INFLUENCE OF ALUMINUM AND TITANIUM ADDITION ON MECHANICAL PROPERTIES OF AISI 430 FERRITIC STAINLESS STEEL GTA WELDS

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ABSTRACT

An attempt has been made to study the influence of grain refining elements such as aluminium (Al) and titanium (Ti) on mechanical properties of AISI 430 ferritic stainless steel welds through gas tungsten arc welding (GTAW) process. Aluminium(Al) and titanium(Ti) powders of -100µm mesh was added in the range from 1g to 3g between the butt joint of ferritic stainless steel . The effect of post-weld annealing at 830°c,30min holding followed by water quenching on microstructure and mechanical properties of AISI 430 ferritic stainless steel welds was also studied. From this investigation, it is observed that the joints fabricated by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7 wt %) led to improved strength and ductility compared to all other joints. The observed mechanical properties have been correlated with the microstructure and fracture features.

KEYWORDS: *AISI 430Ferritic Stainless Steel, Gas Tungsten Arc Welding, Aluminium, Titanium, Mechanical Properties*

I. INTRODUCTION

Ferritic stainless steels (FSS) contain 16-30 wt. % Cr depending on alloy element. Since this steel class is easy forming and resistant to atmospheric corrosion, it is commonly used in architecture, interior and exterior decoration, food industry, dry machine and chemical industry. Ferritic stainless steels are increasingly used for the automotive exhaust systems [1] because of their excellent resistance to stress corrosion cracking, good toughness, ductility and weldability, compared with conventional austenitic stainless steels [2, 3]. In certain applications such as the production of titanium by kroll process, where titanium tetrachloride ($TiCl_4$) is reduced by magnesium, austenitic stainless steels are used for the reduction retorts with an inner lining of ferritic stainless steels to mitigate the problem of leaching of the nickel by molten magnesium. Gas tungsten arc welding (GTAW) is generally used for welding of these alloys because it produces a very high quality welds. Lower heat input and lower current density reduces the arc temperature and arc forces in GTAW [4] The principal weldability issue with the ferritic stainless steels is maintaining adequate toughness and ductility in the weld zone (WZ) and heat affected zone (HAZ) of weldments, this is due to large grain size in the fusion zone [5, 6] because they solidify directly from the liquid to the ferrite phase without any intermediate phase transformation. Normally, FSS has a fine grained, ductile and ferrite structure. However, in melting welding method, intergranular carbon settles, grain coarsening and inter granular carbon precipitation negatively effect on mechanical characteristics of welding joint and such grain coarsening results in lower toughness [7-9].The pronounced grain growth takes place in the HAZ and carbide precipitation occurs at the grain boundaries and this makes the weld more brittle and decreases its corrosion resistance. According to the literature, all stainless steels with carbon content above 0.001% are susceptible to carbide precipitation [10,11].Chromium carbide precipitation may be

responsible for embrittlement, intergranular corrosion and may reduce resistance to pitting corrosion. Furthermore, cracks can occur in the weld metal when it cools down. For this reason, the application of this group of alloys is limited [12]. The problem of grain coarsening in the weld zone of ferritic stainless steel welds is addressed by limiting heat input by employing low heat input welding processes [13-16]. The formation of fine equiaxed grains in weld fusion zone helps in reducing solidification cracking and also in improving the mechanical properties [17, 18]. It has also been suggested that nitride and carbide formers such as B, Al, V and Zr can be added to FSS to suppress grain growth during welding [19]. Studies have been conducted to grain refining of ferritic stainless steel welds by electromagnetic stirring, current pulsing [20, 21], as well as through liquid metal chilling [22]. The current pulsing reduces overall heat input without any spatter [23]. Earlier, attempts have been made to grain refine the welds of these steels by addition of elements such as titanium, aluminium and copper [24, 25].
From the reported literature it is observed that the grain refinement in the weld zone of ferritic stainless steel welds by the addition of grain refining elements such as aluminium (Al) and titanium (Ti) with specified weight percentage for increasing the mechanical properties is not studied. The objective of the present study is to investigate the influence of Al and Ti addition on the microstructure and mechanical properties of AISI 430 ferritic stainless steel welds.

