Reliability of Dissimilar Metal Joints using Fusion Welding: A Review

Rakesh Chaudhari, Riddhish Parekh, and Asha Ingle

***Abstract*—**This paper is an endeavor that reviews different methods used to join dissimilar metals -with particular focus to reduce sharp changes in composition and properties of the metals being joined. Such changes lead premature failure of the joint formed. Indeed joining of dissimilar metals has drawn to itself a great deal of interest in modern fabrication and manufacturing. The conventional fusion welding is used for this task has already become relegated. TIG welding is another method that joins dissimilar metals, and is especially effective in joining thin sections. For metals that are immiscible in solid state yet miscible in liquid state, one now has MIG welding. Yet another method known as Laser Engineered Net Shaping (LENS) also uses direct deposition, facilitated by Lasers. LENS forms transition joints which controls local material composition as a function of its position throughout the components. The paper ends with a list of open issues in this arena.

***Keywords*—**Dissimilar metals welds, laser beam welding, TIG welding, MIG welding, Laser Engineered Net Shaping

I. Introduction

DISSIMILAR metal joints are used in various engineering applications such as nuclear power plant, coal fired boilers and automobile manufacturing. As joining of dissimilar metals are typically involving high temperature and pressure welding is preferred instead of other joining methods. Welding creates a strong joint but also introduced long term reliability issues in these types of joints. The significant difference in material properties such as Coefficient of Thermal Expansion (CTE), modulus of elasticity, Poisson's ratio combined with the configuration of the joint leads high stresses around the joining interface. Joining of dissimilar metal is a task of composing different properties of metal together to form the reliable joint.

The conventional methods such TIG welding and LASER beam welding can be used to form reliable dissimilar metal weld. The direct deposition method called Laser Engineered Net Shipping forms the transition joint. The material composition and properties are controlled as a function of position throughout the component to avoid the sharp changes or the length of the joint.

LASER beam welding is useful to join dissimilar metals with significantly different heat expansion coefficient and require deep penetration for joining. It gives very small Heat Affected Zone (HAZ). TIG welding is useful in DMW due to high welding quality, high stability and the wide range of applications. This welding is used to join thin sections or sheet metals with a shallow penetration depth.

The direct deposition method called Laser Engineered Net Shaping (LENS) is also used to join dissimilar metals. It forms the transition joints in which local material composition is controlled as function of position throughout the component. The sharp changes in microstructure and properties of DMWs extended over the component length help to avoid early failure. It is observed that these types of joints exhibits optimized mechanical properties and helps to reduce the microstructure, chemical potential and other property differences.

But these conventional welding processes have number of issues during and after welding. The direct change in properties of base metals at the welding interface decreases the reliability of joints. It becomes difficult to form the DMW using fusion welding as cracks occur in heat affected zone. Also melting of one base metal earlier than other does not allow them to mix completely with the weld pool and form a joint with poor strength. The non-ferrous copper is when joined with steel dissipates the heat away from weld due to its high thermal conductivity. This causes difficulty in reaching the melting temperature. The heat affected zone shows hot cracking due to early melting of copper and penetrating in to the grain boundaries of stainless steel. The studies suggest that joint of copper and lightweight aluminum contains many cracks in the lower part of weld. The cracks are brittle in character and all stopped at interface between the weld and the copper, but no cracks are observed in upper part of the weld due to low delusion of aluminum by copper.

II. Methods to join dissimilar metals

Following processes are generally used to join dissimilar metals. The dissimilar metals joints can be formed using any of these methods but low dilution and non-diffusion joining for high production and special application joining. DMWs used in power and process industries are most often fusion welds formed by most common welding processes. The

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categorization along with some key features of welding process used for joining dissimilar metals is given in table 1.

TABLE I
WELDING PROPERTIES USED TO FORM DISSIMILAR METAL WELDS

Fusion welds	Low Delusion Welds	Non Diffusion Joining
Includes Shielded Metal arc, Gas metal arc, Gas tungsten arc and Submerged arc.	Includes Electron Beam Welding, Pulse Arc welding.	Includes Friction welding, Explosion welding, Diffusion bonding along with brazing and soldering
The base metals need to melt for forming a joint.	Relatively minimum base metal is melted.	Generally used for thin sections.
Filler material needs to be added.	Very small amount of filler metal is used.	

