Applications and challenges of arc welding methods in dissimilar metal joining

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Abstract. Dissimilar metal welding is a significant metal joining process with an extensive application in industrial domain. The quality of the welded joint is of critical importance in these applications and quite an issue since the base metals are different primarily due to different physical, chemical and mechanical characteristics. In this paper, the challenges encountered in dissimilar metal joining are enlisted with a brief discussion on the corresponding causes. As discussed in the literature, several methods exist to form dissimilar joints. However, arc-based fusion methods are prominently used. Therefore, an overview of these methods is presented along with the applications in which these methods have been used. The study provides a brief account of the materials that have been successfully joined using these methods and the influence of significant parameters including filler materials on the effectiveness of dissimilar joining.

1. Introduction
Dissimilar metal welding is the joining of two metals that have different chemical and mechanical properties. The difficulty to weld these metals arises due to different behavior and the existence of different alloys systems [1]. These types of joints are required in several applications such as automotive assembly lines, construction industries as well as power plants [2]. The significant criteria for the materials involved in such a diverse environment are the ability to withstand extreme working conditions. In addition, the use of dissimilar metal welded joints minimizes the overall cost in the relevant applications. These joints ensure the optimum design of welded components suitable for the specific applications. It enables the usage of appropriate materials, which subsequently enhances the damage tolerance of the components as required in several applications [3]. For instance, the designer can use high-cost material with superior properties only in case of critical requirements.

The major concern with dissimilar joints is their reliability, which is a function of the weld zone. Also, the metals to be welded consists of a mixture of materials with different compositions. Moreover, in practical applications, the material properties of the base metals are known. Hence, when these metals are joined, large magnitudes of thermal and residual stresses arise owing to unevenly distributed heat [4]. The key challenges in dissimilar joining are stated in the subsequent sub-section.
1.1. Challenges in welding dissimilar metals

The challenges posed by the process of dissimilar metal joining, which are to be accounted for in order to enable its application at the industrial scale [5, 6] are as follows.

- The formation of a transition zone between the joining dissimilar metals: The strength of welded joints depends on the solubility of joining metals. The metals with good mutual solubility form high strength joints. The metals with little or no solubility when joined pose strength related issues.
- The formation of undesirable intermetallic compounds (IMCs): IMCs increase the crack sensitivity thereby making the welded joints susceptible to corrosion. Also, the compound layer formation reduces the ductility of the welded component.
- Different coefficients of thermal expansion: The varying thermal contraction of weld metal and joining metals creates residual stresses in welds. The residual quantity and distribution of these stresses are different across the dissimilar weld joint (DMW). The wide difference in these residual stresses develops internal stresses in HAZ leading to service failure.
- Different melting points of joining metals: It causes one metal to melt and overheat before the other when subjected to the same amount of heating, thereby producing residual stresses.
- The difference of the electrochemical potential of joining metals: This may increase the susceptibility to corrosion at HAZ. Two metals of extremely different electrochemical potential scale may cause a high amount of corrosion. All these challenges are linked to the chemical, physical and metallurgical characteristics of the metals to be joined.

The welding of dissimilar metal is possible only when the joining metals are soluble with each other. There exist numerous welding methods to produce high strength dissimilar metal welds. These are classified broadly into three types as shown in figure 1. The methods based on arc welding are more commonly used to join dissimilar metals in power and processing industry. The welding methods under this category are, shielded metal arc welding, gas tungsten arc welding, gas metal arc welding and submerged arc welding which are abbreviated as SMAW, GTAW, GMAW and SAW respectively. An important point to be considered is that alloying of base metals and filler metals is critical and need special consideration while forming dissimilar metal welds [7]. The other category of methods is the low dilution methods. Electron beam welding, laser beam welding, abbreviated as EBW and LBW respectively, pulse arc welding (PAW) are three major methods under this category. While third category designated as non-fusion welding methods comprises of FSW-friction-stir welding, USM-ultrasonic welding and ERW-electric resistance welding, diffusion welding are used for special applications where less amount of alloying is observed between the joining metals [8].
In this paper, a discussion on arc welding methods that have been used in joining of dissimilar metals along with their types and applications is presented. The aim is to consolidate the knowledge pertaining to the domain of dissimilar joining using such methods that could serve as a reference for relevant future research.