II. EXPERIMENTAL PROCEDURE

The rolled plates of 5mm thick AISI 430 ferritic stainless steel were cut into the required dimension. The chemical composition and mechanical properties of the base material (AISI 430 ferritic stainless steel) were presented in Tables 1 and 2 respectively. GTA welding was carried out using a Master TIG AC/DC 3500W welding machine (Make: kemppi). GTAW process is well suitable for joining thin and medium thickness material like aluminium alloys, steels and for the applications where metallurgical control is critical. The advantages of the GTAW process are low heat input, less distortion, resistance to hot cracking and better control of fusion zone, there by improved mechanical properties. A single 'V' butt-joint configuration (Fig.1) was selected to fabricate the weld joints. Prior to welding the base metal plates were wire brushed and degreased using acetone and preheated to 100°c. All the necessary care was taken to avoid the joint distortion during welding. A filler material confirming to the composition given in Table 1 is used.

Table 1. Chemical composition of the base material and filler material (wt. %)

Material	C	Mn	Si	P	S	Ni	Cr	Fe
Base material (AISI 430 FSS)	0.044	0.246	0.296	0.023	0.002	0.164	17.00	balance
Filler material (AISI 430 FSS)	0.044	0.246	0.296	0.023	0.002	0.164	17.00	balance

Table 2. Mechanical properties of base material

Material	Ultimate Tensile Strength (UTS), MPa	Yield Strength (YS), MPa	Percentage of elongation, (% El)	Impact Toughness, J	Fusion zone hardness, Hv
Base material (AISI 430 FSS)	424	318	13	22	220

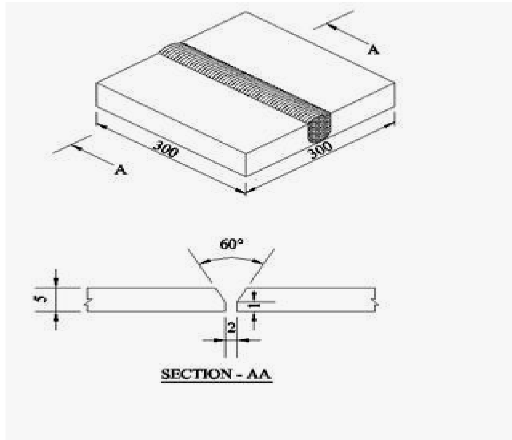

Figure 1 Schematic sketch of the weld joint (All dimensions are in 'mm')

Al and Ti were added as a powder of -100μm mesh (99% purity level) in the range from 1g to 3g between the butt joint of ferritic stainless steel. Weld joint is completed in three passes. The welding parameters were given in Table 3. In order to investigate the influence of post-weld heat treatment on microstructure and mechanical properties of welds, the post-weld annealing at 830°C, 30min holding followed by a water quenching was adopted [26].

Table 3. GTA welding parameters

Parameter	**Value**
Welding current (Amps)	120
Welding speed (mm/min)	50
Electrode polarity	DCSP
Arc voltage (V)	10-13
Arc gap (mm)	2
Filler wire diameter (mm)	1.6
Electrode	2% Thoriated tungsten
Number of passes	3
Shielding gas (Argon), flow rate (L/min)	10
Purging gas(Argon) flow rate (L/ min)	5
Preheat temperature (°C)	100

2.1. Metallography

The objective of this section is to carry out the detailed weld microstructural examinations of ferritic stainless steel weldments using optical microscope and Scanning electron microscope (SEM).
In order to observe the microstructure under the optical microscope, specimens were cut from the welds, and then prepared according to the standard procedures, and etched using aquaregia (1part HNO_3, 3parts HCL). Micro structures of welds in as-welded and post-weld annealed conditions were studied and recorded. Scanning electron microscope was used for fractographic examination.