III. LASER BEAM WELDING

Laser welding is a versatile technique which offers high power, high speed, and chemically pure heat source to join the materials of different properties. It gives good control over amount of power that is useful in joining extremely thin and thick plates. Therefore using the laser welding to weld the dissimilar joints has been attractive in the recent years [1-3]. Laser welding is used as heating effect of concentrated beam of monochromatic laser light to produce a fused weld bead. The main process variables for any joint and material combination are beam power, focused spot size and welding speed. An inert gas such as helium or argon used in the process protects the weld bead from contamination and reduces the formation of absorbing plasma. The majority of industrial applications of laser welding involve structural and stainless steel. If the process variables are controlled it can be used to join the metal with nonferrous alloy too [4], [5]. A binary Cu-Ni alloy is also formed by continuous welding using CO2 laser.

A. Weldability of Metal Pairs

The solid solubility is essential for good properties of dissimilar metal welds; the following table suggests the weldability of metal pairs depending on their temperature factor.

TABLE II
WELDABILITY OF METAL PAIRS

	Al	Ag	Au	Cu	Pt	Ni	Fe	Ti	W
Al	-	C	X	C	X	X	X	X	X
Ag	C	-	S	C	S	C	D	C	D
Au	X	S	-	S	S	S	C	X	N
Cu	C	C	S	-	S	S	C	X	D
Pt	X	S	S	S	-	S	S	X	X
Ni	X	C	S	S	S	-	C	X	X
Fe	X	D	C	C	S	C	-	X	X
Ti	X	C	X	X	X	X	X	-	X
W	X	D	N	D	X	X	X	X	-

In table, Metals (Al: aluminum; Ag: silver; Au: gold; Cu: copper; Pt: platinum; Ni: nickel; Fe: iron; Ti: titanium; W: tungsten) joined using LBW and their results (C: Complex structures may exist X: Intermetallic compounds formed; undesirable combination S: Solid solubility exists in all alloy combination D: Insufficient data for proper evaluation N: No data available) are shown. [6]

B. Issues of LBW in dissimilar metals

When LBW use to join similar metals and alloys its symmetrical heat source about the centerline of the butt joint it shows well-structured and similar microstructures, the reason for patterned microstructure are continuous weld pool solidification that creates the columnar grains at the center of weld. The research also shows that the weld pool appears symmetric about the centerline. However in case of dissimilar metals there are many features that are different than similar metal welds. The difference in physical properties of metals creates complexity in weld pool shape.

A research of G.Phanikumar et al [7] and Z.Sun et al [8], [9] explains the effect of solidification on microstructures using laser beam techniques to join dissimilar metals. The high purity metals such as copper and nickel when joined by continuous wave CO2 laser as a heat source and the microstructures are observed at transverse sections of weld. The welds formed by using high and low laser scan speed shows that the shallow metal pool is for high scan speed while it shows deep and narrow for low one and a symmetry in a pool with more melting of nickel appears nearly at all speed with some porosity. A symmetric segregation patterns in microstructures is also observed at the interface of the weld. Nickel weld interface sharp and shows cellular growth of base metal in to the weld and bend near the interface is observed[7], [10].Which is also termed as low velocity bands by Kurz ans coworkers [11]. The grain size considerably becomes coarse near the weld pool in copper while it remains same at nickel side.

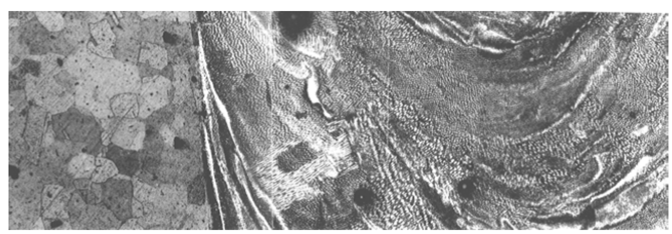


Fig. 1 Microstructure on the top view from nickel side [7]

This difference in grain structure may cause early failure of weld due to uneven stresses. The small focus diameter of fiber laser forms the heat affected zone and formation of intermetallic in laser welding. The laser welding perform on different metals such as titanium aluminum alloy, copper 304 stainless steel and copper aluminum alloy gives significant understanding of weak strength at interface of dissimilar metals.