2. Fusion welding methods for joining dissimilar metals
In fusion welding, two metals are melted by heat source and fused together. An electric arc produces the required heat for welding or the heat is also derived from electrons or photons beams, or by the resistance offered by metals to passing of the electric current. Few fusion welding processes requires pressure to join two metals. The need and type of filler material is decided by the requirement of joining process [9]. The fusion welding methods have been successfully used for joining combinations of various metals. However, fusion welding faces many challenges due to formation of brittle IMCs at weld zone along with segregation of melting phases [10]. Development of residual stresses due to compositional difference of joining metals is another significant issue in this method. In spite of this, fusion welding is most preferred technique in joining of different types of ferrous alloys [7].

The fusion welding processes are further classified according to the source of heat generation as listed in table 1.

| Methods of Heat Generation |
|-----------------------------|
| SMAW | EBW | Spot Welding |
| GTAW | LBW | Seam Welding |
| GMAW | | Flash Welding |
| SAW | | Upset Welding |

Table 1. Classification of fusion welding methods.
3. Arc welding methods for dissimilar metal joining

Joining of dissimilar metals has been performed extensively using arc-based fusion welding. The arc is produced by electrical means in these processes. Brief description of these methods is presented in the following sub-sections.

3.1. Gas Tungsten Arc Welding (GTAW)

GTAW is also known as tungsten inert gas- TIG. Tungsten electrode is used produce the weld. It doesn’t get consumed. The arc developed between the workpiece and electrode melts the metals to be joined to form the weld pool [11]. The use of filler material depends on thickness of metals. Argon or helium or sometimes mixture of both is used to protect electrode to avoid oxidation [12]. It is most suited to weld thin sections due to lower heat inputs and can be performed on variety of metals.

3.2. Gas Metal Arc Welding (GMAW)

In GMAW, metals are joined by melting them with electric arc formed between a filler wire (electrode) and base metals. The gas is used to protect the weld from undesirable atmospheric ingress during solidification of molten weld pool. The inert gases like argon and helium are often used for protecting the arc and the molten weld pool. Hence, GMAW alternatively is called the metal-inert gas (MIG) welding process. The process is very clean due to use of inert shielding gas. It produces a uniform and slag-free weld zone [13].

3.3. Shielded Metal Arc Welding (SMAW)

A flux-coated electrode is used in this process to join the metals. The heat is produced by passing an electric current through the electrode. The molten metal is protected from atmospheric air by gaseous shield. It produces clean weld due to protection of electrode by slag. SMAW is mostly used for welding high-strength steels susceptible to hydrogen cracking [13].

3.4. Submerged Arc Welding (SAW)

In this process, base metals are joined by melting them using high energy arc produced between consumable wire electrodes and base metal. The arc is shielded by molten slag and granular flux therefore no separate shielding gas is required. It is used to joint thick sheets where long longer welds [12].

Following section discusses the state of research in the area of dissimilar metal joining using arc based welding methods causing complete fusion of the base metals.

4. Arc welding methods: Application overview

Even though there are several challenges in dissimilar metal joining, significant amount of research has been done to investigate its feasibility and effectiveness in terms of properties exhibited by the joints. In the subsequent sub-sections, a brief review of significant applications of each of the arc-based fusion welding method used in dissimilar metal joining have been presented.

4.1. Applications of GTAW

This method is used for welding of different ferrous and nonferrous metals such as steel and its alloys, aluminium and its alloys, titanium and its alloys. In the case of dissimilar metal welding using the GTAW, selection of filler metal becomes very important due to the varying base-metal composition [14].

Borrisutthekul et al. [15] and Lin et al. [16] investigated the feasibility of using GTAW to form the joint between steel and aluminium alloys. It has been reported that this welding technique can be effectively used to weld aluminium, stainless steel and titanium. However, some limitation in reliability and strength were experienced. Khalid et al. [17] experimentally investigated the dissimilar metal welds of
ferrous and nonferrous metals such as steel and aluminium formed by GTAW. It was found that the accuracy and quality of weld formed has been greatly influenced by various welding parameters like power supply, welding speed and shielding gas.

