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Article

Mathematical & Computational Analysis of Process Parameters in Gas Metal Arc Welding of Austenitic Stainless Steels: A Review

Abhishek Chakraborty[1,], Anshul Gangele[2], Chaitanya Sharma[3]

[1,2]Department of Mechanical Engineering, Amity University- Madhya Pradesh, Gwalior (India)
[3]Department of Mechanical Engineering, BIT Sindri, Dhanbad, Jharkhand (India)

Abstract: Since, the transition of human civilisation from stone age to metal age, metals and alloys have become the inevitable parts of human life. Since its invention, steel has been a material of prime importance in the field of fabrication. With the addition of various types of impurities in various compositions, thousands of varieties of steels are formed. These alloys, thus, find wide range of applications in our day to day life and engineering applications as well. Moreover, with the advent of arc welding technique in mid-1800s, manufacturing got even easier and diversified. MIG welding, also known as Gas Metal Arc Welding (GMAW), is a special kind of arc welding, developed later, in which inert/active gases are used. It is a more user friendly and robust technique, which has got wider range of applications and thus, increased industrial production rates by manifolds. Accordingly, over the period of time, both steels & MIG welding technique have captured the attention of researchers across the globe and generated the curiosity among them to explore these manufacturing gems more deeply. Nevertheless, with the consideration of various input & output process parameters as well as application of various mathematical & computational techniques, research has become more precise and easier. In this investigation work, the authors have tried to compile the various input/output process parameters and computational & mathematical research tools employed to explore the various facets of MIG welded Austenitic Stainless steels and further research prospects thereof.

Keywords: Gas Metal Arc Welding (GMAW), Austenitic Stainless Steel (ASS), Mathematical Tools, Computational Tools, Optimisation Techniques

1. Introduction

Metal Inert Gas (MIG) welding, also known as Gas Metal Arc Welding (GMAW) is a kind of arc welding which is preferred for the welding of thicker plates, owing to its ability to achieve greater depth of penetration (DOP), which ensures better strength and durability of the joint formed. Basically, in this mechanism the electrode, in the form of a thin wire, is constantly feed at a particular rate by means of a feeding mechanism. The shielding of weld pool is accomplished by providing constant flow of an inert or active gas like argon, carbon dioxide etc by a gas cylinder. The biggest advantage of MIG welding over Shielded Metal Arc Welding (SMAW) is the provision for uninterrupted continuous welding, which increases its commercial viability hugely.

However, the biggest commercial & technical challenge to industrialists is to find the best match of metals & alloys, which are most compatible with MIG welding in terms of process feasibility, commercial viability and strength and durability of welding joints. This can aptly be accomplished by performing in-depth analysis of the past work done so far by welding researchers across the globe and by making right predictions as well.

Amongst the huge catalogue of commercial metals and alloys used in industries, steel always finds a special mention owing to its vast range of available grades & desirable properties. Nevertheless, excellent corrosion resistant property of stainless steel gives it an edge over other grades due to the presence of chromium. This property, together with other desirable mechanical properties can be found in various proportions amidst the different families and grades of stainless steel. Within the stainless steel family, Austenitic stainless steel is the most sought after type due to its very high weldability.

In research domain, once the steel grade and welding type to be done on it are fixed, input process parameters & process outcomes need to be identified & optimised to ensure best results. This process helps in overall cost optimisation also. The researchers in the present investigation work have tried to overview and conclude the various research work done so far on Austenitic Stainless Steels using MIG welding and have also tried to find out the research gaps and future prospects as well.

1.1 History of Welding

In the manufacturing domain, among various available processes, welding is the most sought after joining process. Out of all the welding types, arc welding is the most common type of welding applied for joining of metals and alloys, which itself has many sub categories.

The history of welding dates back to 1000 BC, when forge welding would be performed to make weapons and tools in Egypt and other parts of eastern Mediterranean area. Traces of Forge-welded bronze articles were later recovered from the pyramids of Egypt during archaeological surveys. Forge welding was an extended form of forging by hammering only. In this way, forging and blacksmith trades laid down the foundation of welding and further developed it till the Middle ages. Forge-welded articles of iron and other metals of that time were found later in various parts of India and European countries. Later on, in 1880s, two landmark discoveries were made separately, by Sir Humphrey Davy in the form of electric arc and acetylene gas. These discoveries laid down the scientific foundation of the modern day welding technology and led to the development of Carbon Arc Welding and Gas Welding respectively. These welding techniques were more convenient and efficient and could be applied to a wider range of metals and alloys. All these merits popularised the commercial and industrial use of welding for joining of metals and alloys [1].

The concept of GMAW was developed in 1920s but was commercially available from 1948 to weld Aluminium only using inert gases. Subsequently, active gases, prominently CO_2 or its mixture with any inert gas at various proportions was used. Moreover, of late, this technology started incorporating low current density and pulsed DC current supply, unlike earlier versions, which diversified its range of metals and alloys to be welded, by manifolds [2].

1.2 History of Metals & Alloys

Discovery of metals must be accidental by pre-historic men and had been instrumental in the development of human civilisation after Stone Age. Copper was discovered first and soon men learnt the technique of alloying it also. This marked the beginning of bronze age that lasted from 3300 BC to 1200 BC. Bronze is an alloy of copper which found wide acceptance in human civilisation and was extensively used in making utensils, weapons, idols etc. Thereafter came the dawn of iron age, which lasted from 1200 BC to 500 BC. Soon after discovering iron and exploring its wide utilities further, men learnt to make steel from it by smelting process during 400 BC. Steel is primarily an alloy of iron and carbon with varying percentage composition. Further alloying with other metals were also done as impurities in steel, to engineer its properties as per requirements. In this way thousands of grades of steel were manufactured. In fact, iron and steel played pivotal roles during industrial revolution that took place in Europe. Thereafter, many more metals were discovered and subsequently their alloys were made during at various points of time, which changed the human civilisation forever.

Advent of arc welding technology and various other types of welding, at different points of time, took fabrication engineering to the next level. Welding made possible the joining of different types of metals and alloys with each other to create new metal combinations and structures. Accordingly, suitable welding processes and filler metals were opted as per the compatibility with base metals. As such, in the welding sector, choosing the right Alloy-Welding combination becomes the most important task of production engineer. Both must be best compatible to each other so as to ensure manufacturing of the best quality product at minimum cost. This is the underlying theme of any manufacturing sector, which is always sought after by industrialists and consumers, alike.

1.3 Principle & Physics of GMAW/MIG Welding

In MIG/GMA Welding process, electrode is fed constantly in the form of a thin metal wire to generate the arc. This is made possible with the aid of a constant wire feeding mechanism fitted inside the MIG welding set up. The electrode is generally made positive (Reverse polarity) with thinnest possible wire diameter. This ensures generation of high current density and thus, higher amount of heat at electrode for its melting. It’s also called Metal Active Gas

(MAG) welding when instead of an inert gas, an active gas like carbon dioxide is used as a shielding gas. The welding system consists of a filler wire feed mechanism with a welding torch fitted at its tip. A gas cylinder filled with an inert gas like argon or carbon dioxide or mixture of both in various proportions is always kept alongside fitted with gas pressure control valve at the top of the cylinder. The torch contains electrode wire, shielding gas line and current carrying wire. A typical MIG setup, based on reverse polarity (Electrode: Positive &Work Piece: Negative), is shown below.

