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DISSIMILAR METAL WELDING IN MODERN ENGINEERING APPLICATIONS: A REVIEW OF CURRENT TRENDS AND FUTURE PROSPECTS

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Abstract
Dissimilar metal welding (DMW) enables the integration of diverse material properties to enhance performance in modern engineering systems. It supports weight reduction, increased strength, and improved corrosion resistance across various industries. This review presents the major challenges in DMW, including residual stress, brittle intermetallic formation, and metallurgical incompatibility. Welding methods such as GTAW, FSW, and explosion welding is evaluated for their effectiveness. Recent developments such as artificial intelligence (AI)-based optimization, additive manufacturing, and simulation techniques are discussed. The paper also outlines future research prospects with a focus on sustainability and Industry 4.0. Overall, DMW plays a critical role in the evolution of high-performance, lightweight, and corrosion-resistant structures.

INTRODUCTION

Welding is a manufacturing process used to form permanent joints by fusing the surfaces of materials, with or without the application of pressure and filler materials. The materials involved may be either similar or dissimilar [1]. Heat for welding is typically generated by an electric arc or gas combustion, with the former being more widely adopted due to its speed and efficiency [2]. Welding is crucial in modern fabrication, replacing traditional methods like forging or casting and serving as an effective alternative to bolted or riveted joints. It is also widely used for repair applications, such as rebuilding worn surfaces or fixing cracks [3].

Joining of dissimilar metals has found its use extensively in nuclear reactors, petrochemical, electronic, power generation and chemical industries mainly to get tailor-made properties in a component and reduction in weight. However efficient welding of dissimilar metals has posed a major challenge due to difference in thermo mechanical and chemical properties of the materials to be joined under a common welding condition. This causes a steep gradient of the thermo-mechanical properties along the weld [4]. A variety of problems come up in dissimilar welding like cracking, large weld residual stresses, migration of atoms during welding causing stress concentration on one side of the weld, tensile thermal stresses and compressive, stress corrosion cracking, etc. Before discussing these challenges, it is important to understand their underlying causes. In dissimilar welds, weld ability is determined by atomic diameter, crystal structure and compositional solubility of the parent metals in the solid and liquid states [5]. Diffusion in the weld pool often results in the formation of intermetallic phases, the majority of which are brittle and hard and are thus detrimental to the ductility and mechanical strength of the joint. The thermal conductivity and thermal expansion coefficient of the materials being joined are different, which causes consequently the residual stresses and large misfit strains result in cracking during solidification.

Joining of two different metals with different mechanical, physical and chemical properties plays an important role in modern engineering applications. It enables engineers to incorporate into a single component the advantages of several materials, such as high strength, heat resistance, and corrosion resistance. In different industries such as power generation, automotive, aerospace and chemical processing this technique is widely used due to demand of high performance. Additionally, this technique lowers production. The review also highlighted costs, improving efficiency and reducing weight Moreover, dissimilar welding supports the service life of components in harsh environments and development of advanced hybrid structures [6].

2. Challenges in Dissimilar Metal Welding

2.1 Differences in Thermal, Mechanical, and Chemical Properties

Dissimilar metals usually have different expansion rates and heat conductivities. These differences could lead to weak joints or cracking, uneven heating and solidification, and cooling during welding. Additionally, there may be mismatches in strength and ductility at the weld zone due to their different mechanical properties [7].

2.2 Metallurgical Incompatibilities

Poor fusion may result from the different alloying elements of dissimilar metals not mixing well when they are joined. This incompatibility can compromise the mechanical integrity and long-term performance of the weld by causing brittle phases to form, segregation, or a lack of bonding [7]

2.3 Formation of Intermetallic Compounds

Certain metal combinations can create intermetallic compounds at the weld interface when heated to high temperatures. Usually hard and brittle, these substances weaken the joint's ductility and strength and increase its vulnerability to cracking under stress or heat cycling [7].

2.4 Residual Stresses and Distortion

Welding dissimilar metals can result in an uneven distribution of stress as the weld cools because of their varying rates of thermal expansion and contraction. Warping, dimensional errors, or early failure under service conditions can result from the joint's residual stresses and distortions, which are frequently caused by them [8].

