$_2$C (Zhu et al 2007). It was reported by Chang et al (2008) that stellite 6 PTA
clad layer comprised of a hypoeutectic structure with eutectics at interdendritic regions.

### 2.9.4 Wear Characteristics

Many operating difficulties and production losses that have been experienced in industry arise out of wear processes. The problem of wear arises wherever there is a load or relative motion between the contacting surfaces. Therefore, control of wear is very important to increase the effectiveness of mechanical components. Apart from using better wear resistance material and processes, wear still occurs as a result of operating parameters such as high work load, high relative speed or the abrasive nature of the counterface. Hence, it could be inferred that better wear resistance could be obtained by controlling above mentioned operating parameters.


Previously published results on the sliding wear performance of Stellite alloys indicated that the wear mechanisms consisted of the fracture of the hard carbides (Song and Kim 1997), oxide layer (So et al 1996, Wang and Li 2003, Aoh and Chen 2001) and the predominant wearing of the matrix (De
Mol Van Otterloo and De Hosson 1997). The wear resistance of cobalt based alloys deposited by different cladding processes studied by many authors is highlighted below.

Antony (1983) and Aoh and Chen (2001) reported that abrasive wear resistance of stellite 6 alloy was increased with increase in carbide size and the amount of $M_7C_3$ carbides at interdendritic regions. Some research works (Silence 1977, Kramer and Judd 1985) reported that the formation of coherent and incoherent carbides in the microstructure could affect the wear resistance of the alloy. Atamert and Bhadeshia (1989) studied the comparison of the microstructures and abrasive wear properties of stellite hardfacing alloys deposited by MMA, TIG, and laser cladding. They concluded that wear rate of stellite hardfacing alloy decreased with the decrease of scale of microstructure which led to an increase in the deposit hardness in the order of MMA, TIG and laser cladding.

Some researcher’s (Cassina and Machado 1992, Wu and Redman 1994, Shiels et al 1994) suggested that wear resistance was increased in the same proportion as the volume of the hard phases present in the alloy. The addition of carbide particles in stellite 6 alloys provided a further improvement in tribomechanical properties for hardfacing layer as reported by Rajiv and Seshadri (1993). Frenk and Kurz (1994) mentioned that wear resistance strongly depended on hardness and solidification microstructure of the stellite 6 laser clad. They concluded that mild wear occured at low loads or low sliding velocities leading to the formation of oxide debris and severe metallic wear occured at higher loads or elevated sliding velocities leading to the formation of wear debris. The wear resistance was promoted by the presence of harder complex carbides of chromium and tungsten in the microstructure as observed by Kian et al (1995).
Yang and Loh (1995) found that the wear rate of PTA cladded stellite specimen increased with increasing applied load, reduced rotating speed, harder disc material or increasing temperature. So et al (1996) concluded that when the sliding speed or normal load was increased, the decrease in friction coefficient was mainly caused by the change of oxides on the rubbed surface. De Mol Van Otterloo and De Hosson (1997) evaluated the abrasive wear resistance of different stellite coatings produced by laser processing and concluded that wear volume varied directly with applied load, sliding distance and inversely with the macrohardness of the material. Aoh et al (1999) pointed out that superior wear resistance of cobalt base alloys at elevated temperatures could be obtained by the presence of chromium carbide phases in the microstructure.

Aoh and Chen (2001) studied the effect of wear load and sliding speed on wear volume and friction coefficient of stellite 6 clad layer and concluded that wear volume increased with increase in wear load and decrease in sliding speed. Also, the friction coefficient decreased with increase in both wear load and sliding speed. Shin et al (2003) studied the wear resistance of stellite 6 hardfacing alloys with different molybdenum content deposited by PTA process. It was reported that wear resistance increased with the increase in Mo content, increase in the volume fraction of carbides and refinement of the Co-rich dendrites and increase in the amount of carbides present in the interdendritic region.

Liu et al (2004) concluded that the wear resistance of cobalt based super alloys using pin-on-disc wear testing machine increased with increase in metal carbides in the microstructure during solidification. Celik and Kaplan (2004) reported that the wear resistance of stellite 6 alloy with silicon addition decreased with increasing pressure or applied load and with increasing temperature. Vite et al (2005) reported that the generation of more carbide in
the microstructure led to increase in wear resistance. Chang et al (2008) studied on impact wear resistance of laser clad stellite 6 valve seats and concluded that the presence of surface oxides on stellite 6 deposits improved the impact wear performance of valve seats at elevated temperatures.

From the available literature review, it is observed that lot of research works has been carried out to study the influence of microstructure on the wear loss (Frenk and Kurz 1994, Aoh et al 1999, De Mol Van Otterloo and De Hosson 1997, Modi et al 2004) but still very few research papers was published as the effects of operating parameters such as applied pressure, sliding speed, sliding distance, temperature, sliding time etc on wear characteristics of cobalt based alloys (Yang and Loh 1995, So et 1996, Aoh and Chen 2001). Therefore, it is aimed to evaluate the effects of wear testing parameters and PTA heat input on wear rate of hardfaced gate valve by conducting experiments and developing a regression model.

2.9.5 Residual stresses

Residual stresses are the system of stresses, which exists in a body when it is free from external loads. When stress exists in a metal, some of the physical or mechanical properties, such as the propagation velocity of elastic wave, magnetic properties and hardness etc are changed. All residual stress systems are self-equilibrating and produce zero resultant force and moment (James and Lu 1996). There are three kinds of residual stress exists: (i) macroscopic (ii) microscopic and (iii) within the grain. When designing engineering structure the macro residual stresses are taken into consideration.

