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ANALYSIS OF GAS TUNGSTEN ARC WELDING OF AUSTENITIC STAINLESS STEELS (304&316L)

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Abstract: There are huge applications in stainless steels due to its high corrosion resistance. These are classified into different grades based on its applications. In this study, GTAW of AISI 304 and AISI 316 L with the filler as AISI 304. Welding using ER- 309 as filler material has been reported by the researches earlier, by varying both current and voltage. And also, the current required for minimal heat affected zone was not reported. Hence this study, experiments were conducted using tungsten inert gas (TIG) welding of 304 and 316L stainless steel sheets was carried out with three different current value 25A, 30A and 35A with constant voltage. It was observed that the elongation and yield strength, hardness, and weld width were investigated based on the varying voltage and current. Moreover, in order to examine the mechanical and metallurgical behaviour of the weld, non-destructive evaluation, microstructure, thermal analysis was done. It was observed that strength and toughness of samples increased by increasing current in TIG with voltage as constant. There are zero cracks, porosity, blow holes, spatter found in welding process of plate using non consumable tungsten electrode with argon gas. The study was carried to observe the elongation, yield strength, hardness, and weld width were based on three different current 25A, 30A, and 35A respectively. It was also observed that at high current 35A has less heat affected zone which was analysed by simulation.

Key Words: AISI 316, AISI 316L, Gas Tungsten Arc Welding (GTAW), Mechanical & Thermal properties

I. INTRODUCTION

Welding is one of the most widely used processes to fabricate stainless steel structures. 304 is the most commonly used types of austenitic stainless steel and versatile, because it has good mechanical properties such as susceptibility formation and welding, so this type serves the industrial sector in a wide range. 304 stainless steel is a widely used material, as it has superior corrosion resistance. In this alloy, 18% chromium is added to improve corrosion resistance, whereas alloying nickel at 8% is used to stabilize the austenite matrix. Alloy 316L stainless steel is a structural material that has been widely used in many industrial fields, such as the nuclear, cryogenic, and shipbuilding industries. It is developed from alloy 304 / 304L. It is characterized by its excellent mechanical properties, and it is often called nickel, chromium and molybdenum alloy. This alloy is used in the marine environment, and at low temperatures. It has an excellent corrosion resistance in the welding conditions. Austenitic is the most widely used type of stainless steel. It has a nickel content of at least of 7%, which makes the steel structure fully austenitic and gives it ductility, a large scale of service temperature, non-magnetic properties and good weld ability. The range of applications of austenitic stainless steel includes house wares, containers, industrial piping and vessels, architectural facades and constructional structures. Austenitic grades are those alloys which are commonly in use for stainless applications. The austenitic grades are not magnetic. The most common austenitic alloys are iron chromium- nickel steels and are widely known as the 300 series. The austenitic stainless steels, because of their high chromium and nickel content, are the most corrosion resistant of the stainless group providing unusually fine mechanical properties. They cannot be hardened by heat treatment, but can be hardened significantly by cold-working.

A. Characteristics Of Stainless Steel

The special material properties of stainless steels affect all four match inability factors: in general, it can be said that the higher the alloy content of a stainless steel, the more difficult it is to machine. The special properties that make stainless steels difficult to machine occur to a greater or lesser extent in all grades of stainless steels but are most marked in the austenitic grades. They can be summarized in five points:

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- Stainless steels work-harden considerably.
- Stainless steels have low thermal conductivity.
- Stainless steels have high toughness.
- Stainless steels tend to be sticky.
- Stainless steels have poor chip-breaking characteristics.

Stainless steel is selected for carrying out the experimental analysis because of its many advantages and easy availability in the market. As the stainless steel is classified in different categories like austenitic, ferritic, martensitic etc… from this we have chosen austenitic stainless steel (304 & 316L) because of its low cost, easy availability in the market. TIG welding process are chosen to carry out the experimental analysis on stainless steel.

B. Gas Tungsten Arc Welding

The process has been called non consumable electrode welding and is very often referred to as TIG (tungsten inert gas) welding. However, because shielding gas mixtures that are not inert can be used for certain applications, the American Welding Society (AWS) adopted gas tungsten arc welding (GTAW) as the standard terminology for the process. Numerous improvements have been made to the process and equipment since the early days of the invention. Welding power sources were developed specifically for the process, some providing pulsed direct current and variable-polarity alternating current. Water-cooled and gas-cooled torches were developed.

The tungsten electrodes were alloyed with small amounts of active elements to increase emissivity, thus improving arc starting, arc stability, and electrode life. Shielding gas mixtures were identified for improved welding performance. Researchers continue to pursue improvements in such areas as automatic controls, vision and penetration sensors, and arc length controls. The fundamentals of the GTAW process and a variation that uses pulsed current (GTAW-P) are discussed in this chapter, along with applications of the process, equipment and consumables used, techniques and procedures, welding variables, weld quality, and safety considerations. The torch is moved along the workpiece and the arc progressively melts the surfaces of the joint. If specified, filler metal, usually in the form of wire, is added to the leading edge of the weld pool to fill the joint.