3. Commonly Welded Dissimilar Metal Combinations

3.1 Low Alloy Steel to Stainless Steel

Low alloy steel is frequently welded to stainless steel for pressure and structural applications. The risk of brittle phase formation and variations in thermal expansion present a challenge. The metallurgical gap is frequently filled with special filler metals like ER309L [10].

3.2 Stainless Steel to Nickel Alloys

This combination is used in high-temperature and corrosion-resistant environments, such as chemical plants. The weld must manage differences in thermal conductivity and prevent the formation of intermetallic compounds. Nickel-based fillers like Inconel 82 or 625 are typically used [10].

3.3 Titanium to Aluminum or Steel

Titanium cannot be directly welded to aluminum or steel due to the formation of brittle intermetallics. Instead, solid-state welding techniques like diffusion bonding or explosion welding are used. These are common in aerospace structures where weight and strength are critical [10]

3.4 Other Critical Combinations in Aerospace, Automotive, Nuclear

Many industries rely on dissimilar welding when components must join together without compromising their best features-lightness, strength, or resistance to rust. Joining aluminum and steel in car frames, or copper and stainless pipe in a nuclear plant, are classic cases. Each task demands careful heat management and the right technique or the bond will fail [10].

4. Welding Processes Used for Dissimilar Metals

4.1 Gas Tungsten Arc Welding (GTAW/TIG)

GTAW uses a non-consumable tungsten electrode and inert shielding gas to produce a high-quality weld. It's ideal for precise, clean joints in metals like stainless steel, nickel alloys, and titanium. Filler metal can be added separately [13].

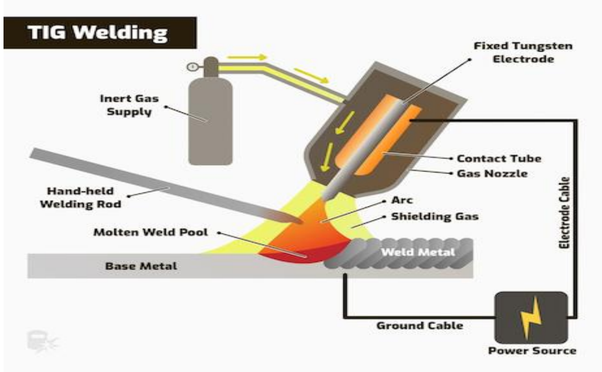

Fig.01 Gas Tungsten Arc Welding

4.2 Gas Metal Arc Welding (GMAW/MIG)

GMAW uses a consumable wire electrode and a shielding gas to create a weld pool. It's widely used due to its automation potential and ease of operation, especially for steel-to-stainless joints [13]

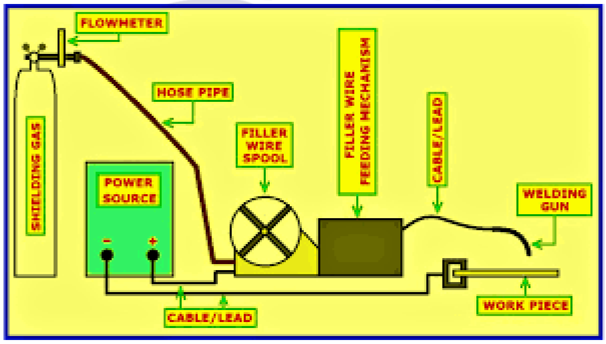

Fig.02 Gas Metal Arc Welding

4.3 Laser Beam Welding (LBW)

LBW utilizes a focused laser beam to melt materials, offering deep penetration and low distortion. It's effective for high-precision dissimilar joints like steel to aluminum[13].

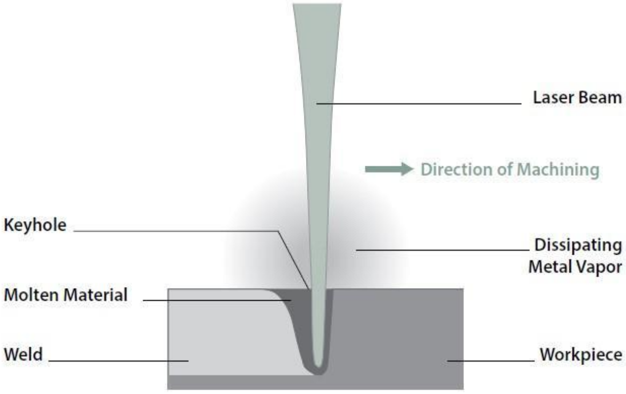

Fig.03 Laser Beam Welding

4.4 Friction Stir Welding (FSW)

FSW is a solid-state process using a rotating tool that stirs the metals together below melting point. It's highly effective for aluminum to steel or aluminum to copper[13].

