Critical Study of Dissimilar Metal Welding of Different Stainless Steels

[1]Hayatu M.A.,[2]Bello, K.A.,[3]Yahaya, H., [4] Bello, L.O.
[1]Department of Welding and Fabrication Engineering, Jigawa State Polytechnic, Dutse, Nigeria
[2]Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria, Nigeria
[3] African Natural Resources and Mines Limited, Kaduna, Nigeria
[4]Defence Industries Corporation of Nigeria, Kaduna, Nigeria
[1]Corresponding author: [1]mabdullahi8003@gmail.com

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Abstract
The need for minimizing fabrication and general production cost as well as to reduce fuel consumption by adopting lighter materials for engineering applications impose the demand for dissimilar metal weld joint. Nuclear, power, petrochemicals, automobile, marine, oil and gas plants among others, are increasingly employing dissimilar metal weld joints in various structures/parts to save cost and improve performance. Stainless steel to carbon and or low alloy steels dissimilar weldment are common in engineering industries and many researches have been carried out on these combinations. However, works on dissimilar metal weld of different stainless steels are grasping attention of engineers. As a result, this study intended to review recent works on dissimilar weld joint of different stainless steels. Weldability properties and applications of different classes of stainless steels were thoroughly reviewed .Applications and welding challenges of dissimilar metal welds were also extensively elaborated. Innumerable original works were studied and information regarding dissimilar welding of different stainless steels were evaluated. Recommendations for future track of research were delivered. It was concluded that further research in dissimilar welding of different stainless steels should focus on advanced welding and manufacturing processes.

Keywords: *Stainless steels; dissimilar metal welding; microstructure; mechanical properties.*

1.0 **Introduction**

The technology of joining different materials system such as carbon steel to low alloy steel, low alloy steel to stainless steel, carbon steel to stainless steel, steel to nonferrous metal or metals to ceramics is termed dissimilar metal welding (Sadek,2015).Joining of different stainless steels is also another important example of dissimilar metal welding (Mvola *et al*.,2014; Lippold and Kotecki,2005).Nuclear, chemical, power, oil and gas ,marine, aerospace and food industries are among key areas for dissimilar metals applications (Manjunath et al.,2023; Mezher,et al.,2022;Hayatu et al., 2021).Other areas of applications of dissimilar metal welding (DMW) are petrochemicals, automobile and desalination plants (Cui et al.,2023).Among many motives for choosing dissimilar metal combinations are reduction in life cycle cost, light weight advantage and solution to many corrosion related problems (Foumani and Moosavy,2023;Hernandez-Trujillo et al.,2021;Verma et al.,2016).Stainless steels (SSs) are the most common metals applicable for dissimilar metal welds and this might be due to their outstanding corrosion resistance and high temperature strength. SSs are often welded to carbon and/or low alloy steels.Hayatu and Bello (2018) reviewed the microstructures and mechanical properties of dissimilar metal welds, but most of their reviewed works inclined to stainless/carbon steels combinations. Mvola *et al.(*2014) reviewed limited works on DMW of different SSs and proposed the possibility of welding different SSs of distinct alloy contents or microstructures; they mentioned conveniences of welding such as, using single filler metal for more than one base metals as a reason for joining different SSs. Other essential factors are economic and /or properties considerations (Jiang et al.,2023). Though, dissimilar welding of different SSs offers tremendous economic and technical advantages, there are a number of weldability challenges associated with the combination. Common examples are formation of complex metallurgical structures, carbon migration from martensitic stainless steel (SS) into austenitic SS welds, which may lead to decarburization in the former. Generation of local stresses, martensitic transformation as well as drastic reduction in toughness are amongst many weldability problems of joining different SSs (Sadek,2015;Mvola *et al*.,2014).Appropriate materials selection and welding parameters are critical in obtaining sound welds for dissimilar welding of different SSs (Bansod *et al*.,2019; Liu et al.,2016). As a result, modern technologies are moving towards searching for new materials, advanced materials processing techniques, suitable welding variables and joining processes or improving the existing ones for better serviceability and cost effectiveness in DMW joints. This study intended to critically review recent original works on dissimilar joining of different SSs with the sole aim of establishing a track for future important research in the area of DMW of different SSs.