Fig.1. A Typical GMAW/MIG Welding Setup

Establishment of arc between a constantly feed electrode wire and the work piece and maintaining of the arc length are the primary factors of GMAW. Arc length is directly based on nozzle-work piece gap, which keeps on changing during manual operation. To compensate for this, an automatic arc regulation mechanism (constant voltage type) is provided. It's a constant wire feed mechanism based on variable current- constant voltage power source characteristic which delivers more current when the arc length gets shorten (due to lesser gap) and vice versa [3]. The schematic layout of a GMAW/MIG welding setup is shown below:

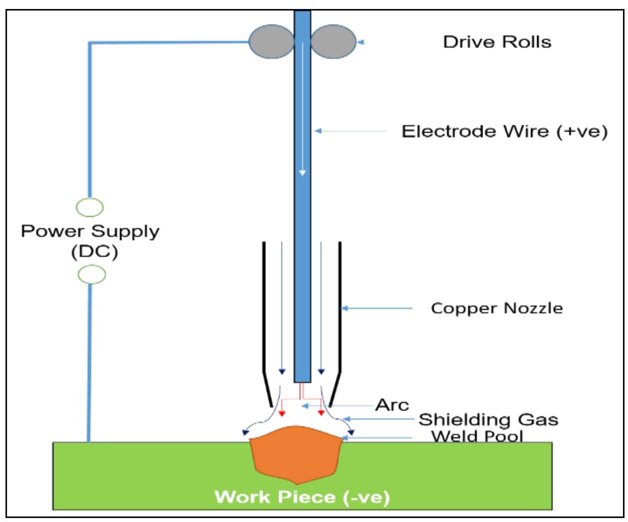

Fig.2. Schematic Layout of a GMAW/MIG Welding Setup

1.4 Industrial Applications of GMAW/MIG Welding

It's a well-known fact that MIG welding technique was first used to join Aluminium alloys [4]. Due to the increasing demand of copper in different industries like automobiles etc, due to its fascinating conducting properties, MIG welding is being used for welding copper also [5]. Besides, AISI 409 has been developed to have the merits of both stainless steels and carbon steels viz. corrosion resistant and low cost [6]. With 11-12 % chromium alloying, ferritic steels are widely used as low cost utility stainless steels [7][8], although, they have poor weldability than austenitic stainless steels [9]. Due to all these features, AISI 409 drawn the attention of welding researchers across the globe. Thus, different levels of extensive research work have been carried out on this unique material at different points of time.

It's worth mentioning here the utility of galvanized steel in fabrication. The most unique feature of this alloy is that it can be recycled many times, besides being cheaper and effective [10]. These features themselves speak for its versatile applications in the manufacturing of automobile components, structures, rails, domestic appliances, electrical fitments etc. In fact, during galvanization process, zinc is alloyed with steel to make it more corrosion resistant and thereby increasing its applicability [11]. Galvanized steel is considered a better product than other coatings as galvanization makes the steel corrosion resistant to its full depth, such that even wearing off of the outer layer doesn't effect it [12].

From the welding point of view, the later results in vanishing of zinc coating from the weldments due to the low melting (482 °C) and vaporizing points (906 °C) of zinc as compared to the high melting point of steel (1510 °C) and very high welding temperature range (8300-11090 °C). In such cases, zinc based spray coatings or paints are to be used to restore the surfaces [13] [14] [15]. So, in general, it's preferred to galvanize a component after complete fabrication. However, it is not possible always owing to a voluminous structure and thus, welding has to be done after galvanizing [16]. Sometimes, even thermal spraying of zinc upon the weldment is done to cope up with the situation. Although, prior cleaning of the same has to be done by sand blasting or coarse abrasive conditioning [17] [18]. Although, MIG welding is suitable for welding both similar and dissimilar metals. Still, the later forms weaker joints due to the formation of intermetallic compounds, which led to generation of fatigue concentration [19].

2. GMAW/MIG Welding done on Austenitic Stainless Steels

Different materials show different degrees of weldability. Accordingly, the quality of weld generated and their final applications vary. Austenitic stainless steels show good weldability characteristics and thus, do not require any post weld treatments. Besides, these alloys have excellent malleability and strength, which make them more versatile and cost effective than other stainless steel grades viz. Ferritic, Duplex and Martensitic steels. Some of the commonly preferred Austenitic Stainless Steel grades to perform MIG welding are discussed in the subsequent paragraphs.

Austenitic Stainless Steel (ASS) was patented in 1912 by engineers Eduard Maurer & Benno Straus and contributes to around 70% of total steel consumption worldwide [20]. These are superior quality steels having better corrosive resistance and weldability. They come in 200 and 300 series and the commonly used ASS alloys are SS-202, SS-304, SS-310, SS-316 & SS-316L. Basically, ASS alloys are having face centred cubic crystal lattice structure. They are non-magnetic in nature and have got good tensile strength and moderate yield strength. All these exciting properties make ASS the most sought after alloys for industrial and research purposes [21]. Details of a few research work performed on different grades of ASS alloys have been discussed below.

2.1 SS-202 Grade Alloy

The composition of SS-202 alloy is tabulated below.

Table 1: Composition of SS-202 Alloy [22]

Element	**C**	**Ni**	**Cr**	**Si**	**Mn**	**P**	**S**	**N**	**Fe**
%	0.15	4.0-6.0	17.0-19.0	1.00	7.5-10.0	0.06	0.01	0.25	Remainder

A few characteristics of SS-202 alloy are:

- Although corrosion resistant, still it shows corrosion tendency in moist & acidic environments.
- Harder than 300 series alloys due to the presence of nitrogen.
- Excellent impact resistance & toughness properties, even at cryogenic temperatures.
- Has less ductility and hence, lesser formability than 300 series.
- Cheaper than 300 series due to low Nickel content.

Owing to these features, SS-202 finds its limited applications in:

- Cutlery & Cookware.

- Automobile structural & decorative parts [23].

Due to such limitations, limited research work have been done by welding & metallurgical researchers over the years on SS-202 alloy using MIG welding. Details of a few such work done are tabulated below.

