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Effect of copper and aluminium addition on mechanical properties and corrosion behaviour of AISI 430 ferritic stainless steel gas tungsten arc welds

Mallaiah Gurram[a,*], *Kumar Adepu*[b], *Ravinder Reddy Pinninti*[c], *Madhusudhan Reddy Gankidi*[d]

[a] *Department of Mechanical Engineering, Kamala Institute of Technology and Science, Huzurabad, India*
[b] *Department of Mechanical Engineering, National Institute of Technology Warangal, Warangal, India*
[c] *Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, India*
[d] *Defence Metallurgical Research Laboratory, Defence Research and Development Organisation, Hyderabad, India*

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ABSTRACT

The influence of grain refining elements such as copper (Cu) and aluminium (Al) on mechanical properties of AISI 430 ferritic stainless steel welds through gas tungsten arc welding process was studied. Cu (foil form) and Al powder of −100 μm mesh was added in the range from 1 to 3 g between the butt joint of ferritic stainless steel. In order to investigate the influence of post-weld heat treatment on the microstructure and mechanical properties of welds, post-weld annealing was adopted at 830 °C, 30 min holding followed by water quenching. Corrosion behaviour of ferritic stainless steel welds was also studied. From this investigation, it is observed that the joints made by the addition of 2 g Al (2.4 wt.%) in post-weld annealed condition led to improved strength. There is a marginal improvement in the ductility and pitting corrosion resistance of ferritic stainless steel welds by the addition of 2 g Cu (0.18 wt.%) in post-weld annealed condition. The observed mechanical properties have been correlated with microstructure, fracture features and corrosion behaviour of ferritic stainless steel weldments.

1. Introduction

Ferritic stainless steel (FSS) in the absence of nickel provides moderate corrosion resistance at lower cost. The higher chromium grades offer good resistance to oxidation at high temperature [1]. Ferritic stainless steels are commonly used in automobile exhaust systems [2], furnace parts and combustion chambers because of their excellent resistance to stress corrosion cracking, good toughness, ductility and weldability compared with austenitic stainless steels [3]. For many of these applications welding is a major route adopted for fabrication of components made by these alloys. Gas tungsten arc welding (GTAW) is generally used for fabrication of ferritic stainless steel components because it produces a very high quality weld. Ferritic stainless steels exhibit the problem

* *Corresponding author.*
E-mail: gmallaiah_kits@yahoo.co.in (M. Gurram).
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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	Bal.
Filler material (ER 430)	0.044	0.246	0.296	0.023	0.002	0.164	17.00	Bal.

Table 2 – Mechanical properties of base material.

Material	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Impact toughness (J)	Microhardness (HV)
AISI 430 ferritic stainless steel	424	318	13	22	220

of grain coarsening in the weld zone and heat affected zone of fusion welds and consequent low toughness and ductility [4]. This is due to the absence of phase transformation during which grain refinement could occur. The problem of grain coarsening in the weld zone of FSS welds is addressed by limiting heat input by employing low heat input welding processes [5–8]. Studies have been conducted to grain refine FSS welds by electromagnetic stirring [9] by employing alternate current gas tungsten arc (GTA) welding process [10–12]. Grain refining elements such as aluminium (Al) and titanium (Ti) are added to transform the columnar grains in the centre of the weld to equiaxed microstructure in GTA welds. This has been reported to result in elimination of weld centre line cracking and also improve the toughness of welds. The transition from columnar to equiaxed grains is reported to be due to fine precipitates of carbonitrides aiding heterogeneous nucleation. It has also been suggested that nitrogen (N) in the shielding gas can refine the weld metal grain size by the formation of nitride (Ni) [13]. It was attempted to achieve grain refinement in the welds of these steels by addition of elements, such as, Ti, Al and Cu [10,14].

From the reported work it is observed that the grain refinement in the weld zone of FSS joints by the addition of Cu and Al with specified weight percentage has, so far, not been studied. The objective of the present study is to investigate the influence of Cu and Al addition on mechanical properties and corrosion behaviour of AISI 430 FSS welds.

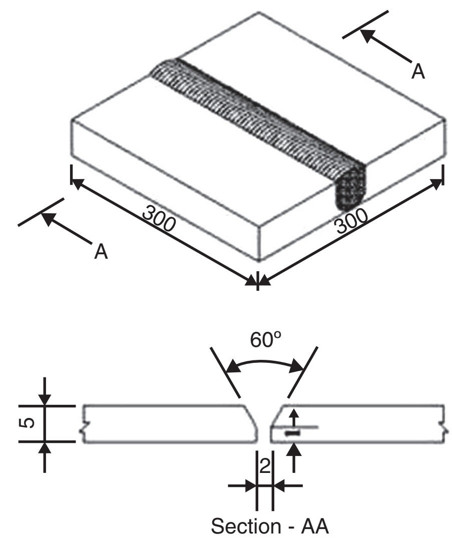


Fig. 1 – Schematic sketch of the weld joint (all dimensions in 'mm').

2. Experimental procedure

The rolled plates of 5 mm thick AISI 430 FSS were cut into the required dimension using CNC cutting machine. The chemical composition of the base material is given in Table 1 and its mechanical properties are presented in Table 2. GTA welding was carried out using a TIG AC/DC 3500W welding machine. A single V butt-joint configuration shown in Fig. 1 was selected to fabricate the joints. The base metal plates were wire brushed and degreased using acetone and preheated to 100 °C. A filler material conforming to the composition given in Table 1 is used. Copper (in foil form) was added between the butt joint of FSS after the root weld. Aluminium powder of −100 μm mesh (99% purity level) was added to the molten pool in the range from 1 to 3 g through hopper and a fine pipe by the controlled way using the motor mechanism over a length of 300 mm of the FSS joints. Weld joint is completed in three passes. The welding parameters are 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, 30 min holding followed by a water quenching was adopted [15].