The four basic components common to all GTAW setups are a

- Torch
- The electrode,
- A welding power source
- Shielding gas

C. Advantages Of Argon Over Helium Inert Gas

For general, purpose quality weld, argon offers many advantages over helium

- Easy arc initiation,
- Cost effective and good availability
- Good cleaning action
- Shallow penetration required for thin sheet welding of Nickel and magnesium alloys.

II. MATERIAL SELECTION

For welding of AISI 304 and AISI 316 L using AISI 304 Filler wire was studied. Survey explains that the process used for welding of stainless steel are SMAW, MIG, TIG, are widely used for welding of AISI 304 and AISI 316 L. It is observed that Tungsten inert gas welding is the most feasible process for welding AISI 304 and AISI 316 L most productively and economically.

Material Selection:

- AISI 304
- AISI 316 L

A. Properties Of AISI 304

The material is selected is grade AISI 304 which is class of Stainless steel and Austenitic type material, it's common name is Chromium-Nickel steel. This is the most versatile and one of the most widely applied of the 300 series stainless steels.

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TABLE I CHEMICAL COMPOSITION OF AISI 304

Elements	C	Mn	Si	Cr	Ni	P	S
Weight %	0.060	0.86	0.031	18.350	8.200	0.0310	0.010

B. Properties of AISI 316L

316/316L is an 18/8 austenitic steel enhanced with an addition of 2.5% Molybdenum, to provide superior corrosion resistance to type 304 stainless steel.316/316L has improved pitting corrosion resistance and has excellent resistance to sulphates, phosphates and other salts.316/316L has better resistance than standard 18/8 types to sea water, reducing acids and solution of chlorides, bromides and iodides.

TABLE III CHEMICAL COMPOSITION OF AISI 316L

Elements	C	Mn	Si	P	S	Cr	Mo	Ni
Weight %	0.03	2	0.75	0.045	0.030	18.850	2-3	10.0

C. Properties of AISI 304 Filler Material

For welding the AISI 304 and AISI 316 L. The Filler wire chosen was AISI 316 L because it has the matching properties with both the metals. The chemical composition foe the filler wire of AISI 316 L was tabulated below in the table. Properties of AISI 304 filler material:

- Density - 8.0 g/cm3
- Melting point - 1400°C
- Ultimate tensile strength -485 Mpa
- Yield strength - 170 Mpa
- Elongation - 40 %

TABLE IIIII CHEMICAL COMPOSITION OF AISI 304 FILLER MATERIAL

Elements	C	Mn	Si	Cr	Ni	P	S
Weight %	0.060	0.86	0.031	18.350	8.200	0.0310	0.010

D. Welding Parameters

- Weld type – Butt Joint
- Groove type – Single V groove
- Current range – 25A,30A,35A
- Voltage – 70 Volts
- Shielding gas – Argon
- Shielding gas flow rate – 21.5psi
- Polarity – DC Electrode Negative
- Mode of Operation – Manual
- Electrode – 2% Thoriated Tungsten Electrode
- Electrode diameter – 1mm
- Torch position – Vertical

E. Dimensions of Welding Specimen

A simple butt joint has following dimensions:

- Length of specimen – 105mm
- Breadth of specimen – 25mm
- Thickness of specimen – 2mm
- Single V groove depth – 2mm
- V groove chamfer length – 1mm

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F. Welded Specimen

For welding Stainless steel of AISI 304 and AISI 316 L plate using the filler wire of AISI 304 bead on plate welding using the different current ranges varying at 25 amps, 30 amps, 35 amps. From the bead on plate the correct current range of 35 amps has chosen from the figure and characterized it by bead width, penetration, melting rate of filler wire etc. Almost all the parameters was good during welding except these,

- Linear Misalignment - Due to application of heat.
- Lack of Side Fusion - Due to improper feeding of filler wire.
- Improper bead width

III. RESULTS AND DISCUSSION

A. Liquid Penetrant Testing

Liquid Penetrant processes are non-destructive testing methods for detecting discontinuities that are open to surface. They may be effectively used in the inspection of both ferrous and non-ferrous metals and on non-porous, non-metallic materials, such as ceramics, plastics and glass. Surface discontinuities, such as cracks, seams, laps, cold shuts and laminations are indicated by these methods. Flaw detection with the help of liquid penetrant is being increasingly used in various industries in the country and recommendations of a general character providing guidance on the applications of these methods are considered necessary.

Surface Preparation: In general satisfactory results can be obtained when the surface is in the as welded. The surface to be examined and all adjacent areas within at least 25 mm should be dry, free from any dirt, lint, grease, welding flux, weld spatter, oil, or other extraneous matter that could obscure surface openings or otherwise interfere with the examination.