Table 2: Details of GMAW/MIG Welding done on SS-202 Alloy

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	Wire Feed Rate (WFR), Welding Speed (W/S), Voltage (V), Standoff Distance, Torch Angle	Angular Distortion	Central Composite Rotatable Design (CCRD), Response Surface Methodology (RSM), Analysis of Variance (ANOVA)	Voltage is the most dominating factor affecting distortion.	[22]
2	WFR, WS, V		Taguchi L8 Orthogonal Array (O/A), Regression Analysis (RA), ANOVA	Wire feed rate has maximum positive effect on distortion.	[24]
3	WS, Current (I) & Gas Flow Rate (GFR)	Ultimate Tensile Strength (UTS) & Hardness	Taguchi L9 O/A	At low gas flow rate, high tensile strength & hardness are observed. High welding speed invites porosity and low weld penetration (DOP).	[25]
4	Fluxes	DOP & Hardness	MS Excel	Ammonium Ferro Sulphate gave max DOP; Ammonium Carbonate gave max hardness	[42]

Accordingly, the frequencies of considering the various input and output process parameters and of using the various mathematical/computer based research tools, during the MIG welding of SS-202 alloy are shown below graphically in figures 3, 4 & 5 respectively.

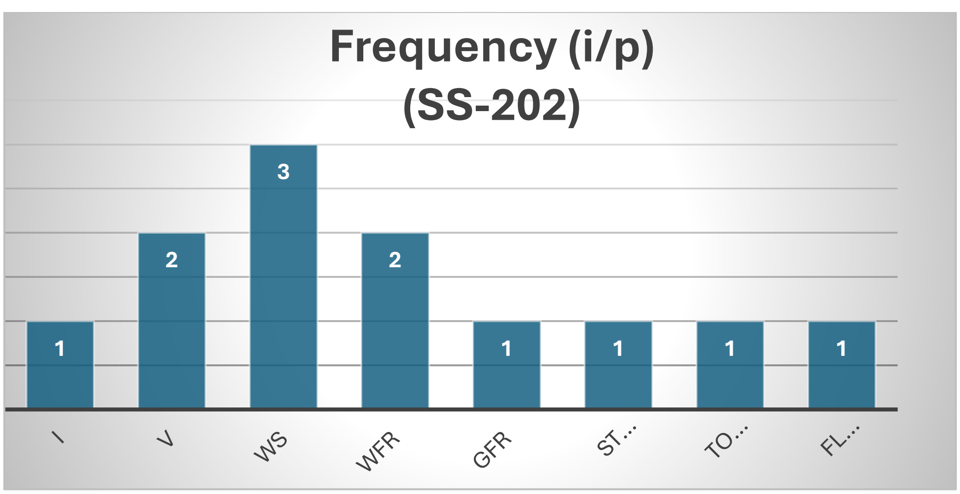

Fig.3. Types & Frequencies of Input Process Parameters considered for SS-202 Alloy

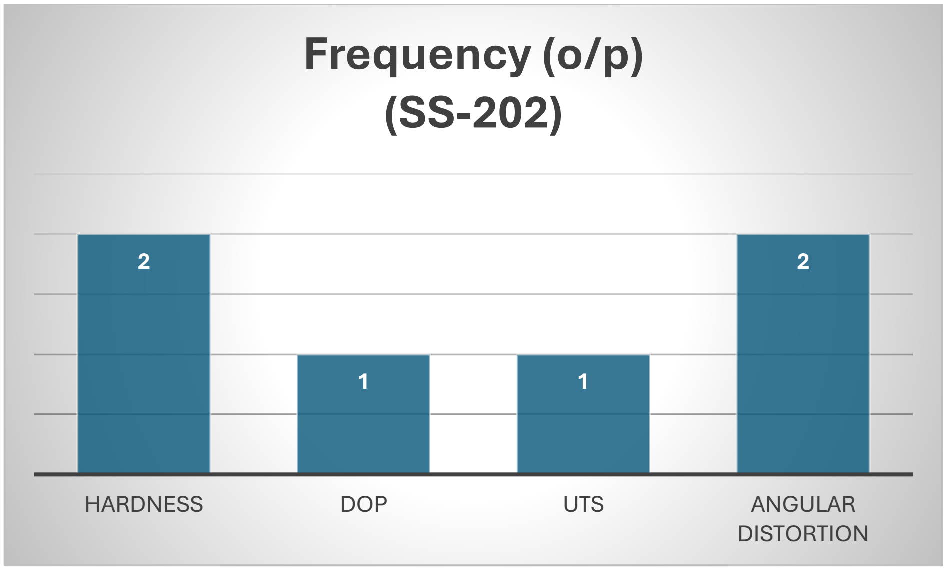

Fig.4. Types & Frequencies of Output Process Parameters considered for SS-202 Alloy

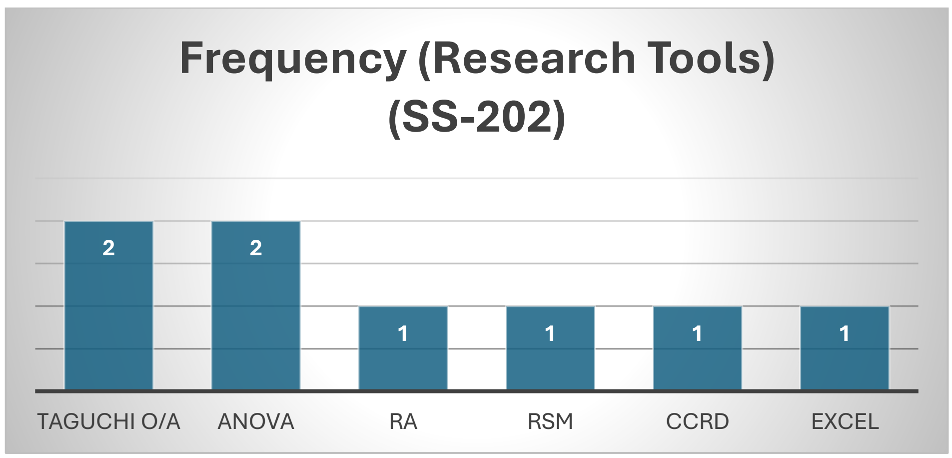

Fig.5. Types & Frequencies of Research Tools used in SS-202 Alloy

The corresponding variation of input & output parameters have been depicted pictorially in Fig. 6.

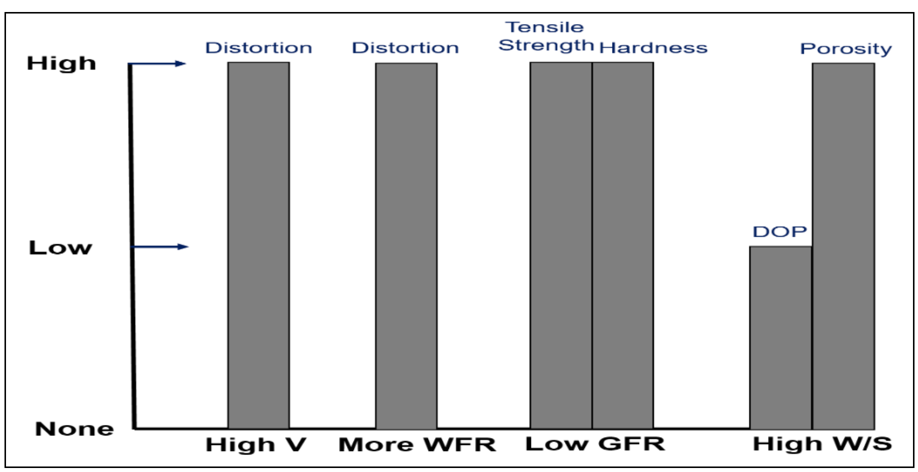

Fig.6. Patterns of variation of Input-Output Process Parameters in SS-202 Alloy

2.2 SS-304 Grade Alloy

SS-304 is amongst the most popular and versatile steel grade and is also graded as AISI-304 or 06Cr19Ni10 or SS-1.4301 or most popularly by SS-18/8. The composition of SS-304 alloy is tabulated below.