2.2. Mechanical Testing

The objective of this section is to evaluate the transverse tensile properties such as tensile strength, yield strength and percentage of elongation of FSS weldments in the as-welded and post weld annealed conditions by conducting the tensile test. Fusion zone hardness of all the weldments is to be measured. FSS are higher in chromium (16-30%) and carbon (0-12%) tends to form chromium carbide at grain boundaries in the weld heat affected zone. The refinement of grains at the weldments and increase of weld ductility and toughness are the major requirements in FSS weldments. In order to assess the toughness of the weld joints, charpy impact tests are to be performed.

The tensile test specimens were made as per ASTM standards by cutting the weld joints and machined by EDM wire cut to the required dimensions. The configuration of the tensile test specimen adopted is given in Fig.2. The tensile test was conducted with the help of a computer controlled universal testing machine (Model: TUE-C- 600) at a cross head speed of 0.5mm/min. During tensile tests all the weld specimens were failed within the weld region. Micro-hardness tests were carried out using a Vickers digital micro-hardness tester in transverse direction of the weld joint. A load of 300g was applied for duration of 10 s. The micro-hardness was measured at an interval of 0.1mm across the weld, 0.5mm across the heat-affected zone (HAZ) and unaffected base metal.

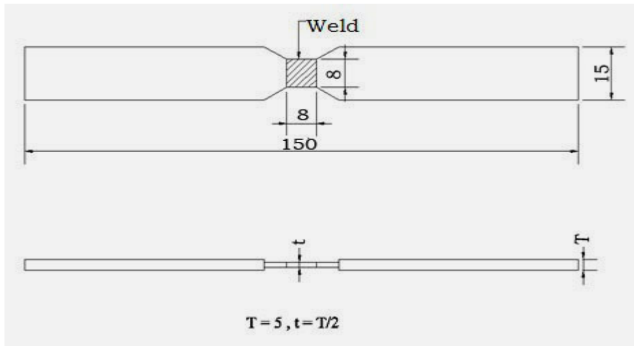

Figure 2 Configuration of tensile test specimen (All dimensions are in 'mm')

Charpy impact test specimens were prepared to the dimensions shown in Fig.3 to evaluate the impact toughness of the weld metal. Since the thickness of the plate was small, subsize [27] specimens were prepared. The impact test was conducted at room temperature using a pendulum type charpy impact testing machine.

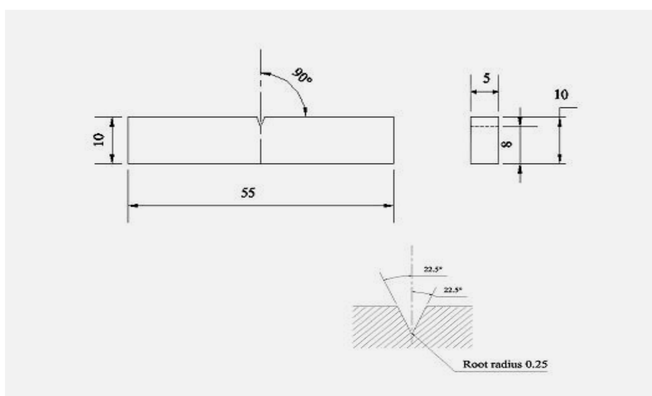

Figure 3 Configuration of Charpy V-notch impact test specimen
(All dimensions are in 'mm')

III. RESULTS

3.1. Mechanical properties

Mechanical properties of all the weld joints in as-welded and post-weld annealed conditions were evaluated and the results are presented in Tables 4 and 5 respectively.