2. 0 Stainless Steels

Iron base steel alloys that contain minimum of 11% Chromium (Cr) are termed stainless steels (Singh, 2012).This percentage of Cr is rich enough to form chromium oxide passive layer that prevents corrosion and oxidation. Other elements such as carbon (C) nickel (Ni), molybdenum (Mo), nitrogen (N) etc., are also present as alloying elements. SSs have exceptional toughness and ductility and are second to carbon steels in wide engineering applications.

2.1 Classification of Stainless Steels

SSs are best classified into five major categories according to their microstructures as Martensitic, Ferritic, austenitic, duplex and precipitation harden able (PH).Each of these groups have specific range of Cr,C and other elements. Table 1 presented a concise comparison of the various classes of SSs.

2.1.1 Martensitic Stainless Steels

Martensitic stainless steels (MSS) have the highest carbon content of all categories of SSs. The Cr content of MSS is within the range of 11.5-18% (Singh, 2012).Examples of this group of steel are: type 403,420,410,416,431,440B, CA-15 etc. Figure 1 is a microstructure of Type 403 MSS.

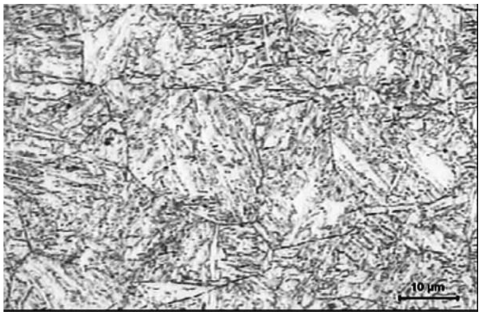


Fig.1: 403 MSS in the as received condition (Das *et al*., 2009)

2.1.2 Ferritic Stainless Steels (FSS)

This class of SSs has predominant microstructure of ferrite phase. Their Cr content is within the range of 10.5-28%.Commom examples are 405,430,409,436, 444, 25-4-4 etc.

2.1.3 Austenitic Stainless Steels (ASS)

ASS represents the largest group of all SSs and has Cr content of 16-26%.They have the advantage of unresolved formability compared to all other classes of SSs. They consist of complete austenitic structure. Most popular among ASS are 304,304L, 316 and 316L.Figure 2 is microstructure of 316L.

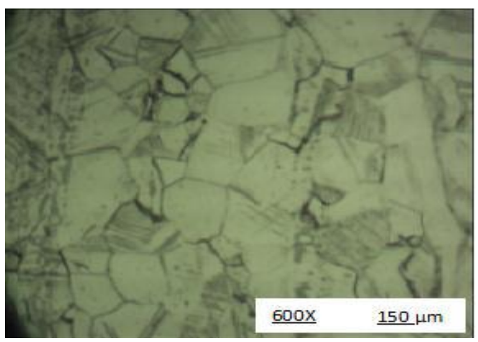
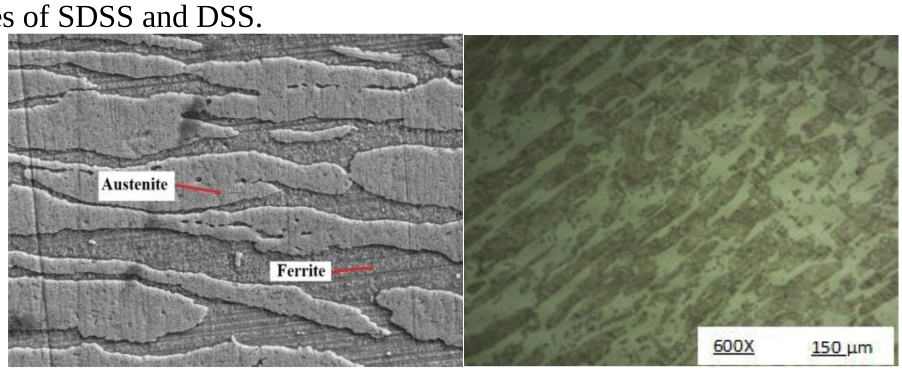