Table 3: Composition of SS-304Alloy [27]

Element	**C**	**Ni**	**Cr**	**Si**	**Mn**	**P**	**S**	**Fe**
%	0.045	8.00	17.1	0.45	1.10	0.028	0.001	Remainder

SS-304 is far more superior and the most versatile alloy in terms of properties as listed below.

- Excellent ductility and thus, can be easily deep drawn.
- Higher tensile strength.
- Good corrosive resistance, even in acidic medium.
- Work hardening can be easily done during both hot & cold rolling processes.
- Excellent machinability.
- Cannot be hardened by any heat treatment process.

All these properties make SS-304 suitable for the fabrication of the following items:

- Springs, nut-bolts & screws.
- Tubes & pipes.
- Cutlery items & saucepans.
- Sinks & sanitary wares, etc. [21]

Details of research work done on SS-304 using MIG welding have been tabulated below.

Table 4: Details of GMAW/MIG Welding done on SS-304 Alloy

S. NO.	**INPUT PARAMETERS**	**OUTPUT PARAMETERS**	**COMPUTATIONAL/ MATHEMATICAL TOOLS USED**	**RESEARCH OUTCOMES**	**REF. NO.**
1	Current (I), Voltage (V), Gas Flow Rate (GFR)	Surface Roughness, Width of Bed Thickness (WOBT), Hardness	Central Composite Design Method (CCDM), Response Surface Methodology (RSM), ANOVA	Current & Voltage are the most prominent governing factors. Low current & moderate gas flow rate ensure better outcomes. Voltage directly varies with WOBT	[26]
2	Strain Strengthening (S/S)	Crack Growth Path & Rate (CGPR), Residual Stress & Microstructure	Numerical Simulation (NS)	Strain strengthening - Has no effec on crack growth path; Reduces cra growth rate; Enhances stress-induc martensite transformations; Reduce residual stress.	[27]

3	Welding Speed (W/S) & Current	Hardness, UTS, Impact Strength & Surface Corrosion	Design Expert Software 6.0.6, ANOVA	Current is the most significant fact that affects micro hardness, tensile strength & impact strength of weld Welding speed & Current influence tensile strength directly.	[28]
4	Groove Angle (G/A), Groove Depth (G/D) & Welding Speed	Weld Pool Width (WPW)	Heat Source (HS) Model , CFD Model, Molten Pool Stress (MPS) Model	With the increase of groove angle groove depth, molten pool gets wid Molten pool width varies inversely with welding speed.	[29]
5	I, GFR, Fluxes	Ultimate Tensile Strength (UTS)	Taguchi L9 O/A, ANOVA, RA	Flux $MgCO_3$ gave max UTS at all current values	[36]
6	I, V, Torch Angle	DOP, Bead Width	Taguchi L9 O/A, ANOVA	Voltage has max influence on both outcomes	[37]
7	V, WFR, Electrode Wire Diameter (EWD)	UTS, Hardness,	Taguchi L9 O/A, ANOVA, Minitab-17	WFR affects UTS the most (48.71%); Voltage affects Microhardness the most (57.94%); Max hardness was obtained at the centre of fusion zone (FZ)	[38]
8	I, WS, WFR	UTS, Yield Strength, Hardness, Microstructure	Direct mathematical formulae, Channel 5 Software (for grain-boundary analysis)	Lower current & lower welding speed ensured greater fusion area based dilution	[44]

Accordingly, the frequencies of considering the various input and output process parameters and of using the various mathematical/computer based research tools, during the MIG welding of SS-304 alloy are shown below graphically in figures 7, 8 & 9 respectively.

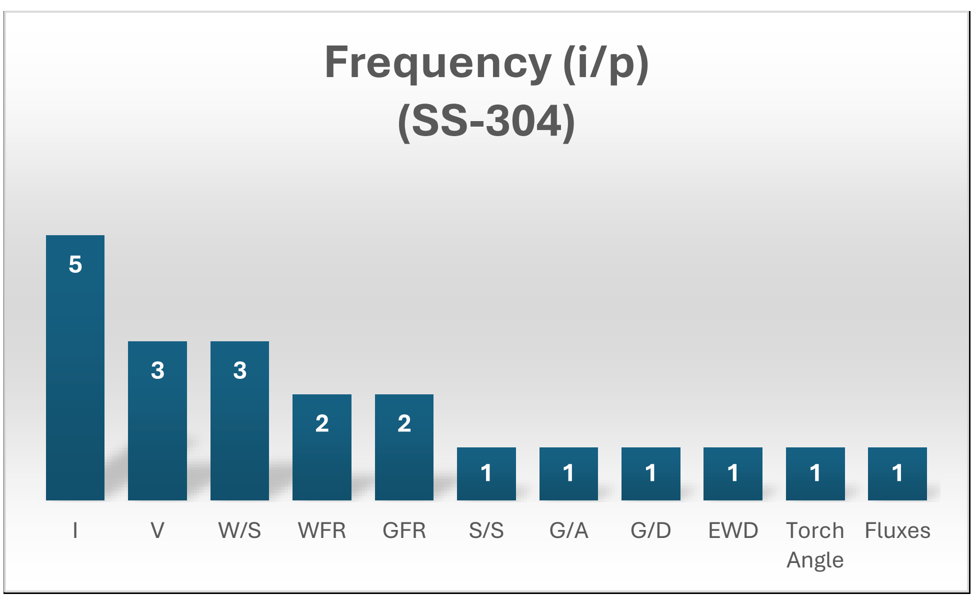

Fig.7. Types & Frequencies of Input Process Parameters Considered for SS-304 Alloy