Table 4. Mechanical properties of AISI 430 ferritic stainless steel weldments in as-welded condition

Joint Condition	Ultimate Tensile Strength (UTS), MPa	Yield Strength (YS), MPa	Percentage of elongation, (% El)	Impact Toughness, J	Fusion zone hardness, Hv
1g Al (1.7 wt %) addition	455	346	3.6	2	200
2g Al (2.4 wt %) addition	468	357	6.0	4	230
3g Al (6.2 wt %) addition	440	328	2.7	4	210
1g Ti (0.3 wt %) addition	419	335	2.7	4	210
2g Ti (0.7 wt %) addition	424	356	4.6	4	245
3g Ti (0.9 wt %) addition	414	330	2.5	3	232
Filler material (AISI 430 FSS) addition without Al and Ti	385	325	2.3	3	195

Table 5. Mechanical properties of AISI 430 ferritic stainless steel weldments in post-weld annealed condition

Joint Condition	Ultimate Tensile Strength (UTS), MPa	Yield Strength (YS), MPa	Percentage of elongation, (% El)	Impact Toughness, J	Fusion zone hardness, Hv
1g Al (1.7 wt %) addition	467	355	12	4	215
2g Al (2.4 wt %) addition	478	385	14	6	240
3g Al (6.2 wt %) addition	450	346	8	4	220
1g Ti (0.3 wt %) addition	421	340	8	4	225
2g Ti (0.7 wt %) addition	484	365	15	6	255
3g Ti (0.9 wt %) addition	415	334	10	4	240
Filler material (AISI 430 FSS) addition without Al and Ti	393	330	7.8	4	200

From the results it is observed that by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7wt %) to the weld pool led to an increase in its strength and ductility as compared to all other joints. This can be attributed to fine grain microstructure and also formation of precipitates such as aluminium carbides (Al_4C_3) and titanium carbides (TiC) respectively in the weld zone of ferritic stainless steel weldments, which are believed to be responsible for the grain refinement.

3.2 Microstructure studies

Microstructures of all the joints were examined at the weld region of ferritic stainless steel welds in as-welded and post-weld annealed conditions and the results are presented in Figs. 4, 5 and 6. From the results it is observed that the joints fabricated by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7wt %) resulted in fine equiaxed grains compared to all other joints. Grain size in the weld zone of ferritic stainless steel weldments were measured by using line intercept method [28] and the results are presented in Table 6. The chemical composition of the all weld metals (wt %) is given in Table 7. Scanning electron microscopy (SEM) was applied to observe the distribution of precipitates in the fusion zone of weldments made by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7wt %). SEM micrographs of precipitations are shown in Fig.7

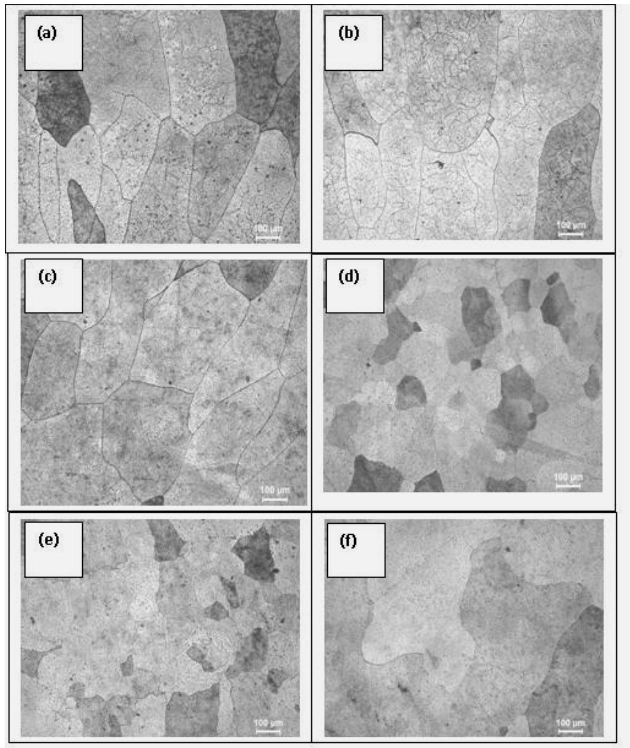

Figure 4 Microstructure of weld region of AISI 430 ferritic stainless welds in as-welded condition
(a) 1g Al (1.7wt %) addition (b) 2g Al (2.4wt %) addition
(c) 3g Al (6.2wt %) addition (d) 1g Ti (0.3wt %) addition
(e) 2g Ti (0.7wt %) addition (f) 3g Ti (0.9wt %) addition