2.1. *Mechanical testing*

Microhardness testing was conducted using a Vickers digital microhardness tester in transverse direction of the weld joint. A load of 300 g was applied for duration of 10 s. The

Table 3 – Gas tungsten arc welding parameters.

Parameter	Value
Welding current (A)	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

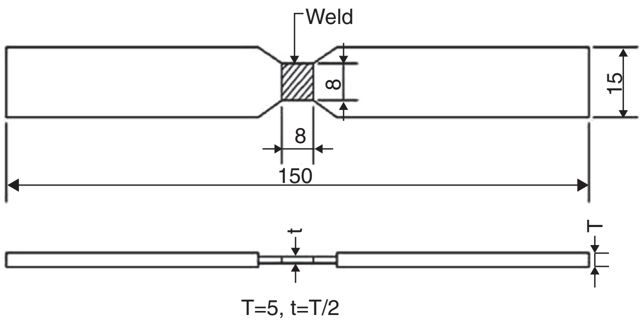


Fig. 2 – Configuration of tensile test specimen (all dimensions in 'mm').

specimens for tensile testing were taken in transverse to the weld direction and machined to ASTM E8 standards [16] by Wire cut Electrical Discharge Machining (WEDM). The configuration of the tensile test specimen adopted is given in Fig. 2. The tensile test was conducted with the help of computer controlled universal testing machine (Model: Autograph, Make: Shimatzu) at a cross head speed of 0.5 mm/min. Specimens for impact testing were taken in transverse to the weld direction and machined according to ASTM (sub size) standards [16]. The impact specimen configuration is shown in Fig. 3. The impact test was conducted at room temperature using a pendulum type charpy impact testing machine.

2.2. *Metallography*

In order to observe the microstructure under the optical microscope, specimens were cut from the weld joints and then prepared according to the standard procedures, and etched using aquaregia (one part HNO_3, three parts HCL). Microstructures of welds in as-welded and post-weld annealed conditions were studied and recorded. Scanning electron microscope (SEM) was used for energy dispersive X-ray analysis (EDX) and fractographic examination. Electron probe microanalysis (EPMA) is carried out to measure the chemical composition of base material (AISI 430 FSS), filler material (ER 430) and all weld metals.

2.3. *Corrosion testing*

The base metal and weld joints were tested for pitting corrosion in an electrolyte of 0.5 M H_2SO_4 + 0.5 M HCL. The electrochemical measurements were made using a potentiometer. Steady state potential was recorded 10 min after immersion of the sample into the electrolyte and the potential was raised anodically using scanning potentiostat at a scan rate of 2 mV/s.

3. Results and discussion

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. From the results it is observed that by the addition of Al to the weld pool up to 2 g (2.4 wt.%), the strength and ductility of the FSS weldments increase due to the formation of precipitates such as Al carbides (Al_4C_3) and Al oxides (Al_2O_3) during welding, whereas by increasing Al content beyond 2 g (2.4 wt.%), the tensile properties are deteriorated due to the strong detrimental effect of ferrite promotion compared to the beneficial effect of precipitation. In the post-weld annealed condition, the weldments made by the addition of 2 g Al (2.4 wt.%) exhibit higher tensile strength compared to all other conditions. This is due to the fine grained microstructure and also formation of precipitates.

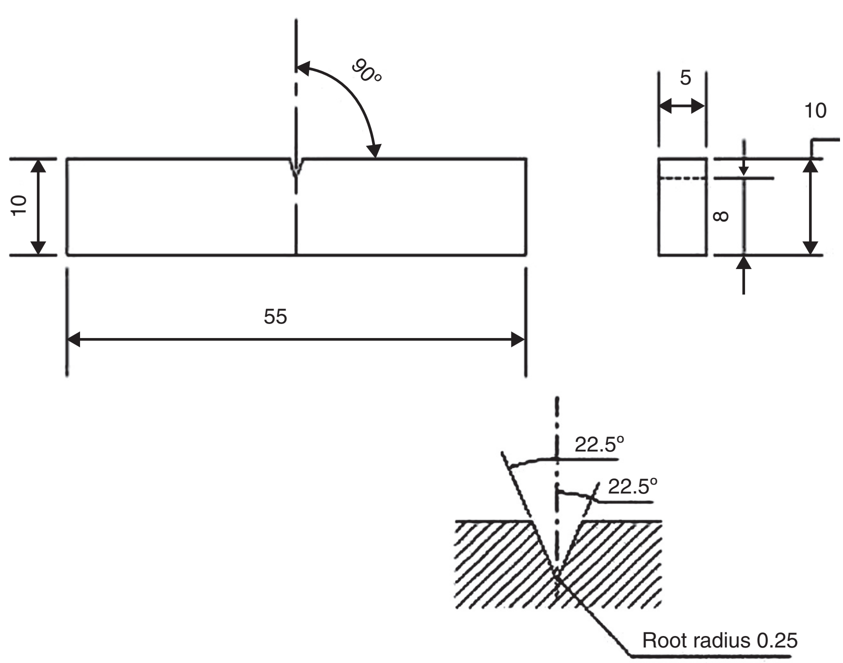
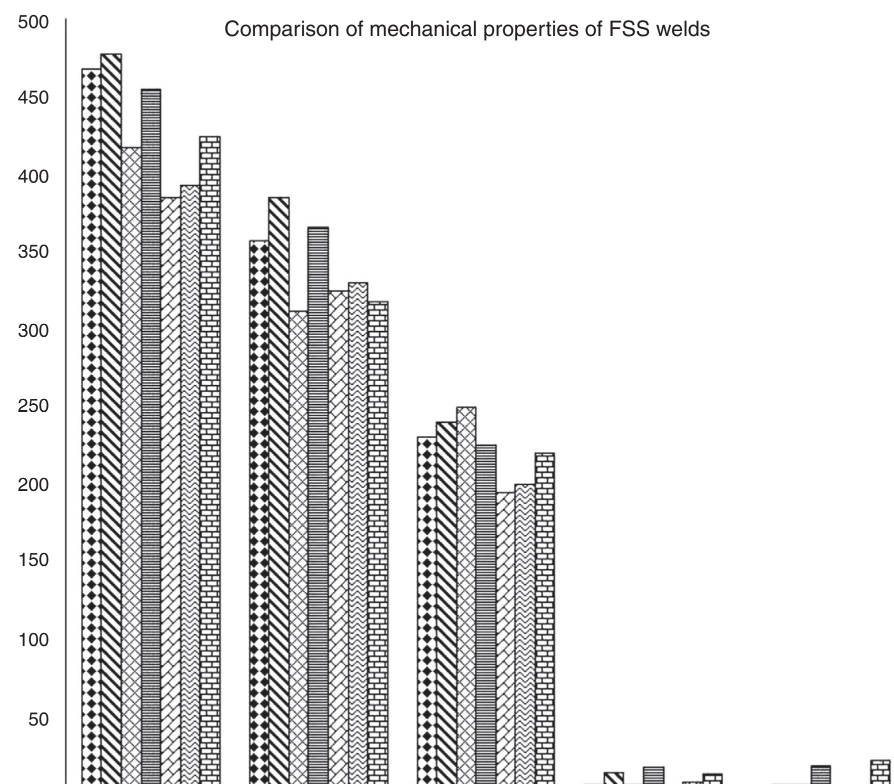