Application of Penetrant: After the part has been thoroughly cleaned, apply the penetrant to the surface to be inspected. In case of small components, they may be dipped in a tank of penetrant. Where only a local area of a component is to be tested, the penetrant may be applied by a brush or spray. Regardless of how it is applied, it is important that all surfaces are wet by the penetrant. The length of penetration time is critical and depends upon the type of material being inspected, type of penetrant, kind and size of defect anticipated together with the temperature of the penetrant. The dwell time is taken as 10 minutes

Application of Developer: After washing off the surface penetrant in the rinsing operation, apply developer to the part to blot back to the surface any penetrant that may have penetrated into discontinuities. Developers are either of dry type or wet type. Developer, whether dry or wet, shall be applied as soon as possible after removal of the excess penetrant. A developing time should be allowed before final inspection of the part to allow the developer to bring back to the surface the penetrant that may be in discontinuities. Excessively long developing time of around 10 min is generally adequate may cause the penetrant in large deep discontinuities to bleed profusely, making a broad, smudgy indication and making appraisal of true size and type of defect difficult. A good practice is to start observation as soon developer is applied.

Fig. 1 Application of Developer

Inspection: After repeating of about 3 cycles of process, there is no volumetric flaws and cracks in the surface of the specimen. Therefore, the good quality of weld and proper penetration of the weld are achieved.

B. Optical Microscope

In this study optical microscope with a magnification of 100X has used. The microstructure was taken only for the sample which is welded using the optimized parameter. The specimen cut across transverse to the welding direction has been polished in the subsequent emery papers such as 220, 400, 600, 800 emery sheet and followed by cloth polishing. After that the welded specimen was etched to reveal the microstructures. The etchant used for this purpose is Ferric chloride, ammonium chloride, HCl and Distilled water etched for few seconds. The microstructures of the welded samples are analysed in the OEM by applying the mixture of these etchants.

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TABLE IVV ETCHANT DETAILS

Adlers etchant	**Concentration**
Ferric chloride	45 gm
Ammonium chloride	9 gm
Hydrochloric acid	150 ml
Distilled water	75 ml

C. Vickers Microhardness Testing

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 500 kgf. The diagram of a Vickers indentation is shown in figure.

The Vickers hardness may be determined from the following equation

Vickers hardness = $2P\sin(\Theta/2)/l^2 = 1.854P/L^2$

Where P = applied load, kg

L = average length of diagonals, mm

Θ = angle between opposite face of diamond = 136°

The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. When the mean diagonal of the indentation has been determined the Vickers hardness may be calculated from the formula, but is more convenient to use conversion tables. The Vickers hardness should be reported like 800 HV/10, which means a Vickers hardness of 800, was obtained using a 10 kgf force.

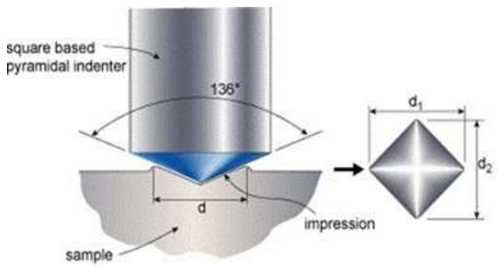

Fig. 2 Vickers Indentation

The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. Several different loading settings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness testing methods.

The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is more expensive than the Brinell or Rockwell machines. The following hardness values has been achieved in the Vickers micro hardness testing method for different current values 25A, 30A, 35A.

TABLE IV VICKERS HARDNESS VALUES FOR LOAD OF 500KGF FOR AISI 304 & AISI 316L AT 25A

NO OF TRIALS	Base Metal AISI 304	HAZ	Weld Metal	HAZ 2	Base Metal AISI 316L
1	322	241	341	243	331
2	309	270	339	265	330
3	315	273	349	259	325

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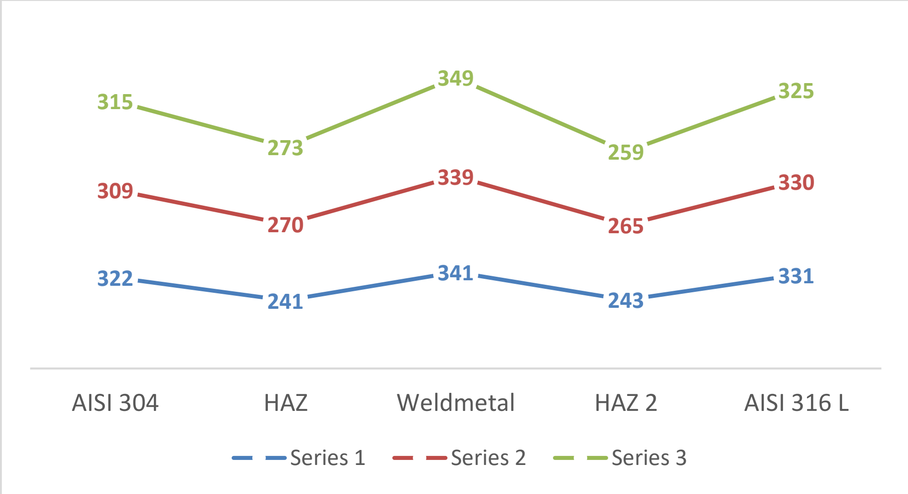