Dissimilar metal welding of 5A06 aluminium alloy and AISI 321 stainless steel was carried out using GTAW [18]. The effect of filler metal on the surface of the welding groove and metallurgical characteristics of the joint was also studied. Liu et al. [19] investigated dissimilar metal weld of magnesium (Mg) alloy and copper (Cu) as lap joint prepared using GTAW welding using iron (Fe) as an interlayer. The welded joint fractured at the intersection of Fe plate and Mg alloy during tensile testing. The mechanical properties of the joint decreased at interface between Mg and Fe due to formation of metallic oxides. Lin et al. [16] performed investigation on dissimilar metals welds of aluminium alloy and galvanized steel formed by GTAW brazing. The purpose was to study aluminium filler metal distribution over the surface of steel. The results of mechanical testing on the welded joint revealed that a zinc-coated layer has improved the dispersion of liquid aluminium filler metal on steel surface. The fusion zone near aluminium showed coarse grains due to grain coarsening. Improper brazing performed at the root of the lap joint decreased the strength of joint causing fracture at same location.

Arivazhagan et al. [20] compared properties dissimilar metal weld of SS 304 and 4140 low alloy steel formed by GTAW, EBW and friction welding techniques. The weld formed by EBW exhibited higher tensile strength relative to GTAW and FSW joints. On the other hand, ductility of weldment formed by EBW and GTAW were larger than weldment by friction welding. The GTAW weldment showed highest impact strength in comparison to other welding processes.

Bonaventur et al. [21] evaluated residual stresses in weld between ferritic steel and 316 stainless steel. The welds were made with and without the use of Inconel-82 for buttering process on ferritic steel side. The failure test carried out revealed that the failure has occurred in the HAZ of ferritic steel side. It was observed that residual stress in the welded joints was a significant factor that caused failure of welded joints. It was also investigated that buttering of Inconel-82 applied in the welded joint helped to reduce residual stresses developed in the HAZ of the ferritic steel and ultimately avoided failure at lower stress values.

Qinglei et al. [22] investigated hardness and element distribution and phase constituents in microstructures of welded joint of Mo-Cu composite and 18-8 cutlery stainless steel formed by GTAW using Cr-Ni filler wires. Higher micro hardness was measured at the weld zone due to formation of γ-Fe (Ni) phases and Fe0.54Mo0.73 compound. The microscopic observations revealed the presence of austenite as well as ferrite phases in the weld zone. In addition, increase in micro hardness was observed at the boundary of fusion zone between composite material and weld zone. The maximum micro hardness was observed at interface between fusion zone and composite as hard and brittle intermetallic compounds layer of Mo and Cu was formed.

4.2. Applications of GMAW

This method is widely used for joining of the variety of metal combinations [23]. Strong welds of dissimilar metals are obtained for metals that do not mix in solid-state but mix in the liquid state. The filler metal used has a great effect on weld zone composition. The important factors that decide the quality of dissimilar metal welds are the current and the speed of arc travel [24]. The method is widely used to form dissimilar metal joints of ferrous alloys as well as alloys of aluminium and copper.

Kumar et al. [25] investigated the weld of copper plates with iron filler using GMAW with special focus to understand the microstructural changes occurring during the process. The welded joint produced higher hardness at the weld zone. The effect of coating of aluminium and galvanized steel on dispersion of fusion metal was studied by Murakami et al. [26] in the joining of 2B50 aluminium and 1Cr18Ni9Ti steel alloy. Wang et al. [27] investigated microstructure of aluminium and magnesium DMW with Al-Si5 filler metal formed by cold metal transfer-CMT GMAW. The microstructural observations showed the formation of brittle intermetallic compound in the weld metal due to use of low heat input during the welding and addition of silicon as filler metal. Pure copper filler was used in the process of joining
Mg and Al [28]. The microstructure observations showed that weld of Mg and Al with moderate bonding strength could be successfully formed using CMT technique.

In the similar studies using this method, butt weld between 304 stainless steel and carbon steel was formed using ER309 filler metal [29] while welding between AA6082 aluminium alloy and AA6092/SiC/25p composite was performed [30].

Ul-Hamid et al. [29] investigated the butt weld between 304 stainless steel and carbon steel formed by MIG using ER309 filler metal. The metallurgical analysis revealed cracks at the intersection of weld root. The interface exhibited the formation of hard martensitic phase due to carbon separation at the temperature of welding followed by quenching. Ferrite formation was observed in the carbon steel near the weld zone primarily due to diffusion.