Fig. 3 – Configuration of charpy V-notch impact specimen (all dimensions in 'mm').

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

Joint condition	UTS (MPa)	YS (MPa)	%EL	Impact toughness (J)	Microhardness at the weld centre (HV)
1 g Al (1.7 wt.%) addition	455	346	3.6	2	200
2 g Al (2.4 wt.%) addition	468	357	6.0	4	230
3 g Al (6.2 wt.%) addition	440	328	2.7	4	210
1 g Cu (0.1 wt.%) addition	400	295	3.3	4	230
2 g Cu (0.18 wt.%) addition	417	312	6.0	6	250
3 g Cu (0.25 wt.%) addition	460	345	3.0	4	265
Filler material (ER 430) addition without Cu and Al	385	325	2.3	3	195

The addition of Cu between the butt joint up to 3 g (0.25 wt.%) resulted in increased ultimate tensile strength (UTS), yield strength (YS) and hardness with marginal decrease in ductility, this can be attributed to precipitation strengthening by copper precipitates. In the post-weld annealed condition, the weldments made by the addition of 2 g Cu (0.18 wt.%) possess slightly superior ductility compared to all other conditions. This can be attributed to the equiaxed morphology of fusion zone grains in the FSS welds. There is a marginal improvement in the hardness of FSS weldments with 3 g Cu (0.25 wt.%) addition in post-weld annealed condition. This is due to precipitation hardening effect of copper [14]. The graphical representation of mechanical properties of FSS welds is presented in Fig. 4. From the results it is observed that the hardness variation is less pronounced from the base material to post-weld annealed welds made by the addition of Cu and Al and filler material (ER 430) addition without Cu and Al compared to ultimate tensile strength and ductility.



	UTS (MPa)	YS (MPa)	Mícrohardness at weld center (HV)	% EL	Impact toughness (J)
2g Al (2.4 wt.%)_as-welded	468	357	230	6	4
2g Al (2.4 wt.%)_post-weld annealed	478	385	240	14	6
2g Cu (0.18 wt.%)_as-welded	417	312	250	6	6
2g Cu (0.18 wt.%)_post-weld annealed	455	366	225	17.5	18
Filler material (ER 430) addition without CU & Al_as-welded	385	325	195	2.3	3
Filler material (ER 430) addition without CU & Al_post-weld annealed	393	330	200	7.8	4
Base metal (AISI 430 ferritic stainless steel)	424	318	220	13	22

Fig. 4 – Graphical representation of mechanical properties of FSS welds.

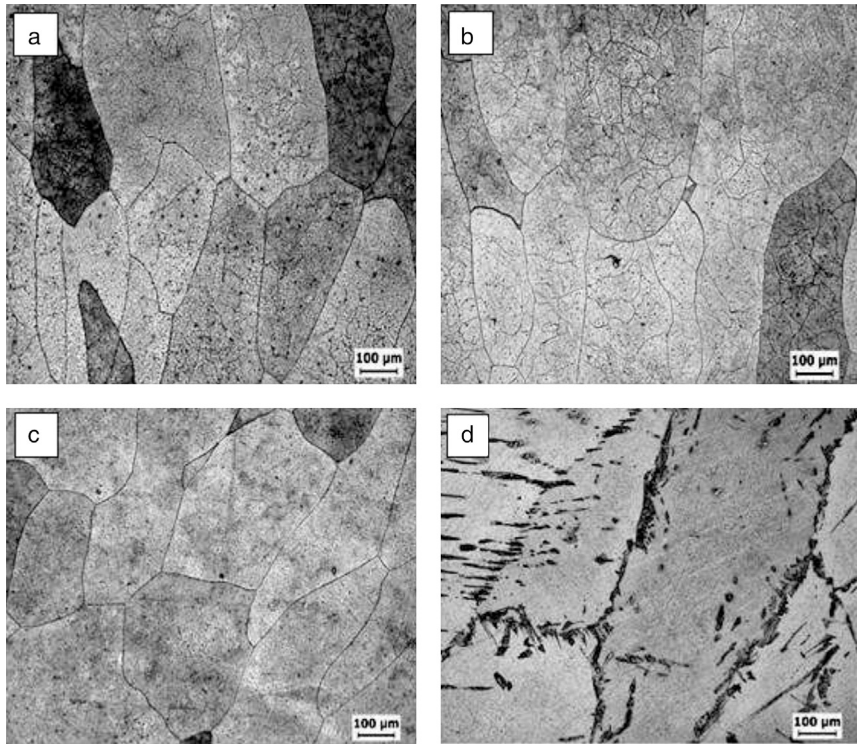


Fig. 5 – Microstructure of weld region of ferritic stainless steel welds in as-welded condition. (a) 1 g Al (1.7 wt.%) addition; (b) 2 g Al (2.4 wt.%) addition; (c) 3 g Al (6.2 wt.%) addition; and (d) filler material (ER 430) addition without Al.