Fig. 3 Micro Hardness Chart for AISI 304 & AISI 316L at 25A

TABLE V VICKERS HARDNESS VALUES FOR LOAD OF 500KGF FOR AISI 304 & AISI 316L AT 30A

NO OF TRIALS	Base Metal AISI 304	HAZ	Weld Metal	HAZ 2	Base Metal AISI 316L
1	314	265	358	266	339
2	312	271	347	259	335
3	321	269	343	270	334

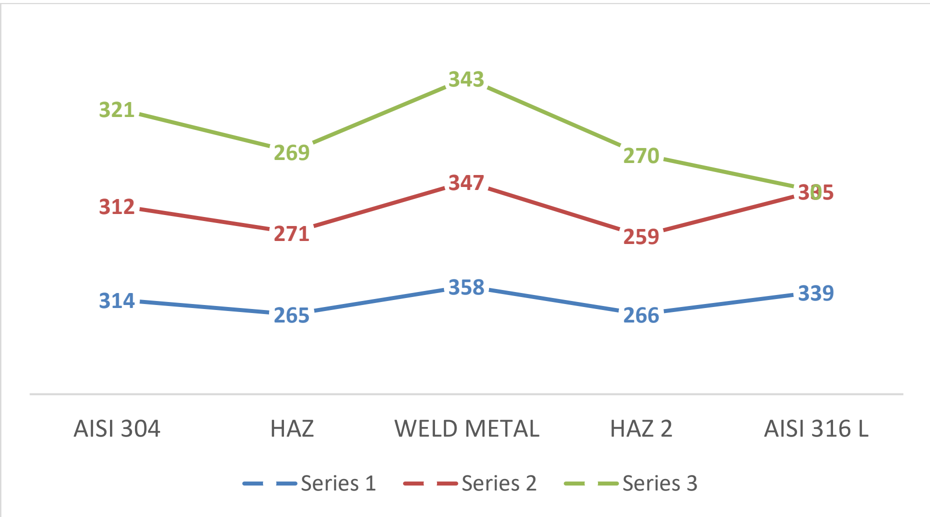

Fig. 4 Micro Hardness Chart for AISI 304 & AISI 316L at 30A

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TABLE VI VICKERS HARDNESS VALUES FOR LOAD OF 500KGF FOR AISI 304 & AISI 316L AT 35A

NO OF TRIALS	Base Metal AISI 304	HAZ	Weld Metal	HAZ 2	Base Metal AISI 316L
1	322	263	348	259	336
2	313	269	343	273	329
3	317	258	351	267	337

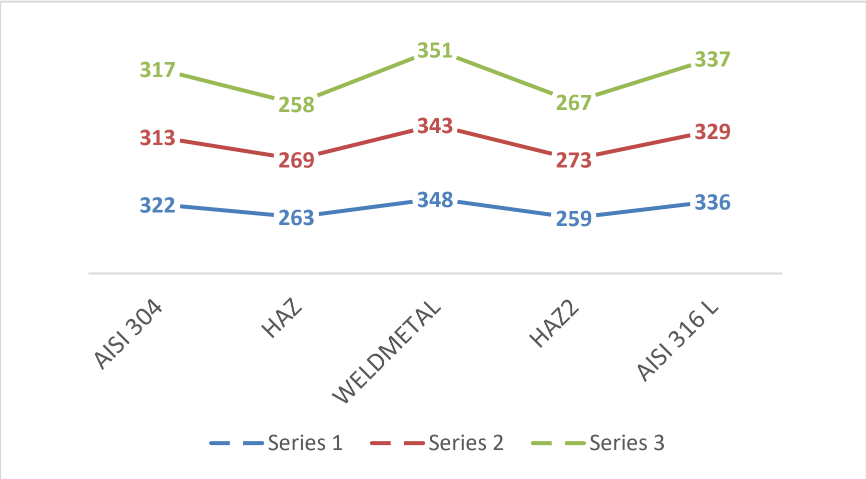
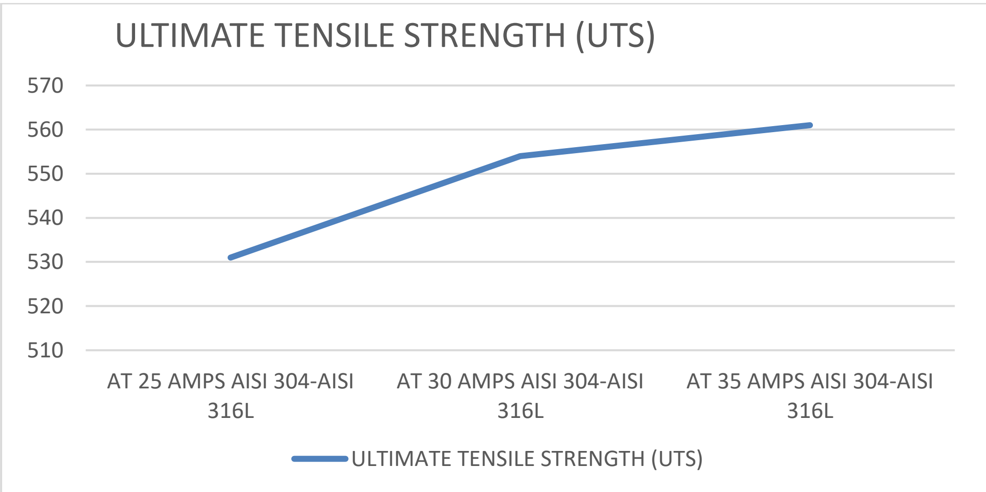