The fusion welding of titanium and aluminum alloy is difficult as the crack occurs in a heat affected zone. The cracks are formed because of the brittle intermetallic compound that is generated at the joint interface. While using LBW aluminum melts earlier than titanium but does not mix completely to form the weld pool. Therefore a fluffy interface is formed due to variable mixing of melted sheets.

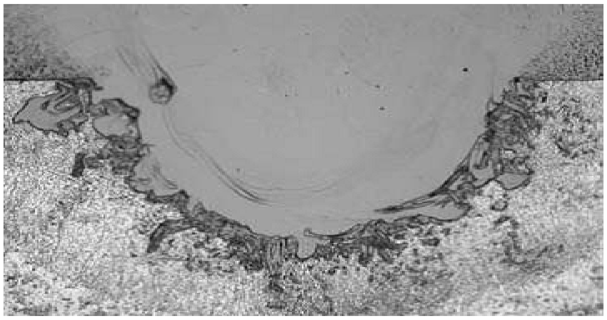


Fig. 2 Aluminum – Titanium alloy DMW [6]

The joints of copper and stainless steels that are used in cryogenic applications have shown some limitations in forming a reliable joint. In this type of joints the high thermal conductivity of copper dissipates the heat rapidly from the weld pool and creates difficulties in reaching the melting temperature. The early melting of copper penetrates in the grain boundaries of stainless steel and causes the hot cracking at HAZ of joint.

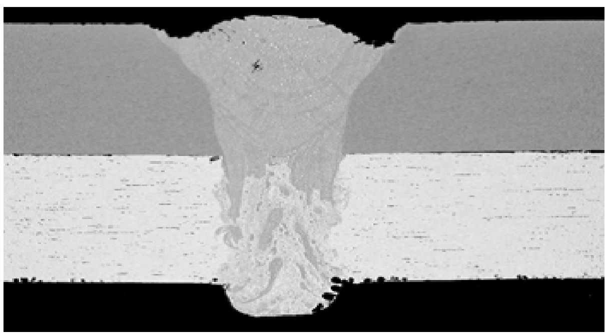


Fig. 3 DMW of 304-Stainless Steel and Cu [6]

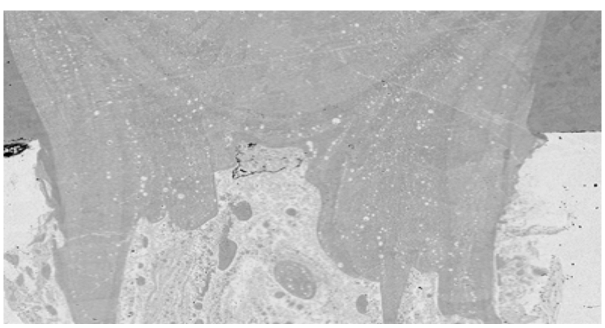


Fig. 4 Partial pressure of Copper on Stainless steel [6]

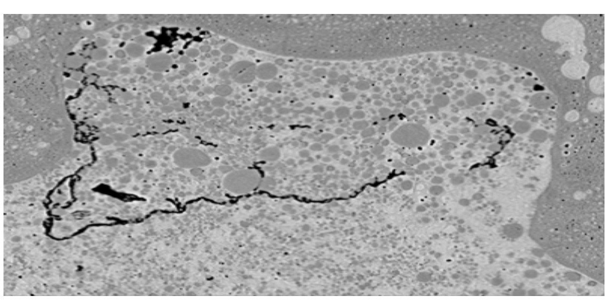


Fig. 5 Hot cracking due to penetration [6]

This inter diffusion of elements in the neighborhood of the interface forms the weak metallurgical bond of joining metal. The liquid phase in fusion zone shows secondary liquid separation due to high cooling rate and high super cooling level of laser welding. The micro cracks are observed in fusion zone due to thermal stress mismatch which sometime are healed by liquid copper filling. The preheating or high power density can improve the joint integrity according to mai and spowage et al. [12] proposed that the car geometry of copper/stainless steel laser joint can be used to improve the high temperature gradients to the thickness direction. The microstructural study of copper/stainless steel reveals morphology of HAZ and interface of copper and fusion joint. The grain in HAZ at the copper side shows the significant growth than the parent metal. The coarse grain structure is observed at the interface. However the HAZ at the stainless steel retains its original streamline structures and the grain growth is little significant.