Lean et al. [30] studied the weldability of dissimilar metal weld of AA6082 and AA6092/SiC/25p composite using gas metal arc. The investigations were carried out on two joints formed by using ER5356 and ER4043 filler metals. Both joints showed similar tensile strength, but less than the similar metal joint of only aluminium alloys. In both joints, the fracture occurred at HAZ of AA6082 aluminium alloy. The heat treatment performed after welding increased the tensile strength of the joints and was equal to unreinforced aluminium alloy.

Taban et al. [31] analysed the mechanical and metallurgical characteristics of dissimilar metal welds of ferritic stainless steel and S355 structural steel formed by shielded metal arc (SMA) welding using AISI 309 as a filler metal. The fracture occurred in base metal during tensile testing. The HAZ exhibited low toughness of about 17 J to 30 J when measured by charpy impact test.

4.3. Applications of SMAW
Verma et al. [32] investigated inter-granular corrosion behaviour of dissimilar duplex stainless steel and 316L austenitic stainless steel formed by SMAW process. The joint was formed by using duplex 2209 electrode with variation in heat input that resulted in formation of ferrite at interface due to higher cooling rate. Also, high heat input had enhanced corrosion resistance owing to formation of large amount of austenite [26].

Comparison of electrode performance was carried out by Bala, et al. [33]. Dissimilar metal joint of duplex stainless steel (DSS) to carbon steel (CS) formed by SMAW using E2209 and E309 electrodes were investigated. It was found that the joint formed with E2209 electrodes showed better hardness and toughness than that formed with E309 electrode. On the other hand, E309 resulted in superior resistance to corrosion but it showed very high pitting susceptibility. The study by Lee et al. [34] developed DMW of Alloy 690 and SUS 304L using SMAW with Ti as a filler material. It has been inferred that Ti addition leads to increased elongation of the weld. At the same time, tensile strength remains unaltered. However, at a larger percentage of Ti content, reduced tensile strength was observed owing to reduced joint weldability.

The hardness and microstructures of super-austenitic stainless steel alloys joints was investigated. The base metals showed austenitic structures whereas weld metals showed dendritic structure. Larger hardness was observed in the weld zone due to faster cooling and thermal cycle during welding. This resulted in decrease in yield stress and the toughness is also observed in weld zone compared to base metal [35].

4.4. Applications of SAW
Labanowski [36] worked on determining the outcome of varying process parameters of SAW on the metallurgical behaviour of welded joint of Duplex 2205 and austenitic 316L steels. Microstructure observations indicated no excessive segregation of ferrite in heat affected zones (HAZ) of the welds. The lowest stress corrosion cracking resistance is observed at HAZ of duplex steel. This was due to the formation of large coarse ferrite grains and precipitation of austenitic phase. A novel application in the form of narrow-gap, SAW was evolved to study the fatigue behaviour of base metals (BM), HAZ and weld zone of the joint of advanced 9Cr and CrMoV steels [37].
The welded joint of chrome molybdenum steel ASTM A387 Gr.12 and ASTM A240 TP 304L formed by explosion welding, submerged arc welding and hot rolling were experimentally investigated by Branko et al. [38]. The as-welded (AW) as well as post heat treated (PHT) specimen were tested for measuring shear strength and impact energy. It was fond that PHT samples had significantly modified impact energy of the joint. The cladding procedure used in welding as well heat treatment had also affected the shear strength of the joint.

5. Conclusion
Dissimilar metal welding is a critical area in the field of materials engineering as well as manufacturing. The process of welding is significantly influence by the properties of the two base metals being joined. Even a slight change in composition critically affects the weld metallurgy and quality. The paper has focussed on providing an overview of arc-based methods used in dissimilar metal joining and presented an account of their applications in joining combination of materials such as aluminium-magnesium alloys, steel-steel alloys, copper-magnesium alloy, aluminium–steel alloys etc. The effect of addition of filler metals in terms of improved metallurgical properties have also been discussed along with welding parameters. The study provides a consolidated information of dissimilar metal welding formed using various types of arc welding methods that is useful for future research.

6. References
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