Fig. 5 Micro Hardness Chart for AISI 304 & AISI 316L at 35A

D. Tensile Specimen Preparation

Tensile test specimens are prepared in a variety of ways depending on the test specifications. The most commonly used specifications are BS EN ISO 6892-1 and ASTM E8M. Most specimens use either a round or square standard cross section with two shoulders or a reduced section gauge length in between. The shoulders allow the specimen to be gripped while the gauge length shows the deformation and failure in the elastic region as it is stretched under load. The reduced cross section gauge length of specific dimensions assists with accurate calculation of engineering stress via load over area calculation.



Fig, 6 Ultimate Tensile Strength at Variable amps

E. Thermal Analysis

The thermal analysis was done using ANSYS software with transient thermal state. Here temperature and total heat flux are obtained as output for the given heat input and moving heat energy. For different current voltage and welding speed, heat input has obtained from the formulae.

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$$Q = \frac{V * I * \eta * 60}{S * 1000}$$

- Q – Heat input (KJ /mm)
- V – Voltage (V)
- I – Current (A)
- η - Efficiency (Considered as 0.8 for TIG welding)
- S – Welding speed (mm/min)

Finally the heat input (KJ/mm) is converted into (W/mm^2). We know that [1W = 1Js]

- W – Watt
- Js – Joule second

Meshing

Creating a mesh in the imported geometry is an important step in ANSYS analysis as the size of the finite element is decided by the mesh properties. Finer the mesh is, more accurate are the results. Equal mesh are provided for butt joint with various current value.

- Total number of nodes – 10313
- Total number of elements – 1484
- Element size - 2mm

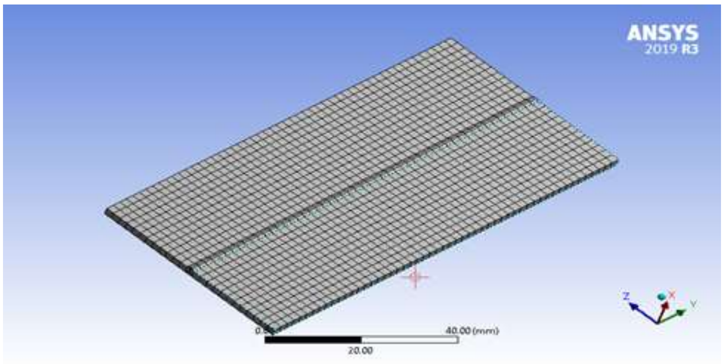

Fig. 7 Meshing

Transient Thermal Analysis at 25A

From the formulae for heat input

$$Q = \frac{V * I * \eta * 60}{S * 1000}$$

- Q – Heat input (KJ /mm)
- V – Voltage (V) = 70V
- I – Current (A) = 25A
- η - Efficiency (Considered as 0.8 for TIG welding)
- S – Welding speed (mm/min) = 60mm/min (considered)

By applying the values: Q = 1.4KJ/mm. Since the length of welded part is 105mm, from the conversion formula

Q = 13W/mm^2.