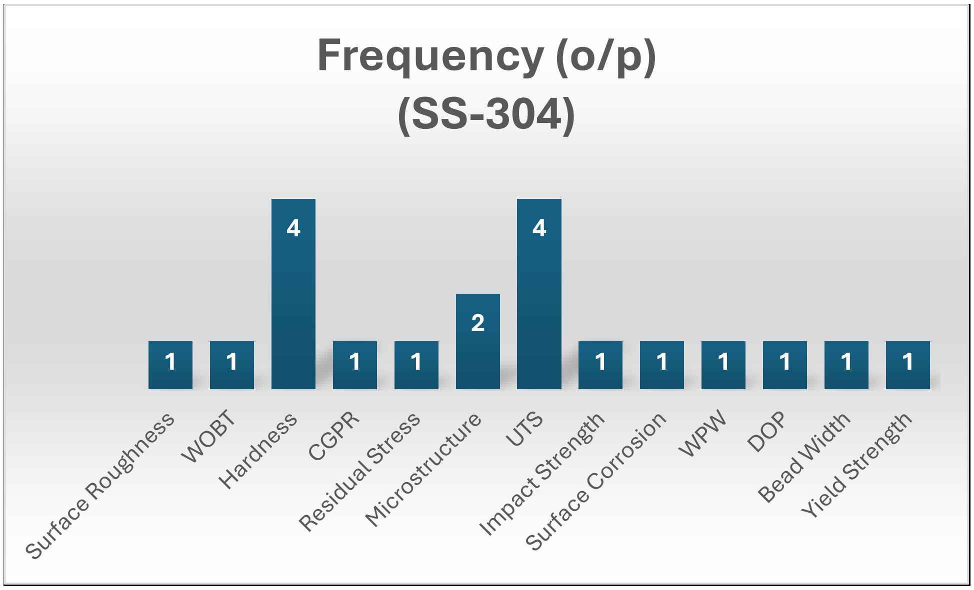

Fig.8. Types & Frequencies of Output Process Parameters considered for SS-304 Alloy

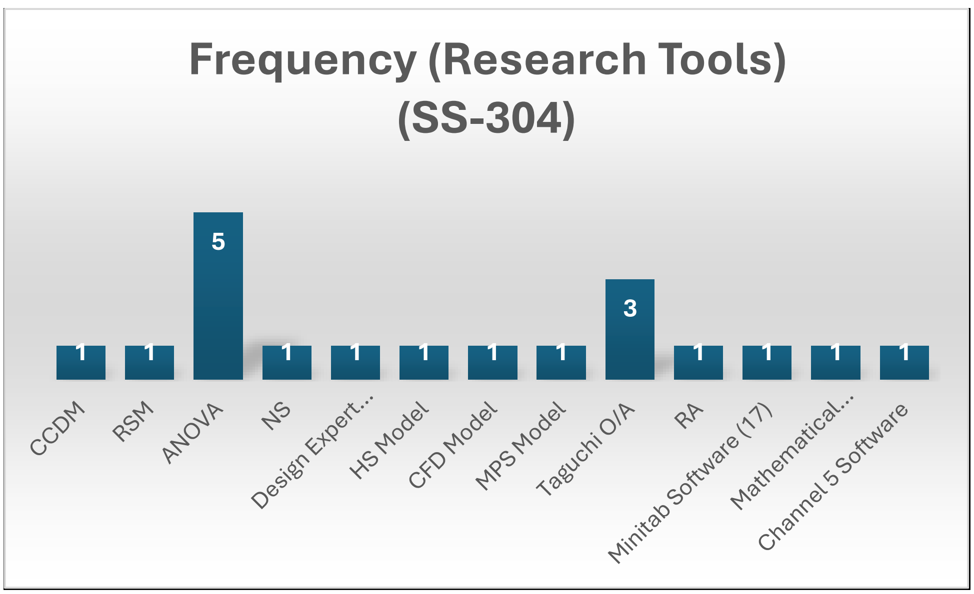

Fig.9. Types & Frequencies of Research Tools used in SS-304 Alloy

The corresponding variations of welding parameters in SS-304 alloy are shown below.

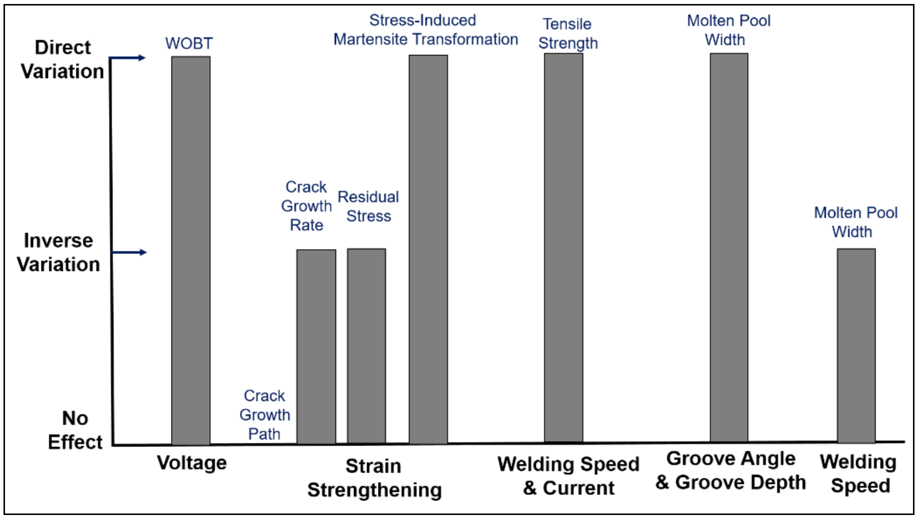

Fig.10. Patterns of variation of Input-Output Process Parameters in SS-304 Alloy

2.3 SS:304-304 Similar Alloy Welded Joint

In many fabrication cases, similar alloys need to be welded together like in automobiles, ships, aerospace, pressure vessels etc. As such, a few welding researchers have conducted investigations on this area as well, across the globe. A few such recent cases have been summarized below where GMAW have been performed to create SS:304-304 joints and then analysed.

Table 5: Details of GMAW/MIG Welding done on SS: 304-304 Joints

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	Heat (H) (primary), I, V, WS	DOP, Bead Width (BW),Microstructure , Hardness, UTS, Yield Strength (YS)	Only direct mathematical formulae were used for calculating heat input, strength & ductility performances	Higher heat input ensures complete recrystallization of HAZ and thus, development of coarser austenitic grains; No effect on hardness	[40]
2	5 Types of oxide fluxes	DOP, Hardness, UTS, Microstructure, Corrosion Response (CR)	Direct formulae were used for calculating aspect ratio, Cr & Ni equivalents, mean and standard deviation	SiO_2 was most effective for penetration; same is for Cr_2O_3 for tensile strength; Fe_2O_3 for overall best bead shape & corrosion resistance	[41]
3	H (primary), I, V, W/S	Microstructure, Hardness, UTS	Only direct mathematical formulae were used for calculating heat input, strength & ductility performances	Higher heat input has no effects on hardness, tensile strength, ductility & bending performance; and it produced a bit larger recrystallised grains in HAZ (within limits; very larger grains are not desirable)	[43]

Accordingly, the frequencies of considering the various input and output process parameters and of using the various mathematical tools, during the GMAW of SS:304-304 similar alloys are shown below graphically in figures 11, 12 & 13 respectively.