Fig.2: Microstructure of 316L (Augustine *et a*l., 2014)

2.1.4 Duplex Stainless Steels (DSS)

Duplex stainless steel (DSS) has equal ferrite and austenite phases and contains Cr and Ni of 20-30% and 5-8% respectively (Singh, 2012).DSS are sub grouped into lean duplex ,standard duplex,super duplex (SDSS) and hyper duplex(Orlowska et al.,2023) stainless steels based on their Cr content. Typical examples are 2304, 2205, 2507, CD4MCu and 329.Figure 3 denoted microstructures of SDSS and DSS.



(a) (b)

Fig.3: (a) Microstructure of SDSS (b) Microstructure of 2205 DSS (Augustine *et al*., 2014).

2.1.5 Precipitation Hardening (PH)

This is the smallest group of stainless steels and has limited applications. This group of SSs derived their strength from precipitation reaction and their corrosion resistance is moderate. They have Cr up to 16% and precipitation elements such as Ti and Al are present for precipitation hardening. Examples of PH are: 17-4PH, PH 13-8 Mo, AM 350, HNM etc.

Table 1 Comparative properties of different classes of stainless steels (Lippold and Kotecki,2005 and Singh,2012)

Properties	MSS	FSS	ASS	PH	DSS
Matrix phase	ferrite and martensite	Ferrite	austenite	austenite, martensite	equal ferrite and austenite
Key alloying elements	Cr, C	Cr, C	Cr, Ni, Mo	Cr, Ti, Al	Cr, Ni,Mo,N
Important mechanical properties	Highest strength and hardness	High tensile strength	Low temperature impact toughness and good ductility	High strength	Combination of high strength and toughness
Thermal conductivity	mederate	moderate	low	_	moderate
Thermal expansion	Low	low	high		moderate
Corrosion resistance	Low	Good resistance to SCC, crevice, and pitting.	Susceptible to SCC	Approaches ASS	Excellent resistance to pitting and crevice
Structure	BCT	BCC	FCC		
Magnetic	Yes	yes	no	Yes/no	yes
Elastic modulus(GPa)	215	220	190-200		200
formability	Low	moderate	high		moderate
HIC		susceptible	Less susceptible		Less susceptible
Weldability	Least	low	Highest	good	moderate
Prone to residual stresses	Low	low	high		low

High temperature application	Induces brittleness	Induces brittleness	Good high temperature strength		Prone to embrittlement
Marine application	Not recommended	not recommended	good	Not common	excellent
Susceptible to Hot cracking	Less	less	high	less	less
Service temperature	below 650°C	below 400°C	760°C and above	315°C	below 300°C
Hardenability	Quench and temper		Cold working	Ageing	
Possible intermediate phases	Carbides, nitrides	Carbides, nitrides	Sigma, chi, laves phases		Chi, laves and sigma phases
Specific applications	Steam, gas and jet engine blades. Steam piping, freshwater canal locks, surgical instrument, gears, and shaft.	Automobile exhaust, pulp and paper industry, water heater.	Cryogenic, nuclear reactor	Propeller shaft, turbine wheels, jet engine frame, surgical instrument, gears, space shuttle engine, missile tubes.	Risers, oil tanker tanks, water heater, marine oil pipeline
Cost	Less	moderate	expensive	Most expensive	Expensive than ASS

3.0 Reasons for Choosing Dissimilar Metal Welds

Reduction of overall cost of production/fabrication and enhancing service performance and integrity of parts/structures are the principal motives behind adopting DMW (Jiang et al.,2023). This segment highlighted various reasons for choosing DMW.