From the temperature analysis at 13W/mm^2:

- Maximum temperature – 3009.9^{o}C
- Minimum temperature – 815.45^{o}C
- Average temperature – 983.34^{o}C

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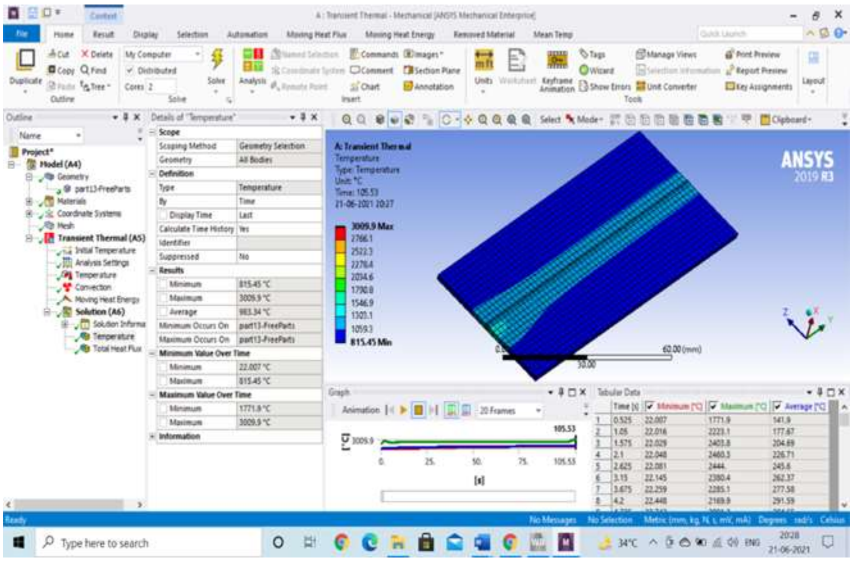

Fig. 8 Thermal Analysis of AISI 304 & AISI 316L at 25A

Total Heat Flux Developed at 25A

From the temperature analysis at $13W/mm^2$:

- Maximum Heat flux – $20.105W/mm^2$
- Minimum Heat flux over time – $7.5W/mm^2$

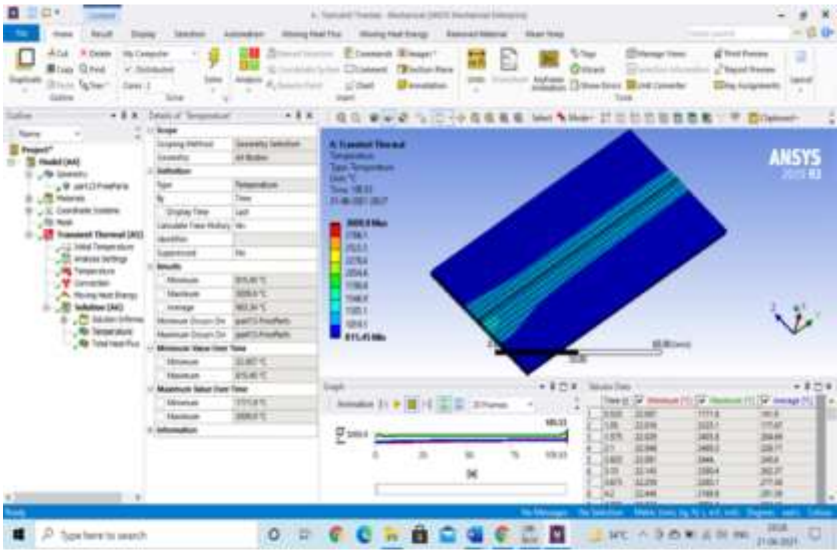

Fig. 9 Total Heat Flux Developed in AISI 304 & AISI 316L at 25A

Transient Thermal Analysis at 30A

From the formulae for heat input

$$Q = \frac{V * I * \eta * 60}{S * 1000}$$

- Q – Heat input (KJ /mm)
- V – Voltage (V) = 70V
- I – Current (A) = 30A

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- η - Efficiency (Considered as 0.8 for TIG welding)
- S – Welding speed (mm/min) = 60mm/min (considered)

By applying the values: Q = 1.7KJ/mm. Since the length of welded part is 105mm, from the conversion formula Q = 16.2W/mm^2.

From the temperature analysis at 16.2W/mm^2:

- Maximum temperature – 3465.6°C
- Minimum temperature – 816.85°C
- Average temperature – 988.9°C