The bio-metallic joints of aluminum and copper are widely used in electrical applications. Such as conductive strips and in the battery of hybrid car, the studies suggest that more amounts of cracks appear in the lower part of the weld. The cracks are brittle in character and all stopped at interface between the weld and the copper parent metal. The low delusion of aluminum by copper causes no crack formation at the upper part of the weld.

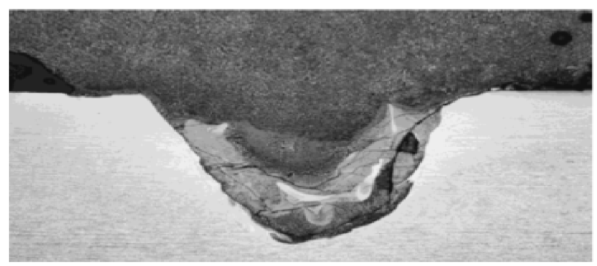
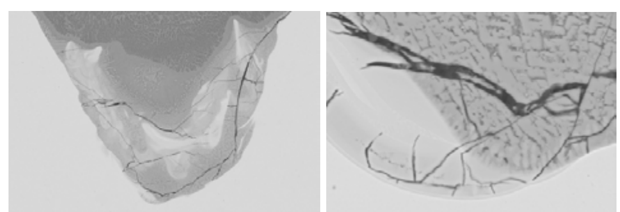


Fig. 6 The root of weld between Al alloy and Cu [6]



(a) (b)

Fig. 7 SEM micrographs of the root of weld showing cracks [6]

IV. TIG WELDING

TIG welding uses non consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by inert shielding gas. This welding method is used to form high quality welds of variety of materials such as aluminum, stainless steel, titanium etc. This process is best suited for joining thin sections. TIG welding helps to suppress the formation of intermetallic reaction phase as it is self-brazing technique. A longitudinal electromagnetic hybrid TIG welding-brazing is used in some cases to produce high quality welding joints. TIG welding could produce partial penetration welding even in 1mm thickness steel sheet.

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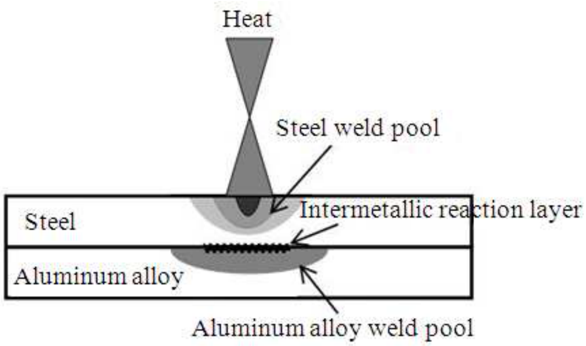


Fig. 8 Schematic of the interface during dissimilar metals welding between steel and aluminum alloy [13]

A. *Issues of TIG welding in dissimilar metals*

The dissimilar metal welds of aluminum and steel using TIG shows number of limitations in reliability and strength of joint [13-15]. A low solid solubility and difference in thermal physical properties of aluminum and steel forms the brittle intermetallic compound which affects the mechanical behavior of weld. The research by Borrisutthekul et al., 2007 [16]; Miyashita et al., 2005 [17]; Lee et al., 2005 [18]; Lee and Kumai, 2006 [19]; Rathod and Kutsuna [20], 2004 shows that the molten zone of steel is controlled to form a partial penetration joint during the lap joint welding of steel and aluminum alloy.

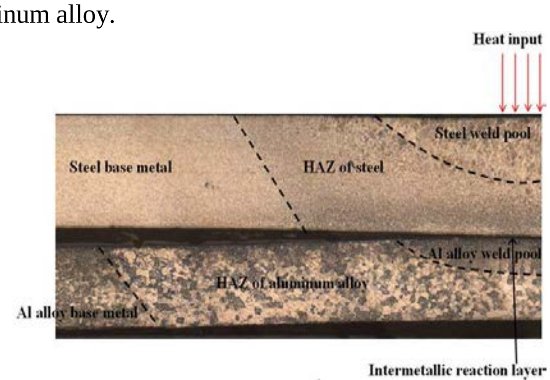


Fig. 9 Different zones of DMW of Stainless steel and Aluminum [13]