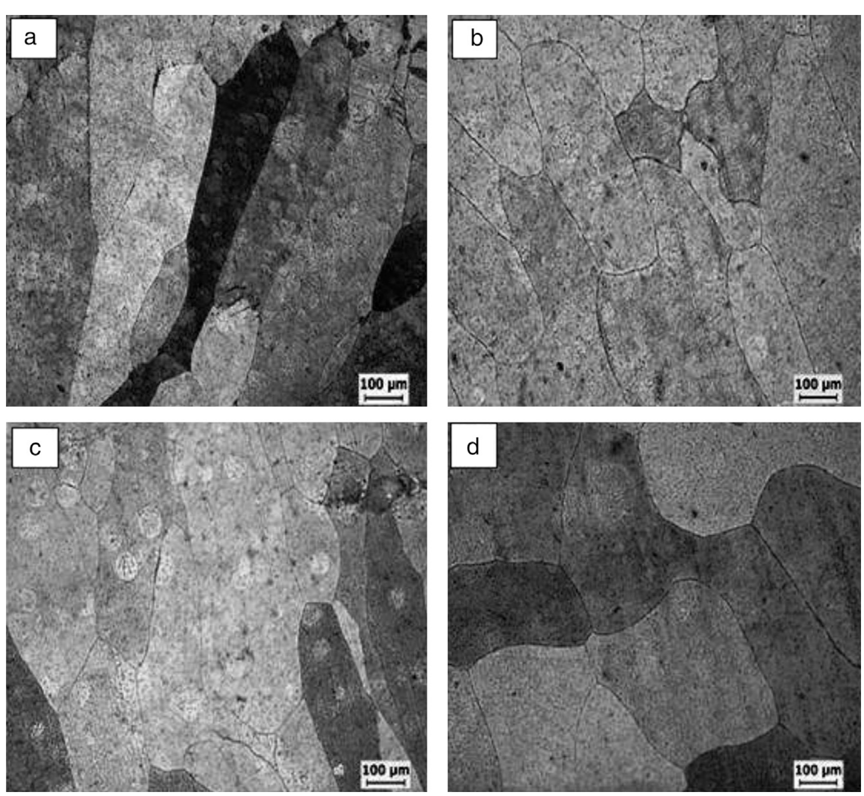


Fig. 6 – Microstructure of weld region of ferritic stainless steel welds in post-weld annealed condition. (a) 1 g Al (1.7 wt.%) addition; (b) 2 g Al (2.4 wt.%) addition; (c) 3 g Al (6.2 wt.%) addition; and (d) filler material (ER 430) addition without Al.

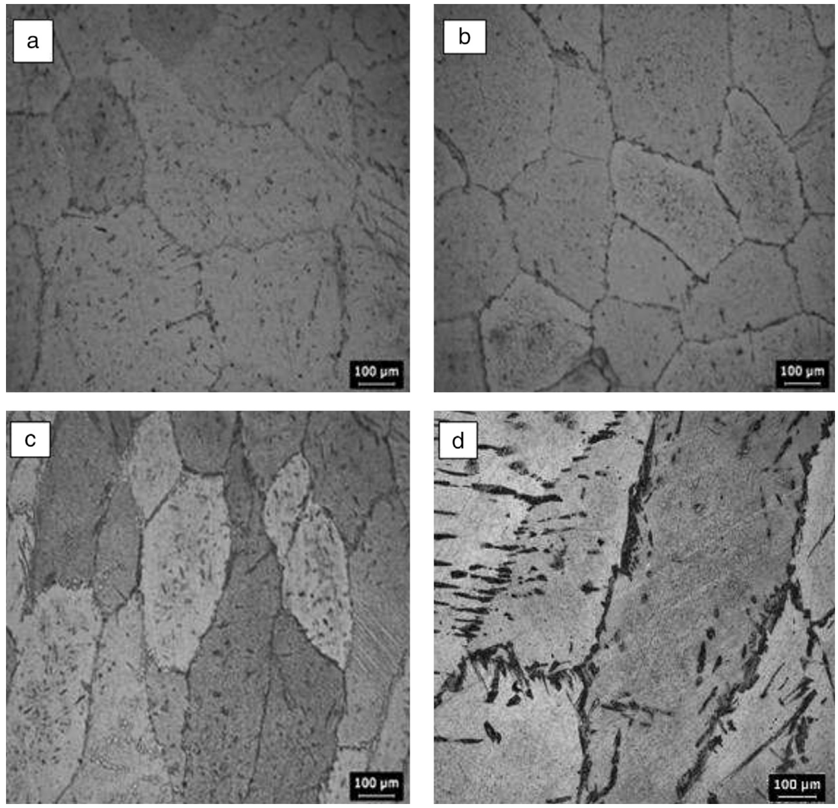


Fig. 7 – Microstructure of weld region of ferritic stainless steel welds in as-welded condition. (a) 1 g Cu (0.1 wt.%) addition; (b) 2 g Cu (0.18 wt.%) addition; (c) 3 g Cu (0.25 wt.%) addition; and (d) filler material (ER 430) addition without Cu.