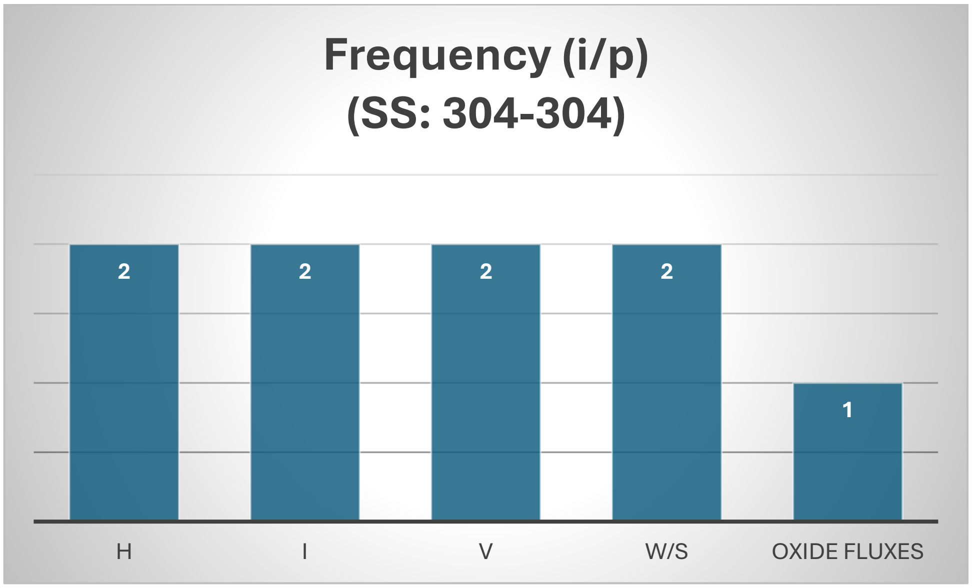

Fig.11. Types & Frequencies of Input Process Parameters considered for SS:304-304 Joints

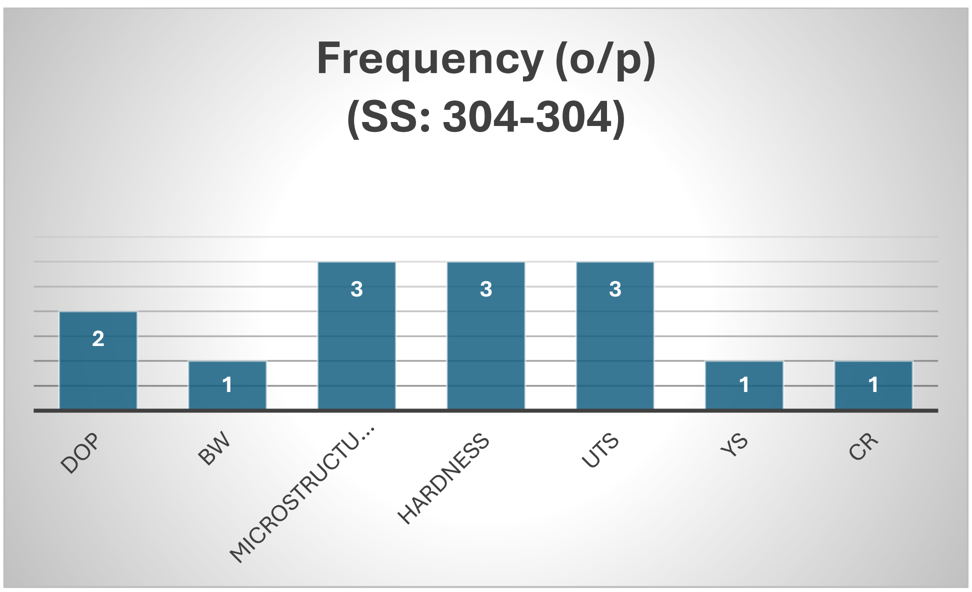

Fig.12. Types & Frequencies of Output Process Parameters considered for SS:304-304 Joints

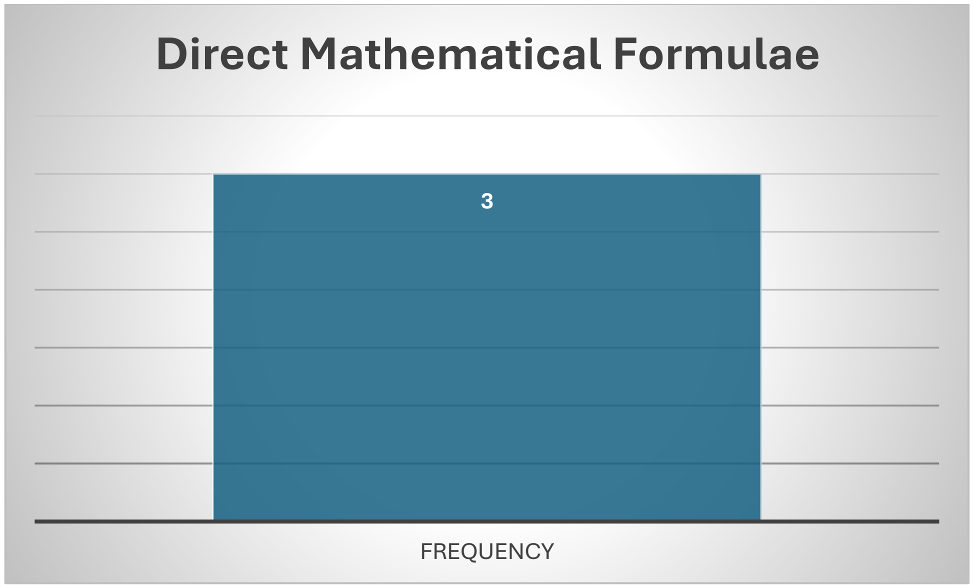

Fig.13. Types & Frequencies of Mathematical Tools used in SS:304-304 Joints

The corresponding variations of welding parameters in SS:304-304 welded joints are shown below.