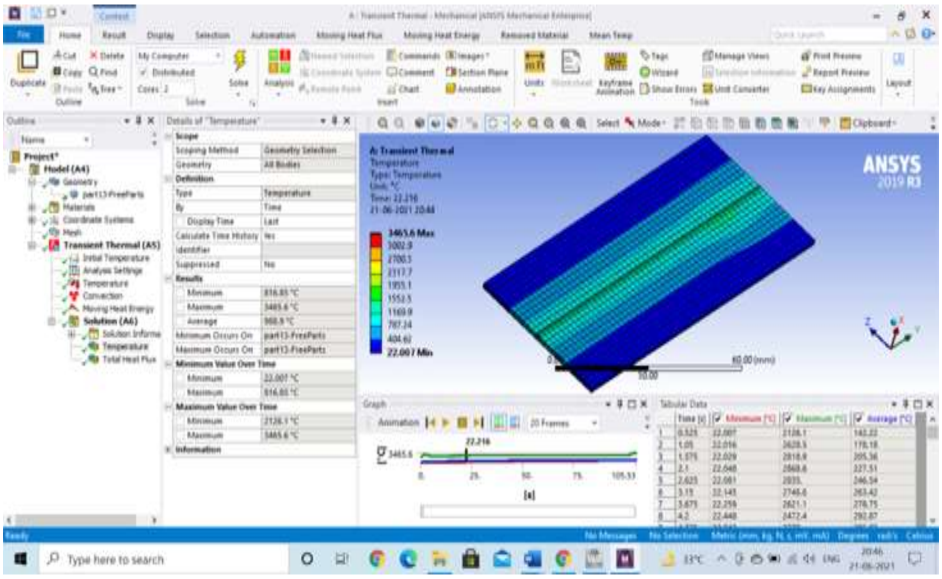

Fig. 10 Thermal Analysis of AISI 304 & AISI 316L at 30A

Total Heat Flux Developed at 30A

From the temperature analysis at 16.2W/mm^2:

- Maximum Heat flux – 25.077W/mm^2
- Minimum Heat flux over time – 9.4668W/mm^2

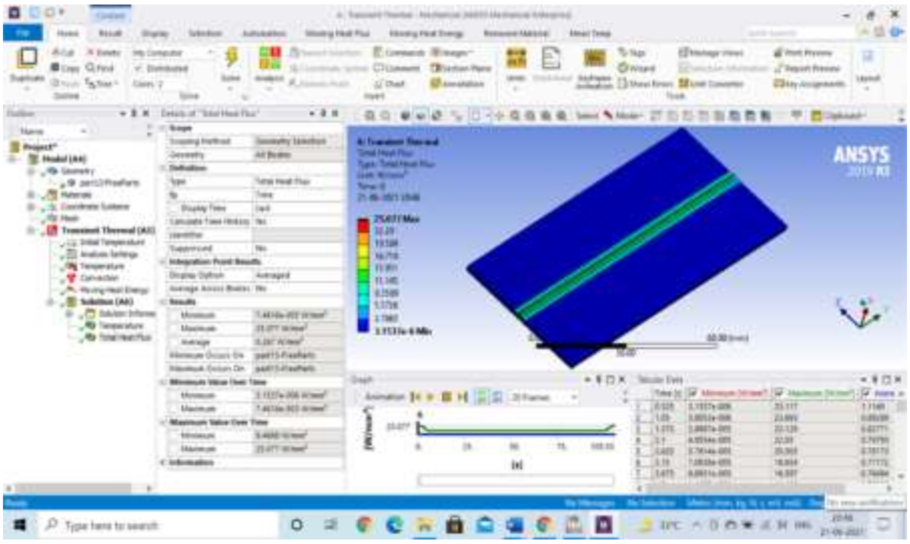

Fig. 11 Total Heat Flux Developed in AISI 304 & AISI 316L at 30A

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Transient Thermal Analysis at 35A

From the formulae for heat input

$$Q = \frac{V * I * \eta * 60}{S * 1000}$$

- Q – Heat input (KJ /mm)
- V – Voltage (V) = 70V
- I – Current (A) = 35A
- η - Efficiency (Considered as 0.8 for TIG welding)
- S – Welding speed (mm/min) = 60mm/min (considered)

By applying the values: Q = 2KJ/mm. Since the length of welded part is 105mm, from the conversion formula

Q = 19W/mm^2.

From the temperature analysis at 19W/mm^2:

- Maximum temperature – 3864.6^{o}C
- Minimum temperature – 818.08^{o}C
- Average temperature – 993.77^{o}C