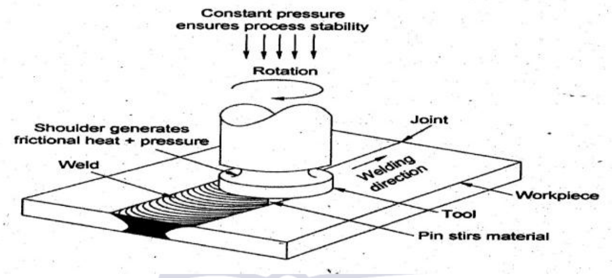

Fig.04 Friction Stir Welding

4.5 Explosion Welding and Solid-State Techniques

Explosion welding uses controlled detonation to bond dissimilar metals at high velocity. Solid-state methods like diffusion bonding and ultrasonic welding avoid melting, reducing defects [13].

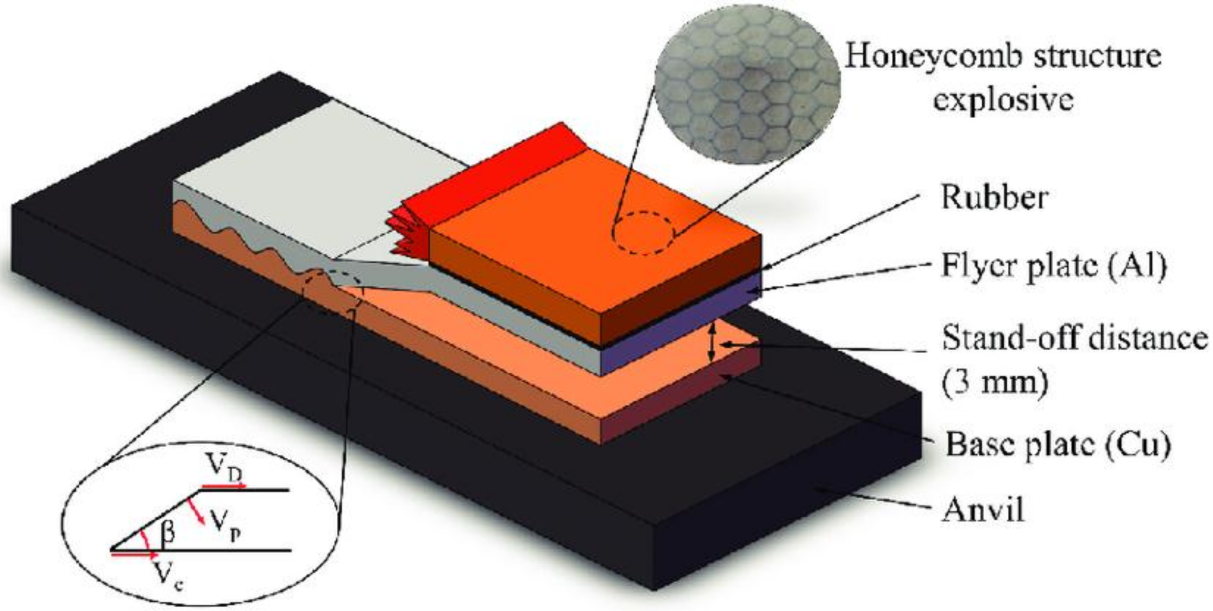

Fig.05 Explosion Welding and Solid-State Techniques

4.6 **Hybrid Welding Techniques**

Hybrid welding combines two methods (e.g., laser + GMAW) to improve penetration and fill capability. It's suited for complex and thick dissimilar joints [13].