3.1 Varying Working Environments.

When a component or structural member such as pipeline/flowline is subjected to multiple or varying environments for one application, needs may arise to incorporate different stainless steels for the varying environments creating DMW (Sadek,2015).The varying environments may be high temperature and low temperature regions or corrosive medium enriched region and neutral region.In each case, two different stainless steels that best suit each environment will be employed constituting DMW.Arc welding processes remain the most reliable joining processes for steel (Casalino,2017).

3.2 Light Weight Advantage.

To reduce overall weight of a structure dissimilar SSs are employed (Ratanathavorn,2017).In many industrial applications; parts of heavy materials are substituted with lighter ones of different chemical composition (Kaya et al.,2023).Denser portion could be replaced with lighter ones that can offer equivalent required properties.

3.3 Life Cycle Cost.

The application of stainless in DMW gives the benefit of life cycle cost (material cost+ manufacturing cost+ operation cost+ maintenance cost+ scrap cost).Stainless steels have shown the capability of reducing the overall life cycle cost of structures such as oil storage tanks,pressure vessels, risers,etc.Carbon steels are replaced with different stainless steels in dissimilar welding and fabrication of different parts in oil platforms(Outokumpu,2013).

3.4 Availability and Scarcity of Materials.

Sometimes when there are scarcities of a particular grade of SS needed for urgent fabrications or maintenance, due to high production cost, delay in delivery of stocks or natural disaster such as covid-19; demand may arise where the available grade with close properties be employed so as to accomplish the intended service. Example is welding available 304l to scarce 304H or vice versa.Stainless steels are very expensive which makes them comparatively scarce compared to other steels. Thus, there will always be need to weld different available materials in fabrication or repairs of parts and structures.

3.5 Conveniences of Fabrication.

The fact that different SSs could be welded with thesame filler metal makes it convenient to weld different stainless steels where high weld quality is not priority. In other note, the capacity of some filler metal such as nickel electrode to successfully weld different SSs especially in repairs welding permits the choosing of DMW. (Hernandez *et al*.,2021; Mvola *et al*.,2014 and Outukumpu,2013).

4.0 Specific Applications of Dissimilar Metal Welds

DMW is being widely adopted in quite number of industries due to economic and technical merits. This section discussed some specific applications of DMW in various industrial plants**.**

4.1 Nuclear Plant.

SSs generally have good corrosion, oxidation and high temperature resistance which qualify them as preferable materials for application in nuclear plant. High temperature environments are common in nuclear plant due to enormous release of heat by nuclear fission in the reactor for power generation or other consumption. As a result,the combination of SSs with good creep resistance is inevitable.The DMW of 316L or 316LN heat exchanger to P91 steam generator is common in nuclear plant (Venkata *et al*., 2015; Karthick *et al*., 2018).Heat exchangers are subjected to frequent elevated temperature (above 500 ^{o}C) for a long period of time while steam generators heat water to boiling point.

4.2 Power Plant

Power plants generate electricity by steam, gas or coal firing of turbine blades. In the case of steam, boilers are used to heat ordinary water to boiling point which will subsequently rotate the turbines to create rotational motion relative to the magnetic field. The boilers and turbines are subjected to prolonged working temperature for stable power generation. This application requires creep resistance SSs that can withstand severe heating to avoid brittleness and embrittlement. Boilers are available in ASS or DSS depending on the corrosive nature of the raw water. Boilers are always welded to low alloy steel (LAS) tube system in power plant (Avery, 1991). Raw water from river or sea and steam are two varying environments in thermal power plant.

