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REVIEW ON HARDFACING AS METHOD OF IMPROVING THE SERVICE LIFE OF CRITICAL COMPONENTS SUBJECTED TO WEAR IN SERVICE

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ABSTRACT
A review on hardfacing is presented. Hardfacing involves applying a consumable with desired wear properties over a soft base metal surface to enhance resistance to different wear mechanisms. Substrate materials used for hardfacing are mainly steel, while the alloys of carbide forming elements dominate the surfacing consumables. Powder metallurgy, atomisation and granulation are methods of producing hardfacing alloy powder. Most welding methods were identified to be successfully used in applying consumable on substrate surfaces. Dilution decreases with increase in the number of hardfacing layers. Buffers, butters and build-up metals are used to compensate for composition differences to prevent spalling, overcome welding difficulties and make up for badly worn surfaces, respectively. Waffle, stringer and dot patterns are the existing hardfacing deposit patterns. Benefits of hardfacing include: reduced downtime, inventory and maintenance cost, increased plant availability and productivity, and a good number of service life extensions through timely reparation.

Keywords: *Hardfacing, wear, substrate, consumable, service life extension, composition compensation.*

1. INTRODUCTION

Critical components of machineries used in mining, mineral processing, construction, agriculture and many industrial processes are subjected to severe wear in service. Classification of some parts subjected to severe wear in service is as follows: Mining – crusher hammers and rolls, concave and mantles of cone crushers, jaws of jaw crushers, grizzly bars; Construction – bulldozer blades, asphalt mixer paddles, grader rippers, wheel loader and excavator buckets; Agriculture – tractor drive sprockets, tractor rollers, tillage tools; Others - punch and forging dies, shear blades, steel mill rolls, railway frog, pump casings and impellers, dredge cutter and teeth. Degradation of the component surfaces due to wear has lead to downtimes, increased production cost and in some cases moribund of plants. Haakonsen [1] defined wear as the damage to solid surfaces due to removal or displacement of material by mechanical action of a contacting solid, liquid or gas.

Preceding restoration of worn surfaces, study of the underlying wear mechanism is pertinent. Mechanisms or modes of wear include: abrasion, erosion, surface adhesion, surface fatigue [2], impact and corrosion [3]. Hawk and Wilson [4] identified abrasion as the dominant type of wear in earthmoving (construction), mining and mineral processing machineries. Dumovic [5] noted that abrasive wear occurs when nonmetallic materials slide under pressure across a metallic surface. Chawla and Shibe [6] described abrasion as the wearing away of surfaces by the rubbing, grinding, or other types of friction. The second prominent wear mode in mining and mineral processing operations can be said to be impact. Impact wear arises from the striking of one object against another. It is a pounding type of wear that changes the original dimensions of the part, deforms or splits metal surfaces; crushing hammers and dipper bucket encounter impact in operation [7, 8].

Changes in the surface topography of a part due to wear can be regenerated using surface engineering techniques which aim at altering the microstructure and composition of the near surface region of the component without affecting the bulk material in order

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to achieve the desired surface properties such as abrasion and corrosion resistance, thereby improving its function and useful life [9, 10]. Service life of worn components and new parts can be economically extended by a surface engineering technique known as "hardfacing". According to Smith [11], hardfacing means adding weld metal (consumable or hardfacing alloy) over an existing surface (base metal or substrate) to improve the substrate surface resistance to abrasion, impact, erosion and so on. Economic criteria for restoration of worn components are based on the premises that:

(i) the price of repair cannot exceed the price of the new part [12];
(ii) restoration is done at low cost compared with replacement costs especially when the component is large and /or expensive or is a part of a larger structure [13].

Considering the inevitable nature of wear in machineries, the objectives of this paper are: to review different methods of producing hardfacing consumables and how they are being applied; different substrates for the hardfaced parts; challenges encountered in hardfacing and solutions proffered.