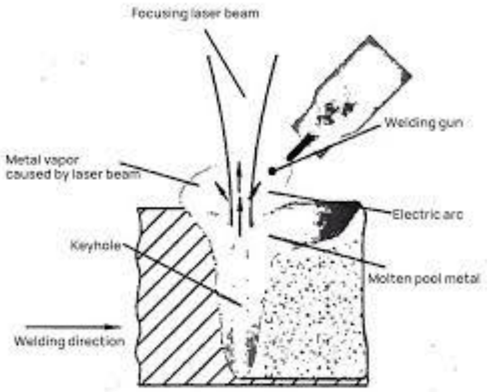

Fig.06 Hybrid Welding Techniques

comparison of common welding processes on the basis of heat input, joint quality, cost, and application area are given in table 01

Table 01 comparison of common welding processes

Welding process	Joint quality	Cost	Heat Input	Application field
Gas Tungsten Arc Welding	Excellent	Moderate to high	Low	Pressure vessels, nuclear industry , Aerospace
Gas metal Arc Welding	Good	Low to Moderate	Moderate	Pipelines, Automotive

Laser Beam Welding	Very high	High equipment cost	Very low	Aerospace, micro welding
Friction stir welding	Excellent	High equipment cost	Low	Automotive, ship building, nonferrous alloys
Explosion welding	Very high	High special setup	No external heat input	Bimetallic joints, nuclear and cryogenic applications
Hybrid Welding	Good	Excellent for consistency	Medium	Automotive structural parts , heavy manufacturing welding

5. Selection of Filler Materials

5.1 Role of filler metals in reducing defects

Filler metals are key to cutting down welding flaws such as porosity, cracks, and spots of lack-of-fusion. Choosing one that matches the parent metal both chemically and mechanically gives the weld pool better compatibility. In turn, that boosts joint strength and lowers the chance of failure once the part is in service [16].

5.2 Filler wire compatibility and design

The filler wire must be compatible with both base metals in terms of composition and melting characteristics. Specially designed filler wires may include alloying elements that enhance bonding, reduce residual stress, or control the formation of brittle intermetallic compounds in dissimilar metal welds [16]. Nickel-based filler wires are frequently used in aerospace applications to weld stainless steel to nickel alloys, minimizing hot cracking and guaranteeing high-temperature strength. ERNiCr-3 filler metal dramatically increased weld toughness and reduced intermetallic formation, according to a study on welding Inconel to stainless steel.

6. Post-Weld Treatments and Their Effects

6.1 Post Weld Heat Treatment (PWHT)

PWHT is a carefully managed step in welding work; workers heat the joint to a set temperature, hold it there for a fixed period, then allow it to cool in a controlled way. Raising the metal that way makes it tougher, cuts back on brittle hardness, and eases the leftover stresses locked inside. As a result, the piece gains better strength and is less likely to crack under pressure. For critical jobs such as pipelines and pressure vessels, PWHT is simply essential [17].

6.2 Mechanical and Thermal Treatments

These include processes like peening, rolling, and controlled cooling. Mechanical methods improve fatigue resistance by inducing compressive stresses. Thermal techniques stabilize microstructures, reduce distortions, and refine grain size. Together, they enhance structural integrity and dimensional stability of welded joints [17].

6.3 Surface Modification

Surface modification increases the longevity of the weld area and strengthens its resistance to wear and corrosion. Cladding involves putting a layer of corrosion resistant metal, whereas coating like thermal spray produce a protective barrier. These techniques are widely used in difficult environments such as offshore, chemical and aerospace industries [17]

7. Microstructural and Mechanical Behavior of Dissimilar Metal Welding Joints

7.1 Microstructural Transitions and Interface Zones

The fusion of various metals creates intricate microstructural variations across the weld interface in Dissimilar Metal Welding joints. These transitions frequently result in carbide precipitations, heat-affected zones (HAZ) with different grain sizes, and the possible development of brittle intermetallic compounds. Because a mismatch in diffusion rates and thermal conductivity can lead to micro crack development and stress concentration, the interface zone is crucial [20].

7.2 Hardness, Tensile Strength, Impact Toughness

The weld's hardness varies greatly, with higher hardness being seen close to the fusion line because of quick cooling and phase changes. Tensile strength is usually lower at the interface than base metals and is dependent on the welding settings and filler material. Because of embrittlement and microstructural alterations, impact toughness is diminished close to the HAZ, particularly if intermetallics or grain coarsening take place [20].

7.3 Fracture and Fatigue Behavior

Interface integrity affects fracture behavior; under tensile or thermal stress, cracks frequently start at the fusion boundary or HAZ. Because cyclic load is concentrated at mismatched mechanical zones, Dissimilar Metal Welding joints have less fatigue resistance than comparable metal welds. Crack propagation under repeated loading is accelerated by residual stresses and microstructural inhomogeneity [20].