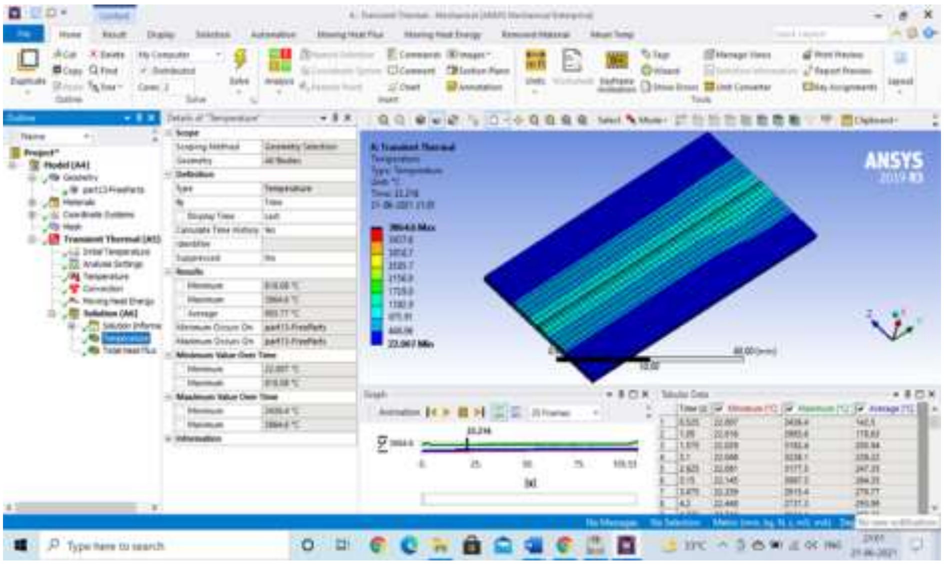

Fig. 12 Thermal Analysis of AISI 304 & AISI 316L at 35A

Total Heat Flux Developed at 35A

From the temperature analysis at 19W/mm^2:

- Maximum Heat flux – 29.429W/mm^2
- Minimum Heat flux over time – 11.183W/mm^2

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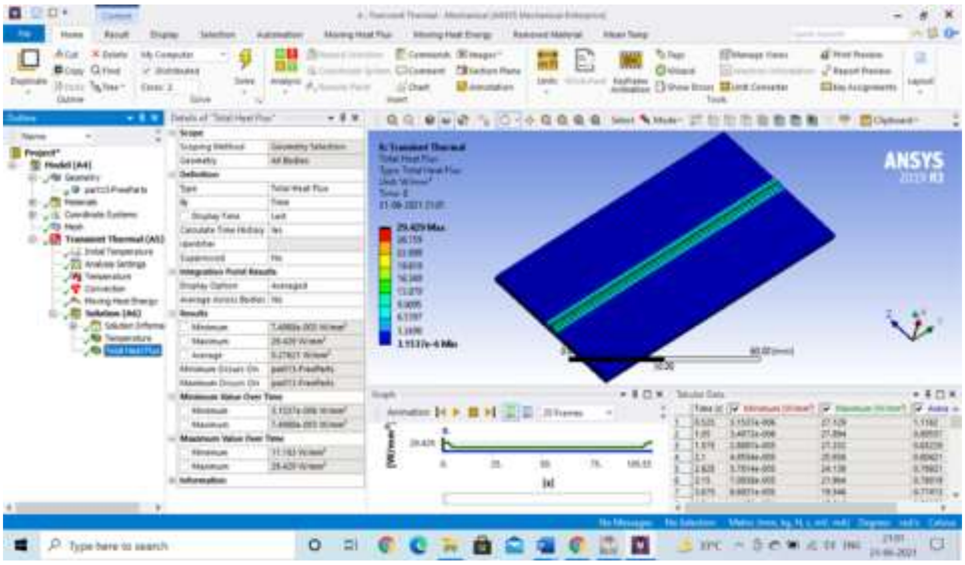

Fig. 23 Total Heat Flux Developed in AISI 304 & AISI 316L at 35A

IV. CONCLUSION

The AISI 304 and AISI 316 L are welded using the filler wire of AISI 304. In Tungsten Inert gas welding by choosing the welding parameter of shielding gas, current range and type of electrode used.
From the test results its observed that from liquid penetrant test, after repeating of about 4 cycles of process, there is no any surface flaws and cracks in the surface of the specimen welded with 30A and 35A. Hence, there is a good quality of weld and proper penetration of the weld are achieved at 30A and 35A as compared to specimen welded at 25A.
From the optical electron microscope having 100X magnitude with 50µm scale test results, it is observed that there is uniform distribution of austenitic grains along the surface of HAZ welded with 35A current, where as the micro structure in 25A and 35A welded specimen shows that the grain coarsening observed at some areas on heat affected zone.
From the results obtained from the micro hardness in table 5.1. It is observed that the welded specimen with 35A shows good hardness in both welded area and HAZ compared to 25A and 30A welded specimen. Table IX shows the average hardness value of three trails obtained from Vickers micro hardness.

TABLE IX AVERAGE HARDNESS VALUE FROM VICKERS MICROHARDNESS

Current (A)	Base Metal AISI 304	HAZ	Weld Metal	HAZ 2	Base Metal AISI 316L
25	322	263	348	259	336
30	313	269	343	273	329
35	317	258	351	267	337

From the tensile test results, it is observed that the weld specimen with 35A has higher tensile strength compared to weld specimen with 30A and 25A and weld specimen broken at HAZ. It is also observed that the hardness in weld metal is higher than the base metal and the HAZ, lower hardness in HAZ is due to high heat input.
From the thermal analysis, the temperature and heat flux obtained in the weld specimen with 35A are higher than weld specimen with 30A and 25A.
From the above results, this study concludes that in Gas tungsten arc welding (GTAW) using argon as inert gas, the minimum current required at constant voltage (70V) for a quality welding obtained with minimum HAZ is 35A. Thus minimal power consumption can be maintained at 35A and 70V for welding stainless steel to obtain minimum HAZ area.

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