2. CLASSIFICATION OF SUBSTRATES, HARDFACING ALLOYS AND BINDERS

2.1 Categories of Substrates

Steels have been the major base metal used for producing hardfaced parts. Categories of ferrous metals that are in use as substrate include: (i) Low carbon steels, (ii) Medium carbon steels, (iii) High carbon steels, (iv) Low alloy steels, (v) High speed steels, (vi) Stainless steels, (vii) Manganese steels, (viii) Low nickel chrome steels, (ix) Cast iron (grey and white) [14,15].

2.2 Categories of Hardfacing Alloys

Categories of hardfacing alloys include: (i) Low alloy ferrous materials (containing 2 – 12% alloy constituent), (ii) High alloy ferrous materials (containing 12 – 50% alloy constituent), (iii) Nickel base alloys, (iv) Copper base alloys, (v) Cobalt base alloys, (vi) Stainless steels and (vii) Carbides [15].

2.3 Binders for Hardfacing

Binders used in forming consumables include: phenolic resins, wax [16] and sodium silicate [17-19]. Langford Jr. and Delwiche [20] listed iron, nickel, copper and cobalt alloys as metal binders or matrix materials for hardfacing alloys.

3. METHODS OF PRODUCING HARDFACING ALLOYS

Hardfacing alloys are usually made from carbide forming elements such as: Ti, V, Cr, Mn, Fe, Zr, Nb, Mo, Hf, Ta and W [21]. Dolman [22], disclosed that higher carbide contents in the microstructure yield greater wear resistance, generally. Hardfacing consumables are often made in powder form prior to their usage in the form of hardfacing powder, paste or tube electrode. Methods of producing hardfacing powders include:

(i) Powder metallurgy, followed by pulverization, grinding and sieving of the sintered alloy [23, 24].
(ii) Atomisation, which produces powders in the range of few microns to 1 mm. Methods of atomising liquid metal are by water atomisation, gas/air atomisation and centrifugal atomisation [25, 26].
(iii) Granulation, followed by grinding and sieving of the granules to obtain the alloy powder. The granulation process results in particle sizes of millimetre range sometimes greater than 10 mm [26].

Welding consumables of the hardfacing alloy can be produced by blending of the carbide (e.g. chromium carbide) and a matrix or binder (e.g. iron) [25], or by encapsulation or embedding of the hardfacing particles (e.g. diamond particles) in a matrix portion (e.g. iron, cobalt) [20]. However, it has been observed that adding free carbon powder to ferroalloy blend in order to increase the carbon content in the hardfacing weld is not effective since the free carbon does not readily dissolve in the molten weld pool during the short arc welding melting time to form hardfacing deposits on substrates [22].

Mechanically mixing the metal powders does not yield homogeneous powder blend as segregation occurs during handling due to density differences between the ferroalloys. This can lead to premature wear of the hardfacing in service due to non-uniform chemical composition and microstructure. The solution to these lies in the melting of the ferroalloy to obtain a homogeneous alloy composition and atomising the melt to obtain alloy powder [22].

4. HARDFACING TECHNIQUES

Hardfacing alloys can be applied to substrates through different welding processes ranging from the traditional oxyacetylene gas welding to more sophisticated plasma transferred arc and laser welding methods [27]. Depending on the nature and quantity of job to be hardfaced, state of the worn component and accessibility of weld equipment, suitable welding process can be selected to suite the job. The welding processes can be grouped as follows: Hardfacing by arc welding – shielded metal arc welding, submerged arc welding; hardfacing by gas welding – oxyacetylene gas welding; hardfacing by combination of arc and gas – tungsten inert gas welding (TIG), gas metal arc welding; powder spraying – flame spraying, high velocity oxyfuel process, electric arc spraying and plasma transferred arc welding; and laser hardfacing/laser cladding [14].