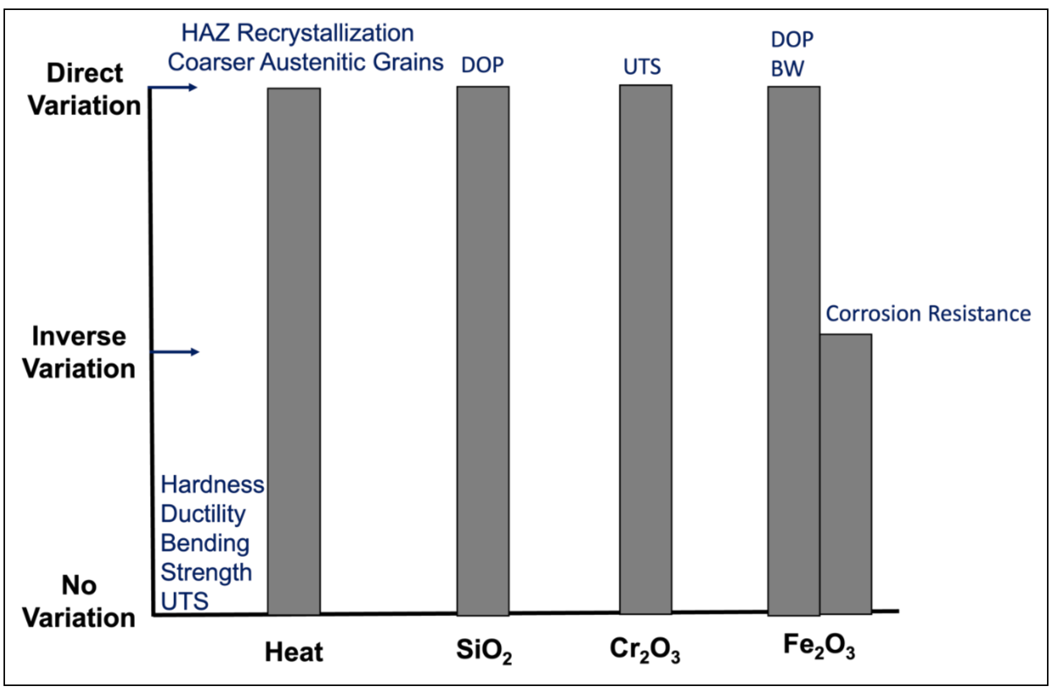

Fig.14. Patterns of variation of Input-Output Process Parameters in SS:304-304 welded joints

2.4 SS:202-304 Dissimilar Alloy Welded Joint

Dissimilar weld joints need to be created in many cases of fabrication. SS-202 & 304 being closely associated also need to be welded together sometimes to harness the benefits of both. The outer surfaces are made up of SS-304 to avoid corrosion, whereas inner parts are made with SS-202. Thus, research investigations are conducted on such joints also. One such recent case has been summarized below where GMAW has been performed on SS:202-304 dissimilar joints and then analysed.

Table 6: Details of GMAW/MIG Welding done on SS: 302-304 Joint

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	I, V, WS	UTS, Microhardness, Bending Load	Taguchi L9 O/A, Grey Relational Analysis (GRA),	Current is the most influential factor followed by Welding speed; The optimum combination is : 200A-22V-3mm/s; Sufficient heat is required to ensure complete fusion	[39]

2.5 SS-310 Grade Alloy

This grade has very high temperature resistant properties. The corresponding composition is tabulated below.

Table 7: Composition of SS-310 Alloy [30]

Element	C	Ni	Cr	Si	Mn	P	S	Fe
%	≤ 0.25%	19-22%	24-26%	≤ 1.5%	≤ 2%	≤ 0.045%	≤ 0.03%	Remainder

The salient features of SS-310 alloy are listed below.

- High temperature resistant alloy.
- Good weldability & ductility.
- Oxidation resistant up to 1150°C etc. [21].

Due to these excellent features, SS-310 alloy is used in the manufacturing of:

- Cryogenic structures.
- Combustion chambers.
- Refractory anchor bolts.
- Radiant tubes & tube hangers.
- Kilns etc. [21].

However, very limited research work is done on SS-310, so far, as tabulated below.

Table 8: Details of GMAW/MIG Welding done on SS-310 Alloy

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	Current, Voltage & Gas Flow Rate (GFR)	Tensile Strength & Hardness	Taguchi L9 OA, Grey Relational Analysis (GRA)	Tensile strength varies directly with voltage & gas flow rate and inversely with current. Hardness varies inversely with all the three input parameters.	[30]

The variation of input-output parameters has been graphically shown below.

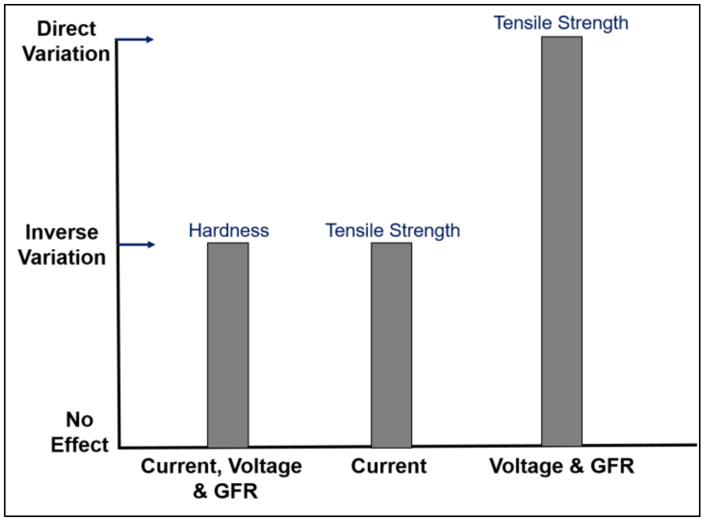

Fig.15. Patterns of Variation of Input-Output Process Parameters in SS-310 Alloy

2.6 SS-316 Grade Alloy

SS-316 alloy is considered very suitable for piping and tubing purposes. Presence of Molybdenum makes it the best corrosion resistant alloy. The material composition of the alloy is tabulated below.

Table 9: Composition of SS-316 Alloy [31]

Element	C	Ni	Co	Cr	Si	Mn	P	Al	Mo	Ti	V	Zr	Fe
%	0.08	9.5	0.51	17.4	2.9	1.51	0.04	0.004	1.96	0.1	0.15	0.1	Remainder

The salient features of SS-316 alloy are listed below.

- Very good corrosion resistant property even in atmospheric, marine &chloride environments except in warm sea water.
- Good oxidation resistance properties under 1000°C.
- Non responsive against heat treatment.
- Very good forming & rolling properties.
- Shows excellent weldability to all standard fusion welding processes.
- Excellent toughness properties even at cryogenic temperatures [21].

Owing to these industrial friendly features, SS-316 alloy is used to manufacture the following:

- Chemical containers,
- Heat exchangers,
- Threaded fasteners,
- Springs,
- Coastal architecture,
- Boat & Ship fittings, etc [21].

On the research front, very limited research has been done on SS-316 alloy as mentioned below.

Table 10: Details of GMAW/MIG Welding done on SS-316 Alloy

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	Welding speed, Current& Gas Flow Rate	Hardness & Tensile strength	Taguchi L27 OA, ANOVA, Genetic Algorithm (GA), Artificial Neural Network (ANN), Regression Analysis (RA)	Current varies directly with tensile strength and has negligible effect on hardness.	[32]

The Input-Output process parameters variation pattern is graphically shown below.

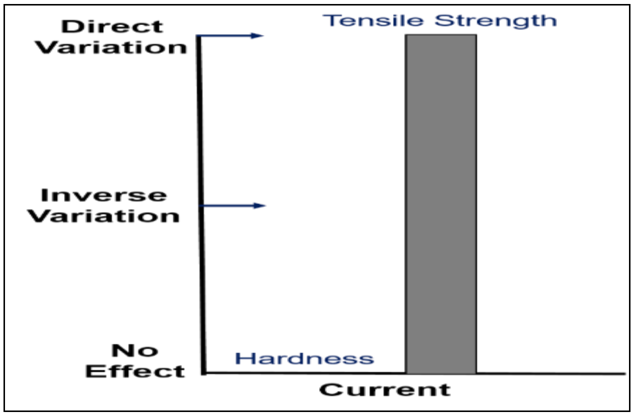

Fig.16. Patterns of Variation of Input-Output Process Parameters in SS-316 Alloy

2.7 SS-316L Grade Alloy

Grade SS-316L is the low carbon variant of SS-316 alloy and is immune to grain boundary carbide precipitation phenomenon. This makes it suitable for heavy gauge welding operations (above 6 mm). It has the following composition.