8. Corrosion and Environmental Resistance

8.1 Galvanic corrosion in dissimilar joints

Galvanic corrosion occurs when two dissimilar metals are electrically connected in a corrosive environment, causing the more anodic metal to corrode faster. This is a common issue in dissimilar metal welding joints. Proper selection of compatible filler metals and electrical insulation between the metals can help reduce this effect. Surface coatings or cathodic protection are also used to control galvanic action [23].

8.2 High-temperature oxidation

At elevated temperatures, welded joints may suffer from oxidation, especially when exposed to oxygen-rich environments. This can degrade the protective oxide layers on metals like stainless steel, leading to material loss and weakening of joints. High-temperature coatings or using oxidation-resistant alloys helps mitigate this. Welding parameters must be controlled to reduce oxidation during fabrication [23].

8.3 Marine and chemical industry exposure

In marine and chemical environments, welded joints face aggressive corrosion due to salts, acids, and chlorides. Dissimilar Metal Welding joints are particularly vulnerable if improper filler metals are used or if there are crevices or microstructural inhomogeneities. Using corrosion-resistant materials like super duplex stainless steels, proper post-weld cleaning, and protective coatings can enhance resistance in such harsh settings [23].

9.Recent Advancements and Research Trends

9.1 Additive manufacturing involving dissimilar metals

Dissimilar metals can be joined layer by layer using additive manufacturing (AM), particularly Directed Energy Deposition (DED) and Powder Bed Fusion (PBF). This makes it possible to create components made of many materials with specific qualities. Process control and interlayer materials are being used to overcome issues including residual stress and intermetallic formation. It is extensively used for functionally graded materials in the biomedical and aerospace industries. [9].

9.2 Artificial intelligence in process optimization

Real-time parameter optimization, flaw detection, and welding outcome prediction are all being accomplished with artificial intelligence (AI) approaches such as machine learning and neural networks. These instruments improve process stability, weld quality, and minimize trial-and-error attempts. In sophisticated dissimilar metal welding, where manual control is challenging, artificial intelligence is very useful [9].

9.3 Advanced simulations and computational modeling

Temperature distribution, residual stress, and phase transformation in welded joints are investigated using Finite Element Modeling (FEM) and multiphysics simulations. Without requiring lengthy experimental trials, these simulations aid in joint behavior prediction and welding strategy optimization. By facilitating virtual prototyping, contemporary computational tools spur innovation in dissimilar metal welding [9].

10. Future Prospects and Research Directions

10.1 Emerging materials and joining techniques

In welding research, new materials including lightweight metals, composites, and high-entropy alloys are being investigated more and more. Improved control over connection quality and compatibility is made possible by advanced joining techniques like additive manufacturing, hybrid laser-arc welding, and ultrasonic welding. These methods seek to strengthen junctions made of different metals and lessen the production of intermetallic.

10.2 Sustainability **and recycling considerations**

Welding research is concentrating on lowering energy use, pollutants, and material waste as environmental consciousness grows. Priority is being given to methods that facilitate the recycling of different materials and the reuse of welded structures. Solid-state welding techniques and environmentally friendly filler materials are becoming more popular because to their low environmental impact.

10.3 Integration with Industry 4.0

Welding is becoming a smart, automated process thanks to the integration of AI, IoT, robotics, and data analytics. Adaptive control systems, predictive maintenance, and real-time monitoring enhance weld quality and lower faults. Before physical execution, dissimilar joints can be optimized and virtually tested thanks to digital twins and simulation technologies.

11. Conclusion

Dissimilar metal welding (DMW) is a critical technique in modern engineering, enabling the integration of materials with different properties to optimize performance, weight, and corrosion resistance. Although challenges such as thermal mismatch, brittle intermetallics, and residual stress persist, advancements in welding processes, filler materials, and post-weld treatments have improved joint quality. Emerging technologies like AI-driven process optimization, additive manufacturing, and Industry 4.0 are transforming the DMW landscape. Future research must focus on sustainable practices, advanced joining techniques, and smart manufacturing integration to further enhance performance and reliability in demanding industrial environments

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