Some of the welding methods that have been successfully used to apply hardfacings on substrates are: gas tungsten arc welding (GTAW) [28], plasma arc welding (PAW) [29], laser beam welding [30,9], tungsten inert gas welding (TIG), gas welding [31], manual metal arc welding (MMAW) [32], shielded metal arc welding (SMAW) [13,18], and flux cored arc welding (FCAW) [33,34]. Shibe and Chawla [35] summarized the three types of hardfacing deposition techniques as thermal spraying, cladding and welding.

5. PERFORMANCE OF SELECTED HARDFACINGS

The results of some hardfacing alloys when deposited on substrates are tabulated as shown in Table 1.

6. HARDNESS OF HARDFACINGS AND WEAR EVALUATION

Hardness can be described as the resistance to plastic deformation by indentation, scratching or other frictional means. Dilution increases with increasing welding current and increased presence of chromium in a chromium carbide paste hardfacing; these result in decreasing hardness; however, lower welding current increased hardness and wear rate of the hardfacing [18, 19]. Gucwa *et al.* [38] noted that differences in the sizes, shape and distribution of primary and eutectic carbides cause significant changes in the hardness of hardfacings.

A hardfacing alloy with chromium (33%) and carbon (4.5%) used to hardface an excavator bucket teeth by manual metal arc welding (MMAW) technique showed better wear resistance than the unhardfaced teeth [39]. Hardness depends on process parameters such as welding current, arc voltage and speed of travel; it decreases from the surface of the hardfacing deposit to that of the substrate and remains constant on the substrate [40].

Gucwa and Winczek [41] identified heat input as one of the most important factors that determine the properties of the remelted or hardfacing surfaces. According to Babu *et al.* [9], the surface hardness of EN25 steel doubled when the laser beam power was varied between 750 – 1250W and travel speed between 500 – 1000mm/min.

Santhosham and Rajendra [42] disclosed that increase in the manganese content with addition of boron in Fe-C-Si-Mn-B electrode resulted in an average hardness of 700VHN when used to hardface low carbon steel of hardness 143VHN. According to Dolman [22], a hypereutectic hardfacing with 30 – 60% volume of M_7C_3 carbides in a ferrous matrix (M = Cr, Fe, Mn) gave a nominal hardness of M_7C_3 carbides of 1200 – 1500HV and 600 – 700HV for the ferrous matrix. More so, Chotěborský *et al.* [43] revealed that the hardness of hypereutectic hardfacing increases with the increasing proportions of carbide phases MC and M_7C_3. Coronado *et al.* [34], showed that hardfacing using flux cored arc welding gives better wear resistance than hardfacing by shielded metal arc welding.

A general equation for the determination of wear rate as reported by Juvinall and Marshek [44], is as stated in equation (1). The wear coefficient of a material undergoing wear can be evaluated using equation (2) [45]. According to Rabinowicz and Hozaki [46]; Dumovic [5] abrasive or metal to metal wear volume can be determined with the equation (3):

$$\text{Wear rate} = \frac{\delta}{t} = \left(\frac{K}{H}\right) . P . \nu \qquad (1)$$

where, δ is the wear depth (mm); t, the time (s); K, the wear coefficient (dimensionless); H, the surface hardness (MPa); P, the surface interface pressure (MPa); and ν, the sliding velocity (mm/s).

While considering that for a given compressive force between surfaces, the volume of the material worn away is independent of the area of contact, a more common equation for calculating the wear coefficient is given by:

$$\text{Wear coefficient, K} = \frac{W . H}{F_N . s} \qquad (2)$$

where, W is the volumetric wear; H, the hardness of the wearing material; F_N, the applied normal load (N), and s, the sliding distance (mm). The wear volume can be determined from the following equation:

$$\text{Wear volume, W} = \frac{K . F_N . s}{H} \qquad (3)$$

7. DILUTION IN HARDFACINGS

Dilution is defined as the percentage of base metal in the weld metal deposit. The higher the percentage of dilution, the higher the percentage of the base metal in the weld deposit; the converse is true [47]. Vasudev and Singh [19] posited that, dilution increases with increase in welding current and depends upon the heat input and chemical composition of the electrode and base metal.