4.3 Oil and Gas and Petrochemical Plants.

Corrosive medium such as crude oil, acids, bases, cabondioxide, hydrogen gas, hydrogen sulphide, seawater, etc are common in oil and gas, chemical and petrochemical plants. Some of these fluids are transported from flowlines or pipelines to processing units such as preheating furnace, distillation column, pressure vessels and storage tanks. Some grades of crude oil may be rich in sulphur which may attack the transporting flowlines or pipelines. Thus, these pipelines must be of materials that have excellent resistance to uniform and localised corrosion. Storage tanks materials must have a good combination of corrosion and mechanical properties. DSS are known to be of excellent resistance to pitting and crevice corrosion as well as outstanding mechanical properties; this property combination certify them for structural applications. Fittings such as elbow, tee, flanges, etc often comes in austenitic SSs, may be due to their combined formability and resistance to pitting and crevice corrosion. These fittings are welded to different storage tanks, pipelines, flowlines and other load carrying members for various functions like changing the direction of fluids or volume regulation. The DMW between DSS oil tanker and ASS fitting joint in oil and gas plant is common example.

4.4 Marine Application

The passive oxide films of SSs impart them with the outstanding corrosion and oxidation resistance properties. However, when SSs structures or components are subjected to seawater applications, chlorine ions locally attack the steel member thereby deteriorating its corrosion resistance potential. SSs structures such as flowlines for subsea applications normally got immersed into the corrosive -salty sea water. This mandates the employment of highly pitting and crevice resistance SSs. In this debate, combination of high mechanical strength and corrosion resistance is principal priority. Mendoza *et al*. (2010) investigated the application of DMW for corrosion protection between SDSS and HSLA for riser structure in offshore exploration of crude oil and concluded that the joint was satisfactory. For more economic consideration, super MSS can be used in place of SDSS.

4.5 Desalination Plant.

Other applications are cladding of carbon steel pressure vessels with ASS and LAS nozzle-ASS safe end joint (Hannu *et al*., 2006).

5.0 Weldability Challenges of Dissimilar Metal Welds

Despite the numerous technical and economic benefits of DMW, there are various challenges associated with the technique. The fabrication challenges could be material-based or process-based.

(i) Filler Metal Selection: The fact that the chemical composition of filler metals influences the final structures of weld metals; it is important to choose the appropriate electrode in dissimilar metal welding of different stainless steels. This often gives a critical decision on selecting the right electrode for a particular combination (Gadallah et al.,2023;Liu et al.,2016).In application of dissimilar combination, availability and cost of the electrode must be critically considered when specifying electrode for dissimilar welding of different stainless steels (Lippold and Kotecki,2005).

(ii) Formation of Brittle Intermetallic Phases: When welding materials of different chemical compositions there are tendencies for formation of intermediate brittle phases (Tanrikulu et al.,2023). This is because some elements have low solubility or may have nil solubility and instead form intermetallic compounds (Foumani and Moosavy,2023; Amirov et al.,2023).These intermediate phases embrittle the weld joint and may also reduce the corrosion resistance of the adjoining metals. A good example is the formation of sigma phase (FeCr) between iron and chromiun during DMW involving SS.

(iii) Reduction in Toughness and Ductility: Like in conventional welding, DMW joint suffers from considerable reduction in toughness and ductility when compared with the base metals. Intermediate phases and metastable structures such as martensite when formed negate the toughness and ductility of the DWM joints. A times post heating or stress relieving operation are carried out to improve the toughness of the joints.

(iv) Residual Stresses: The rapid expansion and contraction of the adjoining metals during welding due to heating and cooling cycles left DWM joints with residual stresses; which practically affects service performance of the joints. Dissimilar Welding involving high heat inputs are more prone to generation of residual stresses (Manjunath,et al.,2023).The thermal properties, melting points,thickness and cooling rates of the adjoining metals play significant role in developing residual stresses. Stainless steels have high coefficient of thermal expansion and thus are susceptible to generation of residual stresses .

(vi) Solidification Cracking: Solidification or hot cracking occurs when their is insufficient liquid metal in the weld pool to fill the gap. Impurities and high strain in the weld pool also cause solidification cracking.Solidification cracking is a common complication of DMW (Jiang et al.,2023; Karthick *et al*.,2018;Bettahar *et al*., 2015).Figure 4 showed crack in DMW joints. Appropriate materials selection and optimization of processing parameters can adequately eliminate or minimise solidification cracking.