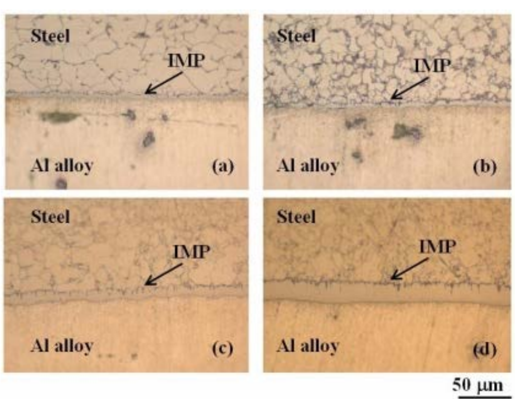


Fig. 10 Intermetallic reaction layer obtained at welding speed of 0.65 m/min and (a) 90 A, (b)110 A, (c) 130 A and (d) 150 A of electrical current used. [13]

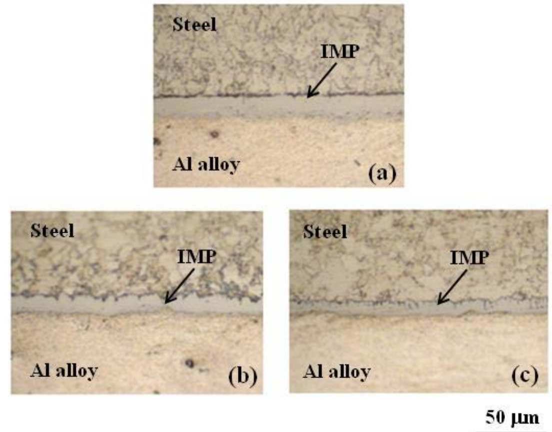


Fig. 11 Schematic of the interface during dissimilar metals welding between steel and aluminum alloy at 130 A and welding speed of (a) 0.55 m/min, (b) 0.60 m/min, and (c) 0.65 m/min. [13]

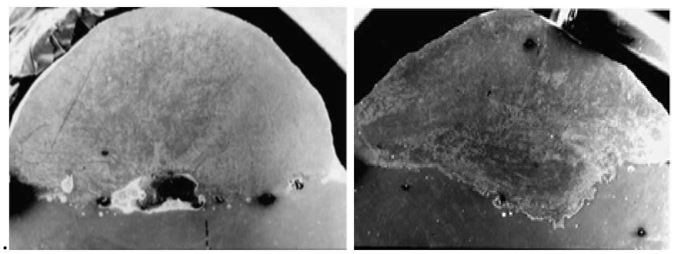
The formation of intermetallic reaction is affected by the speed of welding [13], [21]. The electric current and other welding parameters, from figure 10A shows the thickness of intermetallic layer decreases with increasing welding speed and with increasing welding current. The effect of various apparent heats input for joining on the thickness of intermetallic reaction layer is shown in figure 10B. The microstructures of HAZ of aluminum appears to be coarser then the base metal. The welding speed and apparent heat input also affects the microstructures of HAZ of aluminum alloy. The lower apparent heat input shows the final grain in HAZ of aluminum alloy. The strength of the joint also decreases with the heat input for joining. The strength of joint is found in a range of 500 to 800 N; however it is about 1100-1200 in the base metal for joint of 1mm steel sheet and 0.8mm aluminum sheet [19].

Fig. 12 Grain at Heat affected zone of aluminum alloy [13]

V. MIG WELDING

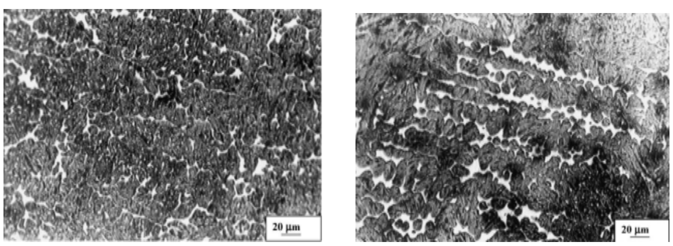
MIG welding is commonly used high deposition welding process in which electric arc is formed between consumable wire electrode and the work piece metal which melts a work piece metal to form the joint. The shielding gas feeds through the welding gun to protect the process form contaminants in the air. This process is capable of joining of most type of metals and it can be performed in many positions. MIG welding is suitable to form dissimilar metal joints of carbon steel, low alloy steel, stainless steel, aluminum and copper [22], [23]. MIG welding is best suited to form the joints of dissimilar metals which are immiscible in solid state and miscible in liquid state. One of the major problems in dissimilar metal welding using MIG is a mixing of metal. The problem not only depends on the heat source and melting point of two constituent materials but also in the relative conductivity.