Table1: List of hardfacing alloys, substrates and results

S/N	Hardfacing alloys	Substrates	Results
1	WC	Hadfield steel wt%) 1 – 1.40C, 11 – 14Mn	Hadfield steel hardfaced with 0.100-0.315mm WC particles showed higher impact wear resistance than that of Hadfield steel. The smaller the WC particles, the better the impact wear resistance [36].
2	High manganese electrode	Low carbon steel	Hardness values decreased as the number of hardfacing layer increased, due to higher contents of Mn and C. Highest erosive wear occurred at impact angle of 90^o for all layers. Deposition with single pass gave good result for low speed erosion test [27].
3	Electrode (wt %) - 0.33C, 0.28Si, 1.15Mn, 2.22Cr	Mild steel (wt %) - 0.18C, 1.47Si, 0.32Mn,	Wear loss decreases with increasing hardness. Highest abrasion resistance was offered by chromium carbide alloy microstructure [3]
4	Filler material (wt %)- 0.20C, 1.00Si, 1.30Cr	Steel Punch (wt %) – 0.20C, 1.00Si, 1.30Cr	Hardfaced shape punches offered more wear resistance and longer service life than new ones due to more favourable microstructure of the hardfaced zones and better bonding between the hardfaced layer and the base material [31].
5	MR3LH electrode (wt %) - 0.08C, 1.10Mn, 0.90Si, 6.00Cr, 0.60Mo, 0.50V	EN-31 tiller blade material (wt %) - 0.51C, 0.47Mn, 0.17Si, 0.14Cr, 0.16Cu	Wear resistance property of the test piece coated with MR3LH increased, while the uncoated showed wear scars [37].
6	EMn17Cr13 electrode(wt %) - 0.60C, 16.50Mn, 13.5Cr	Manganese steel (wt %) - 1.20C, 0.48Si, 12.35Mn	Cost of hardfacing impact beam was 25% lower than the cost of new beam. Working life of parts was extended and downtime reduced [12].

Fig. 1 shows a schematic illustration of dilution in a weld deposit. Dilution has been measured with a profile projector machine and can be calculated using equation (4):

$$\text{Dilution} = (A_1/\ A_1 + A_2) \qquad (4)$$

where A_1 is the area of weldment penetration, and A_2 is the area of weld bead on top surface.

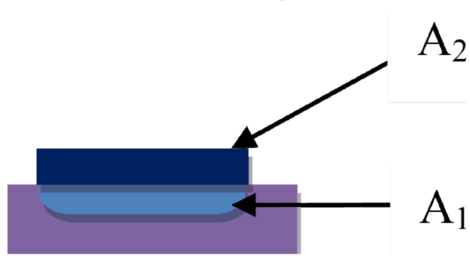

Fig 1: Dilution in weld deposit

Table 2: Dilution factors for some welding processes

S/N	Welding processes	Dilution factors (%)
1	Oxy-acetylene gas welding	0 – 5
2	Tungsten inert gas welding	5 – 15
3	Shielded metal arc welding	20 -45
4	Flux cored wire arc welding	20 – 45
5	Submerged arc welding	25 – 50

Welding process which produces a low percentage of dilution is generally preferred for hardfacing applications [47]. According to Pradeep *et al.* [48], AFROX product reference manual stipulated the dilution factors as shown in Table 2.