Development of residual stresses and distortion in a hardfaced component are strongly affected by structural, material and process parameters. Structural parameters include geometry of plates, thickness, width and the type of joint. Among material parameters, mechanical and physical
properties at various temperatures and the type of filler-metal are important parameters. The process parameters includes type of process employed and input variables such as current, voltage, arc travel speed, powder feed rate and nozzle to plate distance and also arc efficiency (Mahapatra et al 2006).

The residual stress is the initial stress and combined with the applied service load is considered for design calculations (Liang et al 2003). Amount of residual stresses developed in the welded component depends on welding sequence employed in the fabrication.

The residual stresses induced by the forces and thermal gradients during hardfacing operation was investigated by Hsiang and Liang (2004) and found that residual stresses could affect load-carrying capacity and resistance to fracture and fatigue.

Various residual stress measuring techniques are available and grouped into destructive and nondestructive techniques. The destructive techniques are hole drilling method, ring core method, bending deflection method and sectioning method. The most common Non-destructive techniques are X-ray diffraction method, neutron method, ultrasonic method and the magnetic method. Out of these, XRD and contour method have attracted more attention.

2.9.5.1 X-Ray Diffraction Technique

XRD technique is a prominent and widely used to measure surface residual stresses (Maeder et al 1981) at the depth of 10 microns from the hardfaced surface. Diffraction techniques are based on the phenomenon that when a metal is under stress, applied or residual, the resultant elastic strain causes the atomic planes in the metallic crystal structure to change their spacing. Diffraction technique measures the interplanner spacing to arrive at
the stresses present in the crystalline material. The technique is made possible by the fact that wavelengths of the electromagnetic radiations used for investigations are of the same order of magnitude as the atomic spacings in metallic crystals.

**Principle of Diffraction**

A monochromatic X-ray beam of sufficient intensity is made to incident on the atomic planes as shown in Figure 2.2. The reflected beams from successive planes of atoms are observed and recorded. Bragg’s law defines the condition for diffraction by the following equation (2.1).

\[ n\lambda = 2d \sin(\theta) \quad (2.1) \]

Where,  
\(\lambda\) – wavelength of incident X-rays  
\(\theta\) – angle between incident or reflected beams and surface reflecting planes.  
d – interplanar spacing  
n – order of reflection (n=1,2,3…)

![Figure 2.2 Principle of X-Ray Diffraction](image-url)
The above equation shows that, if the wavelength of X-ray is known, the interplanar spacing ‘d’ can be determined by measuring the angle ‘θ’. In the presence of residual stresses, ‘d’ changes, leading to a shift in X-ray diffraction peaks, which is a measure of residual stress.

2.9.5.2 Contour Method

The contour method is a new relaxation method of determining residual stresses of hardfaced components. Compared with other destructive and non-destructive methods, contour method is relatively simple, inexpensive and effectively used to measure residual stresses with parts having geometrically complex cross sections. Welding residual stresses for thicker samples can be accurately measured using contour method (Prime 2001, Prime et al 2004, Prime et al 2006). This technique does not require layer-by-layer material removal.

THEORY

The theory of the contour method is based on a variation of Bueckner’s (1958) elastic superposition principle, which states that “If a cracked body subject to external loading or prescribed displacement at the boundary has forces applied to the crack surfaces to close the crack together, these forces must be equivalent to the stress distribution in an uncracked body of the same geometry subject to the same external loading.” This is illustrated in Figure 2.3.

In A, the part is in the undisturbed state containing the residual stress to be determined. In B, the part has been cut in two and has deformed because of the residual stresses released by the cut. In C, the free surface created by the cut is forced back to its original flat shape. Superimposing the stress state in B with the change in stress from C would give the original
residual stress throughout the part, as shown by the following expression (2.2):

\[
\sigma^{(A)} = \sigma^{(B)} + \sigma^{(C)}
\]  

(2.2)

The superposition principle assumes that the material behaves elastically during the relaxation of residual stress and that the material removal process does not introduce stresses of sufficient magnitude to affect the measured displacements.

\[\text{Figure 2.3  The Superposition Principle upon which the Contour Method is Based}\]

The method involves cutting the sample in two halves along the plane where residual stresses, normal to the cut surface, are desired to be determined. The created cut surfaces locally deform owing to the relaxation of
any residual stresses present before cutting. These deformations can be measured and the deformed FE model was created. The measured deformation was applied to the surface as a negative displacement boundary condition of the hardfaced gate valve. The model was solved and gave the original residual stresses relieved normal to the plane of the cut.

Residual stresses measured in quenched HSLA-100 steel plate by Prime (2005) concluded that the peak compressive residual stresses occurred below the surface and tensile residual stresses existed in the centre of the plate thickness. Mapping residual stresses after foreign objects damage using the contour method was carried out by Prime and Martineau (2002). They concluded that the peak compressive stresses were present at a few mm below the surface and tensile stresses in the centre of the plate thickness.

From the review of available literature, it is evident that experimental and analytical work on the measurement of residual stresses in 2" hardfaced gate valve has not been reported till now. Hence, it is also aimed to analyze the residual stresses in the 2" hardfaced gate valve using contour method and compared the results with experimental XRD technique.

From this extensive literature review, it is observed that the effects of PTAW process parameters on the geometrical (bead geometry), mechanical (macrohardness), metallurgical (microhardness and microstructure) and tribological (wear rate) properties of 2" hardfaced gate valves are not clearly known. Therefore, the research work was aimed to evaluate those effects by conducting experiments and developing regression models. The following chapters explain about the PTA hard-facing of stellite 6 on low alloy steel gate valve and the characterization of the PTA hardfaced gate valves.