K. Suresh Kumar et al. [24] has studied the microstructure development during MIG welding of copper with iron metal filler to understand the process of dissimilar welding. The two copper plates were welded with an iron wire. The effect of different traverse speeds of work piece and input power on strength and microstructure of joint is studied. Although the melting point of copper and iron are different [25]. MIG welding didn't allow much copper to melt and mix in iron.



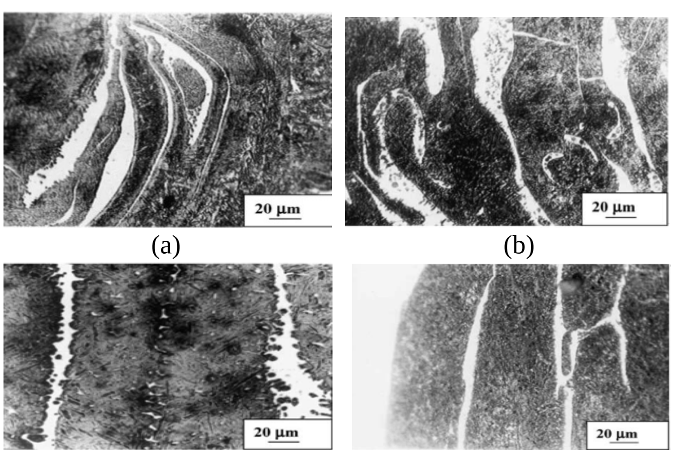
(a) (b)

Fig. 13 Low magnification micrographs of weld bead at (a) low heat input (28 V, 275 A, 325 mm/min) and (b) high heat input (28 V, 275A and 225mm/min) [24]



(a) (b)

Fig. 14 Microstructure revealing copper network in the weld processed at 32V, 200A and 225 mm/min. [24]

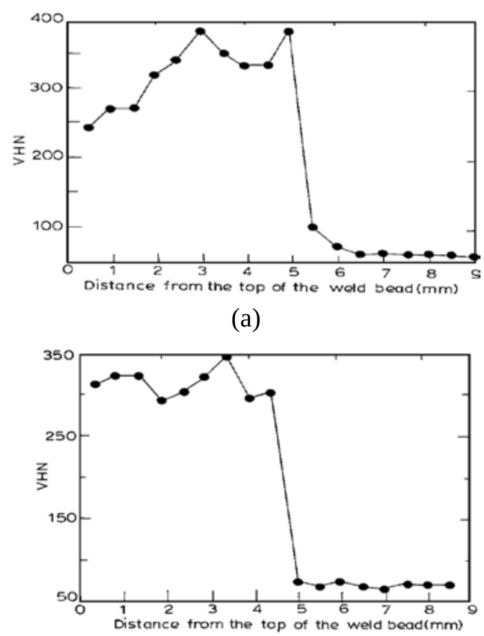


(a) (b) (c) (d)

Fig. 15 Banded morphology of weld bead-base metal interface at (a) 30 V, 215 A, 225 mm/min and (b) 28 V, 275 A, 325 mm/min (c) 32 V, 200 A, 225 mm/min, and (d) 34 V, 235 A, 325 mm/min. [24]

The presence of copper together with BCC iron is observed in the pattern of weldment. The microstructures of top region of bed with identical transverse speed shows copper network in the patterned form. However the microstructures below the top surface show the dendrites characteristics with narrow and elongated grains in the segregated network. The microstructure of copper iron interface shows distinctly different morphology. The banded microstructure of copper and iron is observed near the interface. The nature of band does not depend on input power for the welding. The bands are broader at a slower traverse speed and narrower at higher speed.

The maximum hardness is found in the nearby region of the interface and it decrease away from the interface. The hardness is more uniform at higher scan speed than the lower. The banded microstructure clearly indicates convection driven circulation of melt. The high heat transfer from iron rich bead by copper work piece causes martensitic transformation of iron in the weld bead. The maximum heat transfer near interface serves a mile harness gradient picking near it.