Lower percentage dilution of hardfacing implies that the filler metal has not penetrated the base metal substantially, this may lead to low bond strength [19]. Dilution decreases with increase in the number of hardfacing layers; in general, two to three layers are enough. The main objective of keeping dilution as low as possible is to obtain optimal properties in the hardfacing deposit. Lower heat input results in lower dilution and vice versa. Also, horizontal and flat welding positions give low dilution. However, excessively alloyed weld metal is less sensitive to dilution [49]. Rovatti *et al.* [50] showed that the microstructure of an iron-based hardfacing containing high amount of chromium carbide-boride forming elements shifted from an almost fully hypereutectic to a hypoeutectic structure, when the iron content was raised up to 50% mass.

8. JOINING CHALLENGES AND COMPOSITION COMPENSATION IN HARDFACING

Variation in the composition of the hardfacing alloy and the substrate may lead to difficulty in joining them or penetration of the hardfacing layer into the substrate, leading to spalling as illustrated in Fig. 2; this can be taken care of by buffers. Buffer layers are used as intermediate deposits between the substrate and the hardfacing weld metal to ensure good bonding with the substrate, limit the effect of dilution, avoid spalling, prevent possible cracks in the hardfacing layer extending into the substrate and minimize the consequence of stress. Austenitic consumables are widely used as ductile buffer layers in hardfacing. When hardfacing a soft base material such as mild steel, with brittle alloys such as chromium carbides and cobalt-based alloys, it is advisable to buffer one or two layers with austenitic consumable [49].

The cushion layer or buffer has lower wear resistance compared to the actual hardfacing [13]. Fig. 3 shows buffering technique during hardfacing. Buttering involves joining two metals that are difficult to weld by welding them to an intermediate material that is weldable to each. This can be exemplified using the illustrations below; when joining is to commence from the steel side, a steel electrode is used as shown in Fig. 4, while bronze electrode is used when welding from the copper side as shown in Fig. 5 [49]. Notice that, pure nickel is used as the butter in both cases When a part is badly worn, the worn area is rebuilt to its original form with a suitable filler metal before hardfacing [8]. Alternatively, alternate hard and ductile deposits can be used to build-up the worn surface as shown in Fig. 6. Build-up alloys have good resistance to impact wear but, moderate resistance to abrasive wear [49].

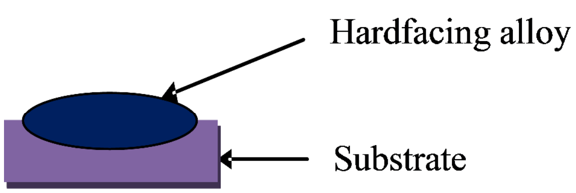

Fig. 2: Spalling in a soft substrate

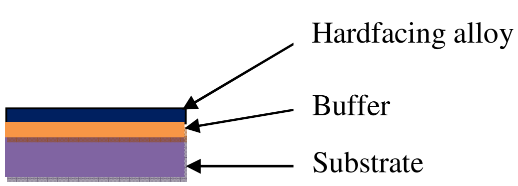

Fig. 3: Buffering substrate before hardfacing

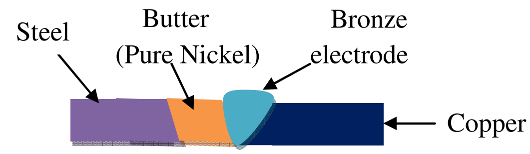

Fig. 5: Buttering with bronze electrode [49]

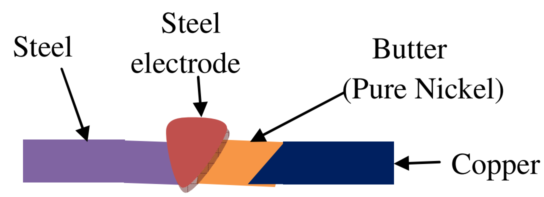

Fig. 4: Buttering with steel electrode [49]