Table 6. Grain size in the weld zone of AISI 430 ferritic stainless steel weldments

Joint condition	Grain size(µm)
1g Al (1.7 wt %) addition	300
2g Al (2.4 wt %) addition	200
3g Al (6.2 wt %) addition	300
1g TI (0.3 wt %) addition	250
2g Ti (0.7 wt %) addition	200
3g Ti (0.9 wt %) addition	360
Filler material (AISI 430 FSS) addition without Al and Ti	380

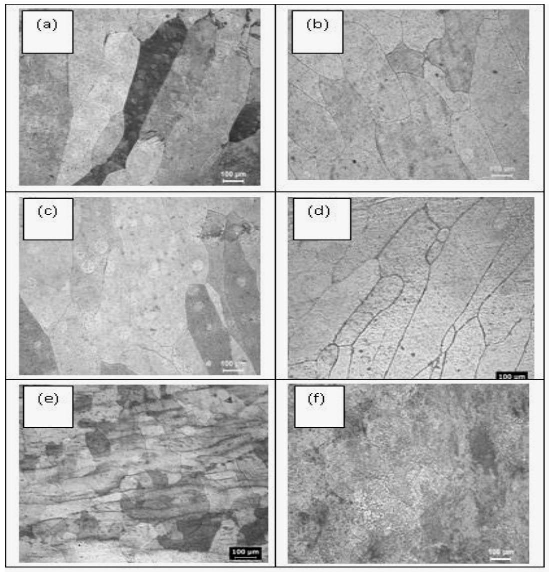

Figure 5 Microstructure of weld region of AISI 430 ferritic stainless welds in post-weld annealed condition
(a) 1g Al (1.7wt %) addition (b) 2g Al (2.4wt %) addition
(c) 3g Al (6.2wt %) addition (d) 1g Ti (0.3wt %) addition
(e) 2g Ti (0.7wt %) addition (f) 3g Ti (0.9wt %) addition

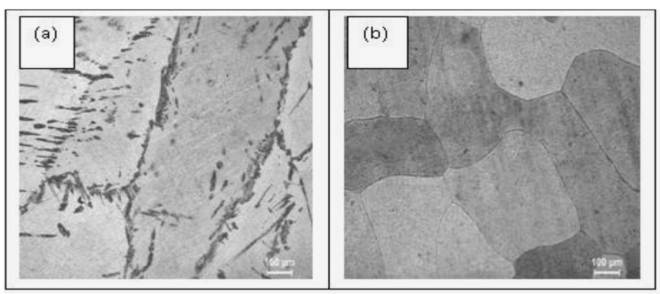

Figure 6 Microstructure of weld region of AISI 430 ferritic stainless welds made by the addition of filler material without Al and Ti
(a) As-welded condition (b) Post-weld annealed condition

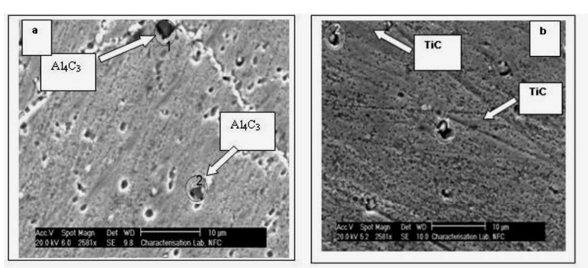

Fig.7 SEM micrographs of the precipitations in the fusion zone of ferritic stainless steel weldments
(a) 2g Al (2.4 wt %) addition
(b) 2g Ti (0.7 wt %) addition

3.3 Fractography

The objective of this section is to analyze the fracture surfaces of tensile and impact specimens of the ferritic stainless steel weld joints using SEM to under stand the fracture surface morphology.