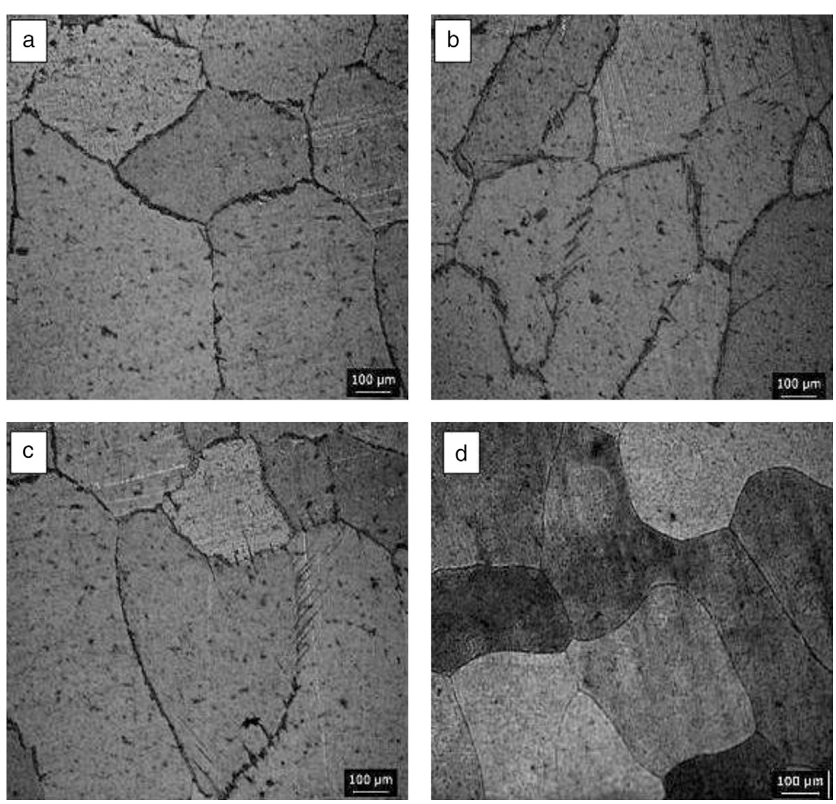


Fig. 8 – Microstructure of weld region of ferritic stainless steel welds in post-weld annealed condition. (a) 1 g Cu (0.1 wt.%) addition; (b) 2 g Cu (0.18 wt.%) addition; (c) 3 g Cu (0.25 wt.%) addition; and (d) filler material (ER 430) addition without Cu.

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

Joint condition	UTS (MPa)	YS (MPa)	%EL	Impact toughness (J)	Microhardness at the weld centre (HV)
1 g Al (1.7 wt.%) addition	467	355	12	4	215
2 g Al (2.4 wt.%) addition	478	385	14	6	240
3 g Al (6.2 wt.%) addition	450	346	8	4	220
1 g Cu (0.1 wt.%) addition	435	356	16	10	200
2 g Cu (0.18 wt.%) addition	455	366	17.5	18	225
3 g Cu (0.25 wt.%) addition	462	371	15	14	235
Filler material (ER 430) addition without Cu and Al	393	330	7.8	4	200

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

Joint condition	Grain size (μm)
1 g Al (1.7 wt.%) addition	300
2 g Al (2.4 wt.%) addition	250
3 g Al (6.2 wt.%) addition	300
1 g Cu (0.1 wt.%) addition	300
2 g Cu (0.18 wt.%) addition	225
3 g Cu (0.25 wt.%) addition	200
Filler material (ER 430) addition without Cu and Al	380

3.2. *Microstructure studies*

Microstructures of all the joints made by the addition of Cu, Al and without the addition of Cu and Al were examined at the weld region of FSS welds in as-welded and post-weld annealed conditions and presented in Figs. 5–8, respectively. It is observed that the joints fabricated by the addition of 2 g Al (2.4 wt.%) and 3 g Cu (0.25 wt.%) resulted in fine equiaxed grains compared to the joints made with 1 g Al (1.7 wt.%), 3 g Al (6.2 wt.%), 1 g Cu (0.1 wt.%), 2 g Cu (0.18 wt.%) and filler material addition without Al and Cu. This is attributed to the formation of fine precipitates such as Al_4C_3, Al_2O_3 and Cu precipitates respectively, which are effective in promoting equiaxed grains and to refine the grain size in the fusion zone. The grain size in the weld zone of FSS weldments were measured using line intercept method [17] and the results are presented in Table 6.

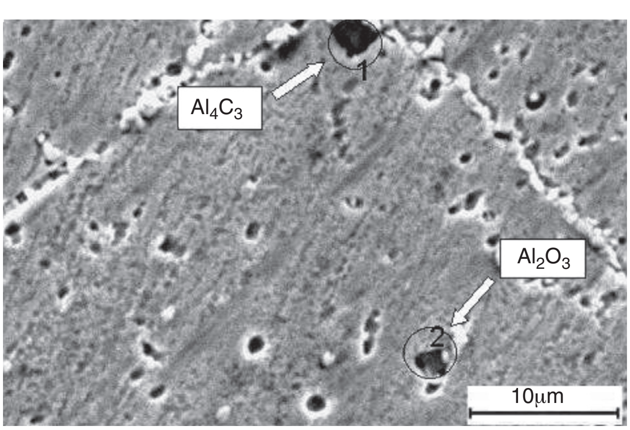


Fig. 9 – SEM micrograph of precipitates in the fusion zone of ferritic stainless steel weldments made by 2 g Al (2.4 wt.%) addition.

The chemical compositions of all weld metals (wt.%) are given in Table 7.

The distribution of precipitates in the fusion zone of weldments made by 2 g Al (2.4 wt.%) addition was observed using SEM and the results are presented in Fig. 9. EDX analysis is carried out to analyze the chemical composition of the precipitations and the results were presented in Fig. 10. From the EDX results, it is observed that the aluminium, carbon compounds such as Al_4C_3 and Al_2O_3 were formed which are believed to be responsible for the grain refinement.