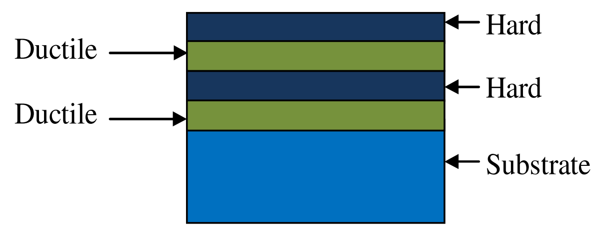

Fig. 6: Build-up of worn surface using alternate hard and ductile deposits

9. DETERMINATION OF THE PREHEATING TEMPERATURE OF THE SUBSTRATE

It is pertinent to note that before hardfacing the substrate, the composition and preheating temperature need to be known. The composition of the substrate can be determined with spectrophotometer and the carbon equivalent (CE) calculated therefrom; the CE can be determined with a carbon equivalent analyzer or from CE values for the substrate from standard tables; while the preheating temperature T_p can be calculated with the aid of the Seferian formulae presented in equations (5) to (7):

$$T_p = 350 . \sqrt{Ce - 0.25}, \ ℃ \quad (5)$$

$$Ce = CE(1 + 0.005 . s), \% \quad (6)$$

$$CE = C + \frac{Mn + Cr}{9} + \frac{Ni + 7Mo}{18}, \% \quad (7)$$

where, Ce represents the carbon equivalent and thickness, CE is the chemical carbon equivalent, and s is the thickness of the substrate [51]. If some elements in the CE formula are not present in the substrate, their values zero out; also, when elements that are not present in equation (7) are found, appropriate CE formula containing those elements are used.

10 HARDFACING DEPOSIT PATTERNS

There are three patterns of deposition of hardfacing alloy on a substrate; these are waffle, stringer or dot patterns. The pattern of hardfacing deposit to be adopted is dependent on the type of wear, location of the wear and the material that causes it [52].

10.1. Waffle Pattern

Waffle pattern, also known as herringbone or crosshatch or crisscross or checker hardfacing bead pattern is formed by laying weld beads at varying angles. It works well with sand or soil containing clay [53]. The overburden like dirt, sand and smaller aggregates will tend to pack into the spaces between the weld beads, and offer further protection to the base metal [52, 54, 55]. A pictorial example of the waffle pattern is shown in Fig. 7.

10.2. Stringer Pattern

This consists of weld beads that run parallel to each other. Stringer beads for handling smaller-grained materials are placed perpendicular to the flow of materials, while large-grained materials require stringer beads that are parallel to the flow of the material [52]. According to STOODY [55], parallel stringer beads act as directional runners, allowing the abrasive material e.g. large pieces of rocks or slag to ride high on the weld beads, and protect the base metal from erosion. Schematic diagrams of stringer bead patterns are shown in Fig. 8 and Fig. 9.

10.3. Dot Pattern

Dot pattern is applied in areas that do not experience heavy abrasion but are subjected to wear and on thin base metals, where distortions and warpage may be a problem [55]. The size of the aggregate the equipment encounters determine the distance between dots; larger aggregates require widely spaced dot pattern, while smaller aggregates require closely spaced dot pattern [52]. Wallin [54] suggested that dot pattern should be applied to base metals that are sensitive to overheating e.g. manganese steel or thinner material where embrittleness may occur. A pictorial example of a dot pattern is shown in Fig. 10.

11. ADVANTAGES OF HARDFACING

Advantages of hardfacing a part include: extension of service life of a part, which results in the lowering of production costs and fewer replacement of parts; maintaining certain dimensions even under adverse conditions such as abrasion, corrosion or impact shocks [7]; this implies reduced inventory since worn parts can easily be rebuilt; hardfacing increases the useful life of parts two times or more and enables worn parts to be repeatedly restored , this leads to an overall increase in work efficiency and reduction of operation cost; consequently, it can be applied to new parts before they are used and reapplied in due time as necessary [8].