Table 11: Composition of SS-316L Alloy [21]

Element	C	Ni	Cr	Si	Mn	P	S	Mo	N	Fe
%	0.03	10-14%	16-18%	0.75%	2.0%	0.045%	0.03%	2.0-3.0%	0.10%	Remainder

Some important features of the alloy are listed below:

- Shows excellent toughness even at cryogenic temperatures.
- Offers higher creep, resistance to rupture and tensile strength at higher temperatures.
- Shows good oxidation resistance at higher temperature.
- Shows excellent weldability to different fusion and resistance welding techniques.
- Does not require post weld heat treatment like SS-316 grade.
- Cannot be welded by oxyacetylene welding.
- Easier to machine due to low carbon content.
- Cannot be hardened by heat treatments. [21]

Accordingly, the alloy finds its major applications in the following:

- Architectural & Marine applications.

- Fasteners.
- Medical implants.
- Utensils. [21]

The details of limited research work done on SS-316L, so far, have been summarised below.

Table 12: Details of MIG Welding done on SS-316L Alloy

S. NO.	INPUT PARAMETERS	OUTPUT PARAMETERS	COMPUTATIONAL/ MATHEMATICAL TOOLS USED	RESEARCH OUTCOMES	REF. NO.
1	Current, Gas Flow Rate & Nozzle-Plate Distance (NPD)	Ultimate Tensile Strength (UTS), Yield Strength (YS) & Percentage Elongation (PE)	Taguchi L9 Matrix, Principal Component Analysis (PCA)	Best mechanical strength & ductility have been observed at lowest current value (100A) and highest GFR (20 L/Min)& NPD (15 mm) values.	[33]
2		Ultimate Tensile Test & Percentage Elongation	Taguchi L9 O/A, ANOVA, S/N ratio	Highest UTS is observed at lowest current, moderate NPD (12 mm) and highest GFR values. Maximum PE is found at the same values of current and GFR, except NPD at lowest level (9 mm).	[34]
3		Ultimate Tensile Strength (UTS), Yield Strength (YS) & Percentage Elongation (PE)	Taguchi L9 O/A, Grey Relational Analysis (GRA),	Best result is found at lowest current value and highest GFR & NPD values. Current is the most significant factor in governing weld strength quality.	[35]

It is observed that the research work on SS-316L alloy has been predominantly done by almost the same set of researchers at different points of time. Furthermore, it can be seen that almost the same set of input and output process parameters have been considered every time, with some significant changes made in the selection of the mathematical tools used, so as to reaffirm the results.

The pattern of variation in Input-Output process parameters is shown below graphically.

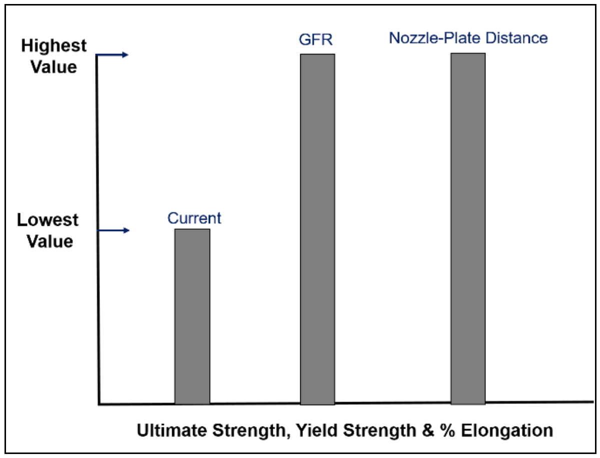

Fig.17. Patterns of Variation of Input-Output Process Parameters in SS-316L Alloy

3. Conclusions

i. Primarily, five types of Austenitic Stainless Steels viz. SS-202, SS-304, SS-310, SS-316 & SS-316L find industrial and commercial applications in different degrees.

ii. SS-304 finds major commercial viability due to its excellent mechanical properties and versatile applications. Accordingly, more research emphasis have been put on SS-304 alloy by researchers across the globe along with similar & dissimilar joints of SS-304 also.

iii. Current, Voltage, Welding speed, Wire fed rate & Gas flow rate have been the most common input parameters considered during the GMAW of Austenitic Stainless Steels. Whereas, input parameters like Torch angle, Strain strengthening, Groove angle etc. have got very limited considerations. However, surface cleaning of faying surfaces before welding, a very important aspect, has not been considered at all, so far.

iv. DOP, Hardness, UTS & Microstructure have been the most sought after process outcomes considered during the GMAW of Austenitic Stainless Steels. On the other hand, Surface roughness, Crack propagation, Corrosion resistance etc. have got very limited considerations in research investigations done so far.

v. Current is the most influential input parameter which governs the overall weld strength/quality and bead geometry followed by voltage & welding speed. However, these have to be kept within optimum range to control the heat input, which in turn governs other weld properties.

vi. Taguchi method is most frequently used for the optimisation of input parameters/design of experiments followed by RSM & GRA. Whereas ANOVA & Regression Analysis are the frequently used tools for data analysis.

vii. PCA, CFD modelling, CCDM, CCRD along with HS & MPS modelling methods are used as advanced mathematical tools in welding investigations, wherever required. However, in certain cases, direct mathematical formulae are also used to calculate certain values.

viii. Classical computational tools like Excel & Minitab are frequently used in welding analysis along with data simulation techniques like Numerical Simulation. AI techniques like Genetic Algorithm & Artificial Neural Networks are also employed for data predictions. Whereas, advanced softwares like Channel-5 & Design Expert 6.0.6 are also used on case to case basis.

Future Scope

i. Future review work on the same domain could be expanded by covering alloy steels other than ASS upon which GMAW had been performed.

ii. More research emphasis could be put on lesser used austenitic stainless steel grades like SS-310, 316 & 316L to explore their hidden properties and thus, to widen their industrial applications.

iii. Even more popular alloys like SS-202 and SS-304 grade alloys could be further investigated by employing other advanced computational tools to explore their hidden features with greater accuracy.

CrediT Authorship Contribution Statement

Abhishek Chakraborty: Conceptualization, selection of materials & content writing.

Dr. Chaitanya Sharma: Guidance & supervision in creating tables & graphs.

Dr. Anshul Gangele: Guidance & supervision in executing overall literature survey.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Being a review work, no experimental data has been generated during the course of this investigation work. However, any information/data, which is borrowed from any other research paper has been duly cited

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