The fractured surfaces of the tensile and impact specimens of AISI 430 ferritic stainless steel weldments in as-welded and post-weld annealed conditions were analyzed using SEM to reveal the fracture surface morphology. Figs. 8,9 and Figs.10,11 displays the fractographs of tensile and impact specimens of weldments made by the addition of Al , Ti and filler material (AISI 430 FSS) addition without Al and Ti in as-welded and post-weld annealed conditions respectively.

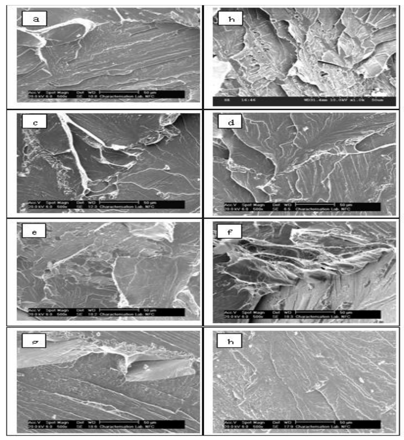

Figure 8 Fractographs of tensile (a, b, c, d) and impact specimens (e, f, g, h) of ferritic stainless steel weldments in as-welded condition
(a) 1g Al (1.7 wt %) addition (b) 2g Al (2.4 wt %) addition
(c) 3g Al (6.2 wt %) addition (d) filler material (AISI 430 FSS) addition without Al
(e) 1g Al (1.7 wt %) addition (f) 2g Al (2.4 wt %) addition
(g) 3g Al (6.2 wt %) addition (h) filler material (AISI 430 FSS) addition without Al

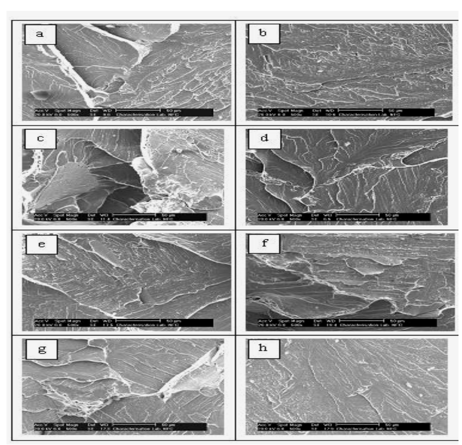

Figure 9 Fractographs of tensile (a, b, c, d) and impact specimens (e, f, g, h) of ferritic stainless steel weldments in as-welded condition
(a) 1g Ti (0.3 wt %) addition (b) 2g Ti (0.7 wt %) addition
(c) 3g Ti (0.9 wt %) addition (d) filler material (AISI 430 FSS) addition without Ti
(e) 1g Ti (0.3 wt %) addition (f) 2g Ti (0.7 wt %) addition
(g) 3g Ti (0.9 wt %) addition (h) filler material (AISI 430 FSS) addition without Ti