Fig. 7: Waffle hardfacing pattern [56]

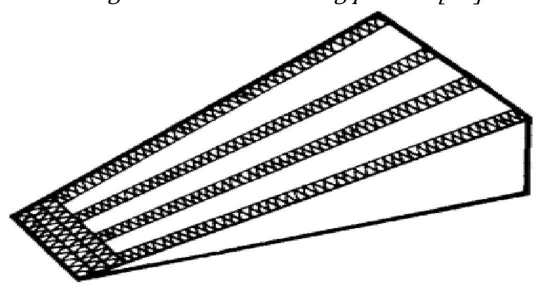

Fig. 8: Stringer bead hardfacing pattern for large aggregates [53]

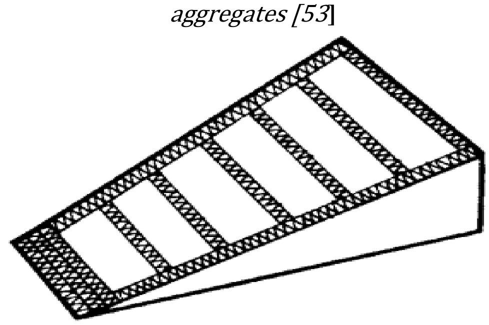

Fig. 9: Stinger bead hardfacing pattern for smaller aggregates [53]

Fig. 10: Dot hardfacing pattern [56]

When properly applied, hardfacing and build-up deposits last longer than the original material; it reduces downtime because parts last longer and fewer shutdowns are required to replace them; it allows the introduction of alloying elements into the base metal in the form of weld consumables, to achieve desirable properties like hardness, wear resistance, abrasive resistance, thereby leading to increased profits and productivity [35].

12. CONCLUSIONS

- Hardfacing is seen as an economical method of extending the service life of worn machine components. Useful life of new critical parts can be prolonged by hardfacing such parts prior to subjecting them to wear applications.
- Identification of the wear mechanism, substrate composition and welding method are prerequisites to selecting hardfacing alloy composition.
- Clean substrate surface, its composition, carbon equivalent, thickness and preheating temperature must be taken into cognizance during hardfacing. Excessive build-up deposits of the hardfacing alloy must be avoided or they may break off in service.
- The use of mechanically mixed metal powders results in hardfacing that lack homogeneity, due to short arc melting time and fewer carbides in the microstructure of weld deposit. This leads to non-uniform wear. Free carbon addition to the weld pool is not the solution either.
- Melting of alloy followed by atomization or granulation, grinding and sieving are the process routes to achieving homogeneous hardfacing consumable powder with reasonable quantity of fine carbides in the microstructure.
- High hardness of carbides of carbide forming elements has direct relationship with their wear resistance. Chromium dominates other higher carbide forming elements such as tungsten and titanium in hardfacing applications, probably due to the high cost of other elements and reasonable hardness value offered by chromium carbide. The smaller the carbide particles in the microstructure of the hardfacing alloy, the better the wear resistance.
- Hardfacing consumables are applied to substrates in the form of tube rod or wire electrode, paste or powder.
- Both traditional and sophisticated welding methods can be used for hardfacing; however, dilution must be kept as low as possible to obtain optimal properties. Low heat input, increased number of layers, horizontal and flat welding positions are some of the ways of achieving low dilution. Hardness of hardfacings vary with the welding method, this may be due to variation in dilution, which increases with increasing current or heat input and vice versa.
- Composition differences that result in spalling, welding difficulties and excessive worn surfaces can be compensated for by buffering, buttering and build-up layer technique, respectively.
- Waffle, stringer and dot patterns are the established patterns of depositing a hardfacing alloy on a substrate.
- Hardfaced parts reduce downtime and inventory; hence, reduced maintenance cost, increased plant availability and ultimately improved organisational productivity.
- There is no specific number of times a part can be hardfaced and reused as badly worn surfaces can be compensated for economically and worn weld deposit on hardfaced new parts can be replaced before the wear gets to the substrate; hence, reparation of worn component can be carried out as many times as possible.

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