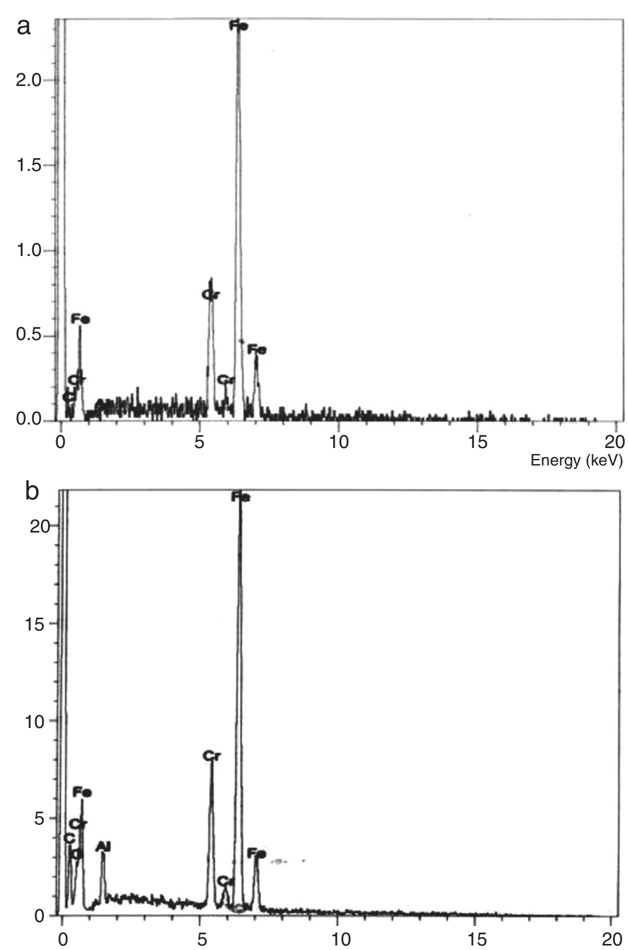


Fig. 10 – EDX (a and b) results of precipitates Al_4C_3 and Al_2O_3 denoted by 1 and 2 of ferritic stainless steel welds (Fig. 9) made by 2 g Al (2.4 wt.%) addition.

Table 7 – Chemical composition of all weld metals (wt.%).									
Joint condition	C	Mn	Si	P	S	Ni	Cr	Al	Fe
1 g Al addition	0.040	0.11	0.27	0.006	0.028	0.261	17.02	1.7	Bal.
2 g Al addition	0.029	0.25	0.30	0.004	0.030	0.330	17.09	2.4	Bal.
3 g Al addition	0.035	0.18	0.25	0.002	0.027	0.235	17.20	6.2	Bal.
1 g Cu addition	0.015	0.390	0.368	0.036	0.007	0.158	15.68	0.10	Bal.
2 g Cu addition	0.022	0.387	0.364	0.027	0.004	0.183	16.46	0.18	Bal.
3 g Cu addition	0.036	0.395	0.347	0.034	0.005	0.172	16.35	0.25	Bal.
Filler material (ER 430) addition without Cu and Al	0.036	0.38	0.41	0.007	0.030	0.241	16.23	0.03	Bal.