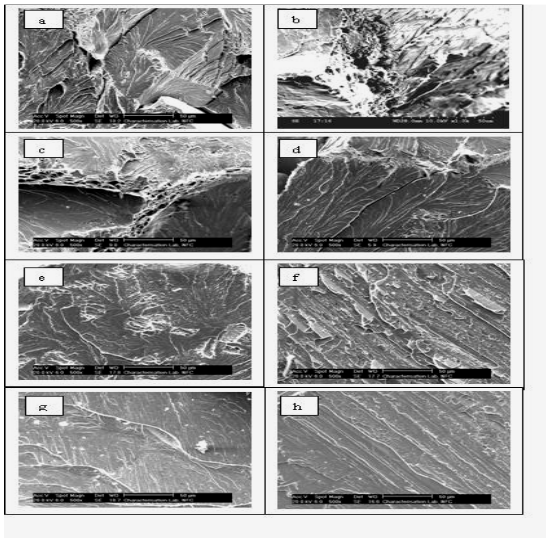

Figure 10 Fractographs of tensile (a, b, c, d) and impact specimens (e, f, g, h) of ferritic stainless steel weldments in post-weld annealed condition
(a) 1g Al (1.7 wt %) addition (b) 2g Al (2.4 wt %) addition
(c) 3g Al (6.2 wt %) addition (d) filler material (AISI 430 FSS) addition without Al
(e) 1g Al (1.7 wt %) addition (f) 2g Al (2.4 wt %) addition
(g) 3g Al (6.2 wt %) addition (h) filler material (AISI 430 FSS) addition without Al

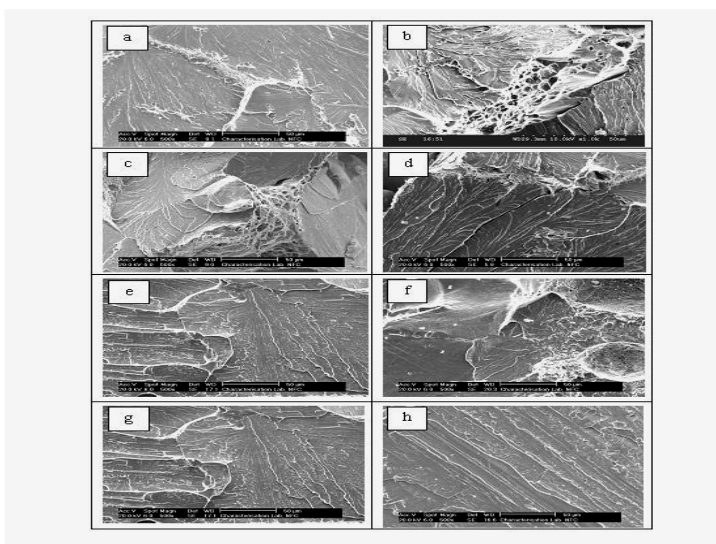

Figure 11 Fractographs of tensile (a, b, c, d) and impact specimens (e, f, g, h) of ferritic stainless steel weldments in post-weld annealed condition
(a) 1g Ti (0.3 wt %) addition (b) 2g Ti (0.7 wt %) addition
(c) 3g Ti (0.9 wt %) addition (d) filler material (AISI 430 FSS) addition without Ti
(e) 1g Ti (0.3 wt %) addition (f) 2g Ti (0.7 wt %) addition
(g) 3g Ti (0.9 wt %) addition (h) filler material (AISI 430 FSS) addition without Ti

Table 7. Chemical composition of all weld metals (wt. %)

Joint condition	C	Mn	Si	P	S	Ni	Cr	Al	Ti	Fe
1g Al addition	0.040	0.11	0.27	0.006	0.028	0.261	17.02	1.7	0.01	balance
2g Al addition	0.029	0.25	0.30	0.004	0.030	0.330	17.09	2.4	0.01	balance
3g Al addition	0.035	0.18	0.25	0.002	0.027	0.235	17.20	6.2	0.02	balance
1g Ti addition	0.035	0.05	0.70	0.021	0.005	0.164	17.04	0.03	0.3	balance
2g Ti addition	0.023	0.36	0.31	0.024	0.005	0.342	17.21	0.06	0.7	balance
3g Ti addition	0.024	0.28	0.29	0.021	0.006	0.322	17.40	0.09	0.9	balance
Filler material (AISI 430 FSS) addition without Al and Ti	0.036	0.38	0.41	0.007	0.030	0.241	16.23	0.036	0.013	balance