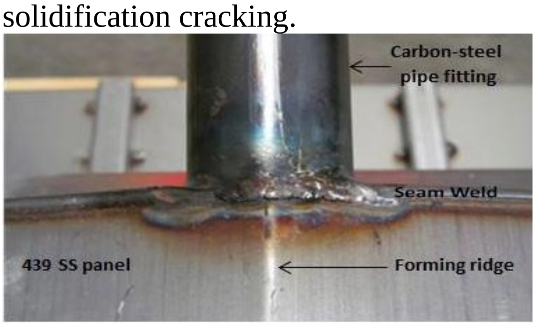


Fig.4: Crack in DMW joint between 439SS oil tank and carbon steel pipe fitting (Wang, 2016)

6.0 Combinations of Different Stainless Steels Welds

The fabrication of different classes of SSs is common in many production and manufacturing plants, as a result; different grades of SSs from various classes are welded to establish dissimilar metal welds.In this sections, different combinations of dissimilar SSs with respect to weldability challenges are discussed.

6.1 Austenitic + Ferritic Stainless Steels: The combination of austenitic to ferritic stainless steel may be for the reason of availability and cost since ASS are expensive than FSS.Example of this combination is welding AISI430 to AISI304L.ASS are suitable for elevated temperature applications while FSS have excellent resistance to hot cracking with comparatively low thermal expansion coefficiient than ASS. ASS filler metal is recommended for this combination. Panchcikiewicz et al.(2020) reported martensitic and intermediate phases transformations in weldmetal of AISI430/AISI304 dissimilar joint (Table 2).

6.2 Austenitic + MSS Steels: In this combination, the high carbon content in MSS is likely to induce martensitic transformation and brittleness within the weldmetal; and for this reason extreme care must be observed when selecting filler metal.Carbon diffusion from MSS may lead to weld decay thereby destroying the corrosion resistance of the steel. Therefore, this combination may not be favourable for high temperature service applications and thus, ferrite-forming filler metal may be better for this combination.Creep failure,coarse chromium carbides and laves transformation were reported in the fine-grained HAZ of MSS in DMW between 304H and T92 MSS (E et al.,2023).

Table 2: Dissimilar Welding of Different Stainless Steel

Author	BM	Process	Electrodes/filler metals	Materials thickness(mm)
Hernandez *et al.*,2021	2205+316L	GMAW	ER2209	6.35
Panchcikiewicz *et al.*,2020	AISI 430+AISI304	LBW	autogenous	D25
Rodriguez *et al.*,2020	2304+2507	GTAW	Ni powder	3.00/2.00
Taheri *et al.*,2020	2205+316L	GTAW	ER2594/ER 312/ER385	
Topcu *et al.*,2019	**304+316L**	**RSW**	**autogenous**	**1.00**
Bansod *et al.*,	**Cr-Mn SS+304**	**GTAW**	**316L/310/308L**	**3.00**
Ubertalli *et al.,2018*	**2101+304**	**SMAW/GTAW**	**-**	**4.00/**
E et al.,2023	**304H+T92**	**GTAW**	**ErNiCrFe-7A**	
Tandon et al.,2023	**316L+201**	**GTAW**	**316L/309I/309IMo**	**3.00**

Sripriyan et al.,2023	**409+316L**	**GMAW**	**AISI308**
Seerangan et al.,2022	**AISI304+316L**	**FSW**	**-**

6.3 Austenitic + Duplex Stainless Steel: Despite the fact that ASSs are suitable for high temperature applications,both ASS and DSS have resistance to localised corrosion and hence the combination is technically advantageous.DSS are extensively used for structural applications in marine industries due to their combined high strength,toughness and resistance to pitting and crevices(Orlowska,et al.,2013).However Fittings such as elbows, flanges,valves,etc often come in ASS and thus the dissimilar weld joints between ASS and DSS are inevitable.Though,ASS are more prone to residual stresses when subjected to high welding heat inputs -like in the case of arc welding; they are more weldable than DSS.Because of the austenitic nature of this combination the dissimilar joint may likely suffer from hot cracking and therefore, ferrite-forming filler metals (316L or ER2209) must be the right option depending on their availability (Lippold and Kotecki,2005).Table 2.presented various combinations of ASS to DSS with their possible welding variables

6.4 Austenitic + PH Stainless Steels: PH SSs have limited applications and hence their combination with other stainless steels are not common. PH SSs have good weldability and high strength but are the most expensive of all SSs.For economic perspective, PH SSs could be welded to ASS.