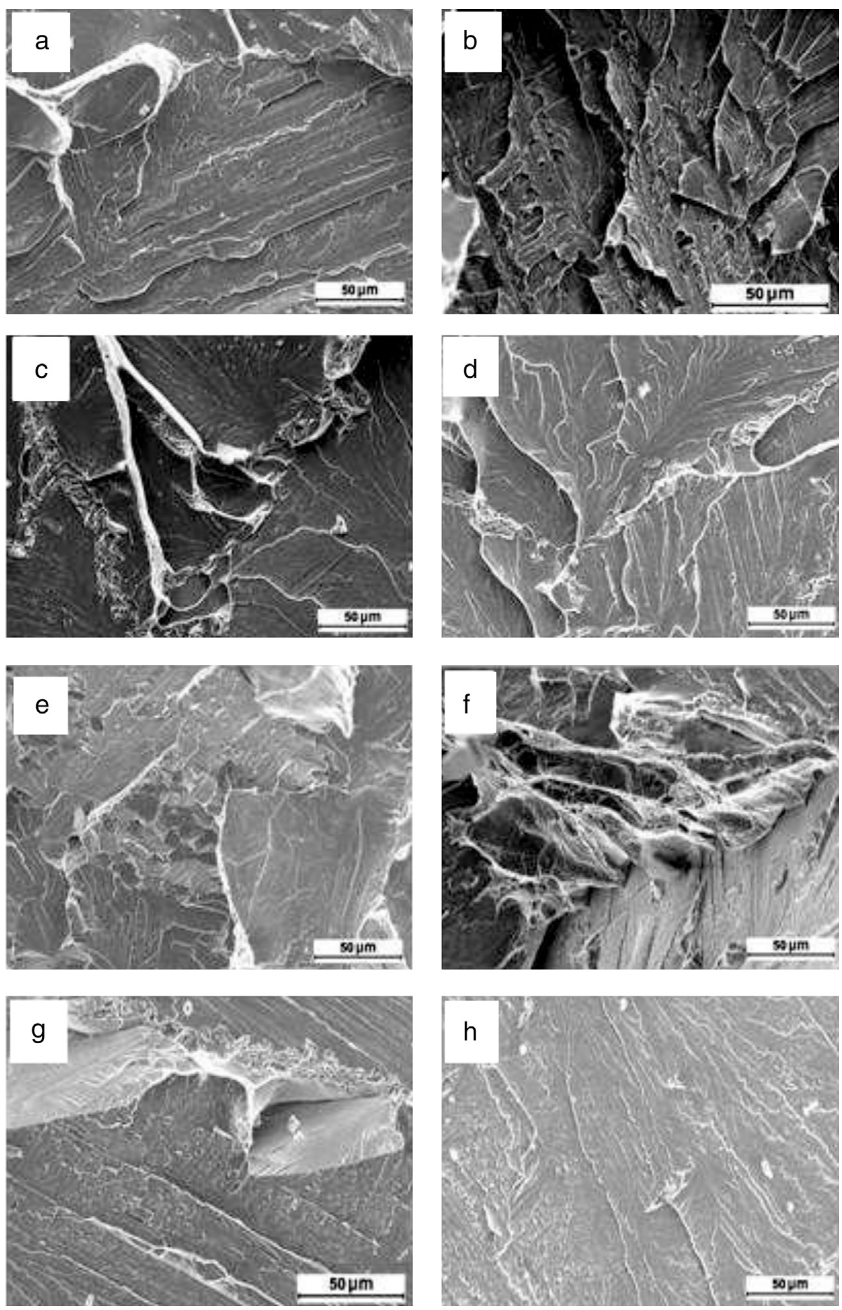


Fig. 11 – Fractographs of tensile (a–d) and impact specimens (e–h) of ferritic stainless steel weldments in as-welded condition. (a) 1 g Al (1.7 wt.%) addition; (b) 2 g Al (2.4 wt.%) addition; (c) 3 g Al (6.2 wt.%) addition; (d) filler material (ER 430) addition without Cu and Al; (e) 1 g Al (1.7 wt.%) addition; (f) 2 g Al (2.4 wt.%) addition; (g) 3 g Al (6.2 wt.%) addition; and (h) filler material (ER 430) addition without Cu and Al.

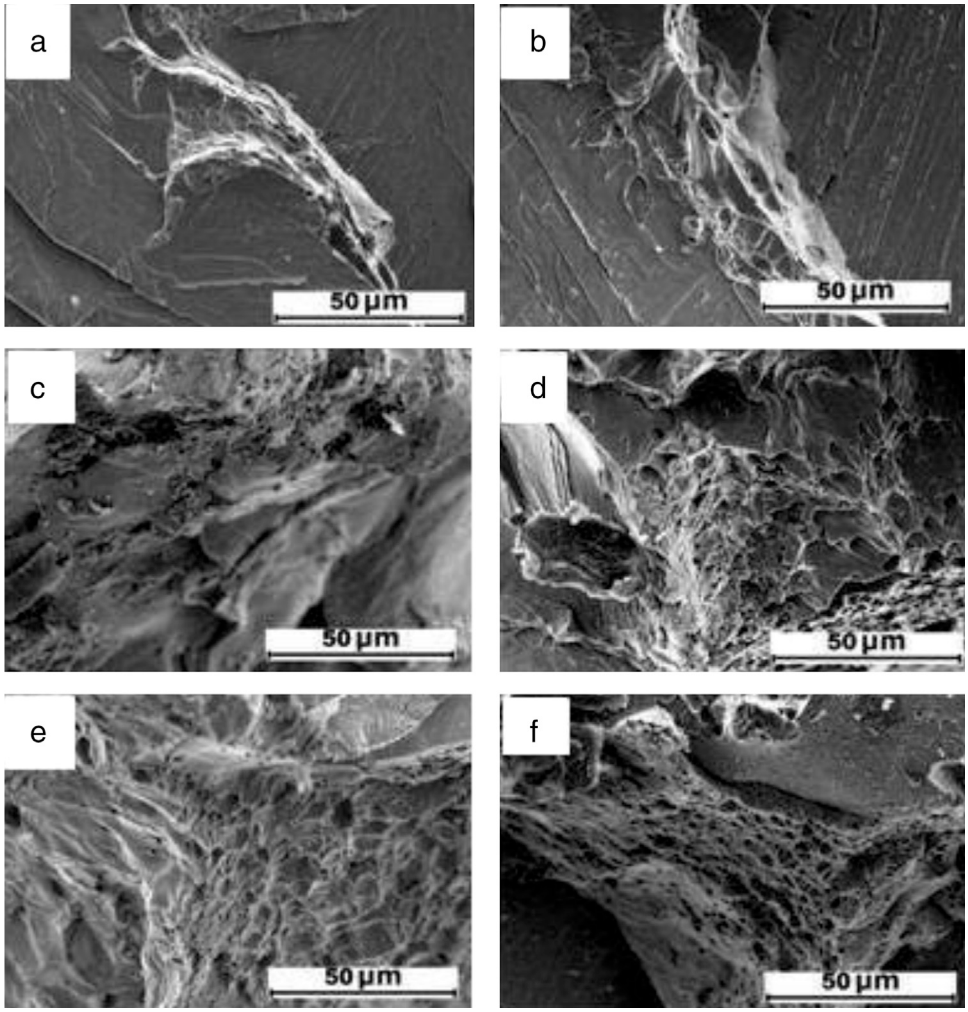


Fig. 12 – Fractographs of tensile (a–c) and impact specimens (d–f) of ferritic stainless steel weldments in as-welded condition. (a) 1 g Cu (0.1 wt.%) addition; (b) 2 g Cu (0.18 wt.%) addition; (c) 3 g Cu (0.25 wt.%) addition; (d) 1 g Cu (0.1 wt.%) addition; (e) 2 g Cu (0.18 wt.%) addition; and (f) 3 g Cu (0.25 wt.%) addition.

3.3. *Fractography*

The fractured surfaces of the tensile and impact specimens of the FSS weldments in as-welded and post-weld annealed conditions were analyzed using SEM to reveal the fracture surface morphology. Figs. 11–14 display the fractographs of tensile and impact specimens of weldments made with Al, Cu addition and filler material addition without Al and Cu in as-welded and post-weld annealed conditions, respectively. The tensile and impact fracture surfaces of ferritic stainless steel weldments with 1 g Al (1.7 wt.%), 3 g Al (6.2 wt.%) addition and filler material addition without Al and Cu in as-weld condition (Fig. 11(a), (c), (d), (e), (g) and (h)) show cleavage fracture indicating brittle failure, whereas the tensile and impact fracture surfaces of ferritic stainless steel weldments with 2 g Al (2.4 wt.%) addition (Fig. 11(b) and (f)) show quasi-cleavage fracture indicating both ductile and brittle failure. The tensile and impact fracture surfaces of FSS weldments with 1 g Cu (0.1 wt.%), 3 g Cu (0.25%) addition in as-weld condition (Fig. 12(a), (c), (d) and (f)) show cleavage fracture indicating brittle failure, whereas the tensile and impact fracture surfaces of FSS weldments with 2 g Cu (0.18 wt.%) addition (Fig. 12(b) and (e)) show quasi-cleavage fracture indicating both ductile and brittle failure. This can be attributed to the fact that 2 g Cu (0.18 wt.%) addition has a greater influence,

Table 8 – Pitting potentials, E_{pit} (mV) of FSS welds and base material.