IV. DISCUSSION

From this investigation it is observed that the addition of Al to the weld pool, up to 2g (2.4 wt %) resulted in increased mechanical properties, this can only be attributed to the formation of precipitates such as aluminium carbides (Al_4C_3). Whereas, by increasing Al content beyond 2g (2.4 wt %) resulted in decreased mechanical properties this may be attributed to the strong detrimental effect of ferrite promotion compared to the beneficial effect of precipitation. The addition of Ti to the weld pool, up to 2g(0.7 wt %) resulted in increased mechanical properties, this may be attributed to solid-solution strengthening by the formation of titanium carbides(TiC), which are believed to be responsible for the grain refinement. Whereas, by increasing Ti content beyond 2g (0.7 wt %) resulted in decreased mechanical properties this can be attributed to the titanium addition can be in excess of that required for the formation of TiC and the effect of ferrite promotion.

The tensile and impact fracture surfaces of ferritic stainless steel weldments with Al addition and filler material (AISI 430 FSS) addition without Al in as-welded condition (Fig. 8 a-h) shows cleavage fracture indicating brittle failure. The tensile and impact fracture surfaces of weldments made by the addition of 1g Al (1.7wt %) , 3g Al (6.2 wt %) in post-weld annealed condition (Fig.10 (a),(c),(e) & (g)) shows quasi cleavage fracture indicating both ductile and brittle fracture. The tensile and impact fracture surfaces of ferritic stainless steel weldments with Ti addition and filler material (AISI 430 FSS) addition without Ti in as-welded condition (Fig.9 a-h) shows cleavage fracture indicating brittle failure. The tensile and impact fracture surfaces of weldments made by the addition of 1g TI (0.3 wt %) , 3g Ti (0.9 wt %) in post-weld annealed condition (Fig. 11 (a),(c),(e) &(g)) shows quasi cleavage fracture indicating both ductile and brittle fracture. Whereas, the tensile and impact fracture surfaces of weldments made by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7 wt %) in post-weld annealed condition Fig.10 (b) & (f)) and (Fig.11 (b) & (f)) respectively represents ductile fracture as fine dimples are seen in the joints. Since fine dimples are the characteristic feature of ductile fracture, the joints made by the addition of 2g Al (2.4 wt %) and 2g Ti (0.7 wt %) in post-weld annealed condition have shown higher ductility compared to all other joints and base material, this is attributed to the martensite formed in the HAZ is tempered during post-weld annealing, which reduces the embrittlement and hence the ductility is improved.

V. CONCLUSIONS

The influence of Al and Ti addition in the range from 1g Al (1.7wt%) to 3g Al (6.2 wt %) and 1g Ti (0.3 wt %) to 3g Ti (0.9 wt %) and filler material (AISI 430 ferritic stainless steel) addition without Al

and Ti on microstructure and mechanical properties of AISI 430 ferritic stainless steel welds have been analyzed in detail and the following conclusions are derived.
1. The addition of 2g Al (2.4 wt %) and 2g Ti (0.7 wt %) resulted in better tensile properties (Ultimate Tensile Strength, Yield Strength & percentage of elongation) compared to all other joints. This is due to the fine grain microstructure and also formation of aluminium carbides (Al_4C_3) and Titanium carbides (TiC) in the weld zone of ferritic stainless steel weldments respectively, which are believed to be responsible for grain refinement.
2. There is a marginal improvement in the ductility of ferritic stainless steel weldments made by the addition of 2g Al (2.4 wt %) and 2gTi (0.7 wt %) in post-weld annealed condition compared to all other joints. This is attributed to the formation of fine dimples, ductile voids in the weld zone of ferritic stainless steel weldments
3. The hardness was the highest in the fusion zone of ferritic stainless steel weldments made by the addition of 2g Ti (0.7 wt %) compared to all other joints. This could be explained by the existence of fine Ti-based carbides (TiC) and solid-solution strengthening by the element Ti during welding

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