(a) (b)

Fig. 16 Hardness profile along the depth of the weld bead at (a) 32 V, 235 A, 225 mm/min and (b) 32 V, 235 A, 325 mm/min. [24]

VI. Laser Engineered Net Shaping (LENS)

A functionally graded transition joint have great potential of joining dissimilar materials in variety of applications [26], [27], especially dissimilar alloys those have large difference in mechanical thermal and physical properties. The difference in stresses temperatures and other environmental conditions needs the range of material properties that often cannot be achieved in the component made with single material composition.

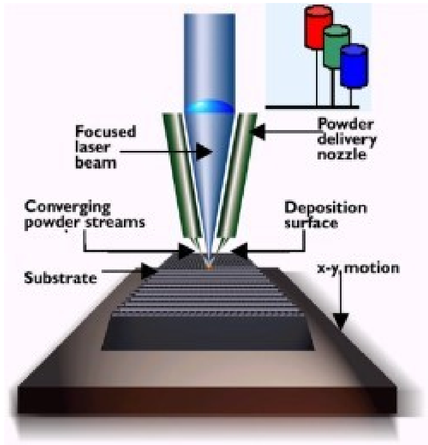


Fig. 17 Laser Engineered Net Shaping Process (LENS) [28]

Laser Engineered Net Shaping (LENS) is the metal deposition technique in which the composition and properties changes gradually as a function of position. LENS is an innovative manufacturing process that fabricates tree dimensional objects using metal powder by a combination of Laser welding and layered manufacturing [28-30]. The process use high power laser beam to create a molten pool at the target and the metal powder is injected through a nozzle into the molten pool to fabricate metals. The small molten pool protected from atmospheric properties and high travel speed of nozzle cools the deposited metal very fast producing fine grain structures [28], [31].

A. LENS for dissimilar metal weld

This technique is often used to form dissimilar metal welds between ferrite low alloy steels and austenitic alloys commonly used in fossil fire power plant. The grading of material composition avoids the sharp changes in microstructure and properties of joining metals at the interface. The changes are extended over the length of the component prevents the premature failure. The DMW formed using LENS technique exhibits optimized mechanical properties compare to joints formed by conventional fusion welding process [32].

The research of Brett S. Snowden [28] at Leigh University consists of developing DMW joints to reduce the stress concentrations at the interface due to sharp changes in properties. This research has proposed grading of metals in a continuous way from stainless steel along with modifying the geometry to reduce the stresses. It is observed that there are essentially three factors that generated the stress concentration in DMW at the interface: different thermal expansions of materials, different elastic properties and non-uniform geometry. The Finite Element model developed has produced exceptional results with 80% reduction in maximum stress with reducing the overall size of the joint. It has also been observed that the reduction in stress is best suited when the grading is done by 50 to 120 material layers. The increase in number of layers has yielded the considerable amount of reduction in stresses at the interface in linear grading model.

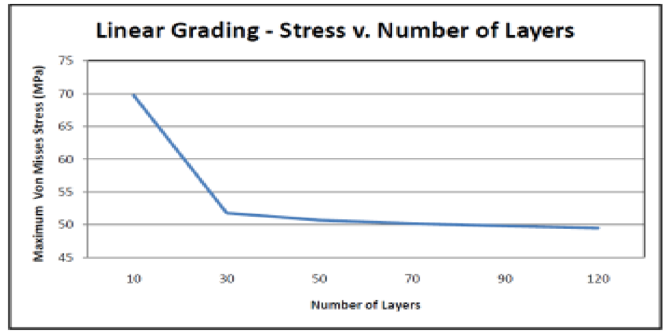


Fig. 18 Plot illustrating the decrease in maximum stress found by increasing the number of grade layers used in Linear Grading Scheme [28]

VII. Conclusion

A review on fusion welding processes for dissimilar metal joints is observed, where stress concentration is a major issue triggering premature failure. The experimental observations with LBW show an asymmetry in joints, due to different melting points of metals which causes penetration on the other metal of high melting point. In TIG welding 1mm thickness steel sheets produces partial penetration due to dissimilar metals. By varying welding speeds, intermetallic layer thickness also varied and spawned coarser microstructure in aluminum alloy. With an expenditure of MIG welding, the banded microstructure of copper and iron is observed near the interface. Due to different melting point, MIG does not consent copper to melt with iron, which leads to penetration. By observing LENS welding, stress concentration is mostly spiked due to increase in number of layers generated at the interface in linear grading model.

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