6.5 MSS + DSS: Since both MSS and DSS are applicable for oil and gas pipelines there combination is possible but favourable where high heat inputs would not be employed; because the high chromium and carbon content of DSS and MSS respectively will definitely trigger carbides precipitation and martensitic transformation resulting in embrittling and deteriorating the corrosion resistance of the weldment.The combination is possible in the case of availability and scarcity of the materials but not for marine application.The filler metal selection is critical due to the wide metallurgical disparity between the two metals.MSS have the least weldability of all SSs while DSS have moderate weldability.Consumables and parameters for this combination should be close to those of DSS.If Post weld heat treatment is necessary, lower tempering temperature and time must be adopted to avoid sigma and chi phases transformation in the HAZ of DSS.

7.0 Summary and Future Trends

It was understood from the study that dissimilar welding of different stainless steels was possible and feasible, however,it is characterized with various weldability problems.The DMW between DSS and ASS are more common- may be due to their close properties-similarities.Other combinations such as ASS +FSS, ASS+MSS,PH+ASS,PH+MSS,DSS+MSS are not much available in the literature and this calls for more researches in this direction.Among the various reasons deduced from the review for dissimilar welding between different SSs are economy,availability and technical aspects.Economy is welding a particular cheaper SS to expensive SS while some combinations are for technical or convenience based reasons.

Despite successes in welding different SSs there are numerous challenges associated with the technique. Typical examples are: martensitic transformation in the weldmetal for DMW between MSS and ASS; formation of various brittle intermediate phases in the weldments and HAZ; and reduction in the impact toughness.Though it is characterised with low single-pass depth penetration for plate thickness above 6mm(Baskoro et al.,2023)-GTAW process was noticed to be the most common arc-basd welding process applicable to dissimilar welding of different SSs (Table 2).This might be due to the low arc energy of the process suitable for welding SSs.

The technology of producing SSs is now moving toward additive manufacturing technology (Mohayla et al.,2022). This is because the economic and technical advantages of additive manufacturing technology have proven to practically replace conventionl materials manufacturing (Ramachandiran,2023); and this is evident by the various additively manufactured SSs replacing the conventionally manufactured ones .Quite number of SSs components such as, fittings and structural parts are now produced by additive manufacturing processes ; and properties of these additively manufactured parts were found to be better from those of traditionally manufactured samples (Oscar,2022;Balbaa and Elbestawi,2022).For this reason, future researches are highly encouraged to target welding of different additive manufactured SSs.Extensive investigation with respect to microstructures,mechanical properties, fractography,weld defects,residual stresses,fatigue and creep resistance;corrosion and non destructive testing of dissimilar weld joints of different additive manufactured SSs are scarce in the literature.Hence more attention should be invested in this angle.
Futhermore, future investigations should adopt activated tungsten inert gas welding process (an advanced GTAW process) for dissimilar welding of different SSs.

8.0 Conclusion

The study of dissimilar welding of different stainless was carried out and the following conclusions were arrived:

• Dissimilar welding of different stainless steels is feasible but associated with many weldability challenges such as precipitation of brittle intermediate phases and lower impact toughness. Subsequent researches should focus on finding lasting solution to these challenges.

•Works on dissimilar welding of additive manufactured stainless steel are scarce and therefore further researches are encouraged to look in to that direction.

• GTAW process was observed to be the most applicable arc welding process in dissimilar welding of different stainless steels. Future research should investigate dissimilar welding of different stainless steels using more advanced process of Activated GTAW process.

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