Joint condition	E_{pit} (mV)
2 g Al (2.4 wt.%) addition	
As-welded	190
Post-weld annealed	260
2 g Cu (0.18 wt.%) addition	
As-welded	250
Post-weld annealed	370
Filler material (ER 430) addition without Cu and Al	
As-welded	203
Post-weld annealed	230
Base material (AISI 430 FSS)	
–	215

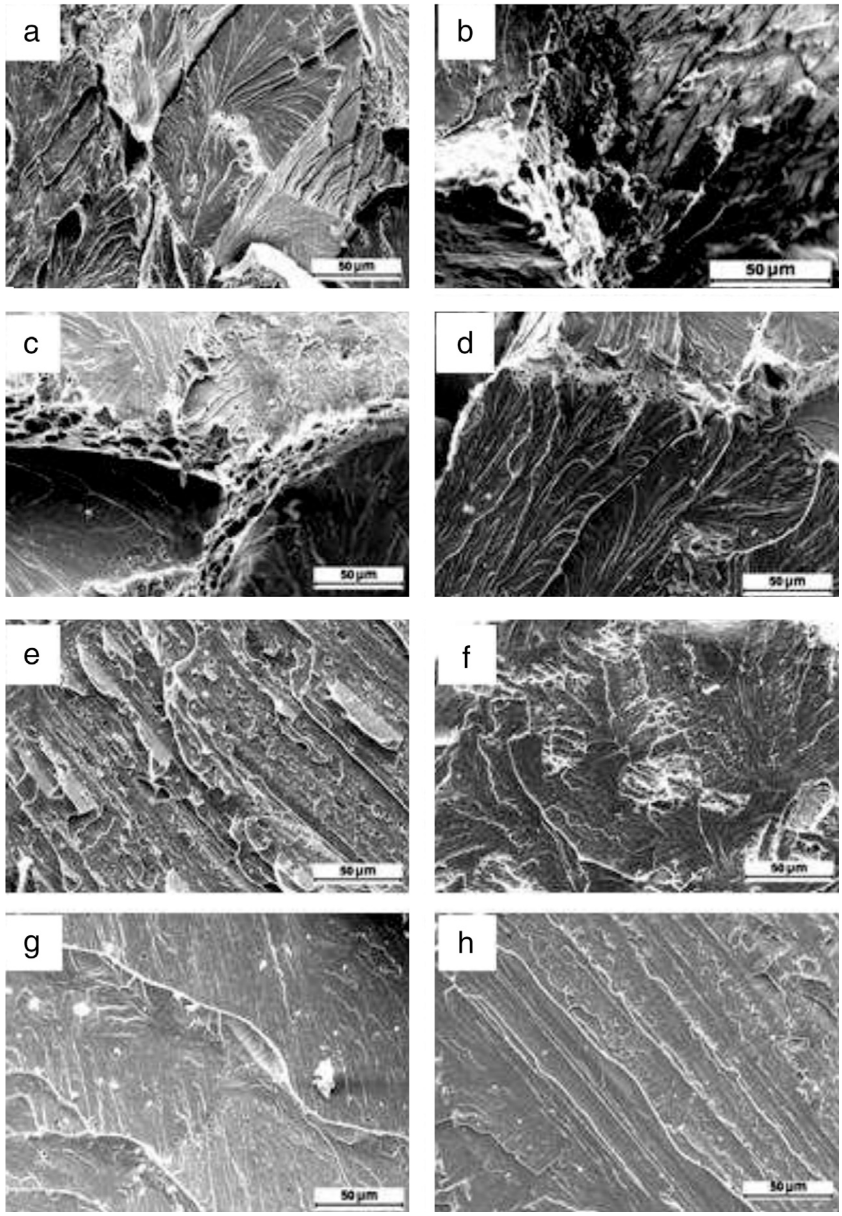


Fig. 13 – Fractographs of tensile (a–d) and impact specimens (e–h) of ferritic stainless steel weldments in post-weld annealed condition. (a) 1 g Al (1.7 wt.%) addition; (b) 2 g Al (2.4 wt.%) addition; (c) 3 g Al (6.2 wt.%) addition; (d) filler material (ER 430) addition without Cu and Al; (e) 1 g Al (1.7 wt.%) addition; (f) 2 g Al (2.4 wt.%) addition; (g) 3 g Al (6.2 wt.%) addition; and (h) filler material (ER 430) addition without Cu and Al.

in that the facets are more equiaxed. This observation suggests that 2 g Cu (0.18 wt.%) addition is more beneficial than 1 g Cu (0.1 wt.%) and 3 g Cu (0.25 wt.%) addition in altering the grain structure of the fusion zone to equiaxed morphology. The tensile and impact fracture surfaces of weldments with 1 g Al (1.7 wt.%), 3 g Al (6.2 wt.%), 1 g Cu (0.1 wt.%) and 3 g Cu (0.25 wt.%) addition in post-weld annealed condition (Figs. 13(a), (c), (e), (g) and 14(a), (c), (d), (f)) represent quasi-cleavage fracture, whereas the tensile and impact fracture surfaces of FSS weldments made by the addition of 2 g Al (2.4 wt.%), 2 g Cu (0.18 wt.%) (Figs. 13(b), (f) and 14 (b), (e)) show ductile fracture as fine dimples are seen in the joints.

3.4. *Pitting corrosion studies*

The pitting potential (E_{pit}) was used as a measure of resistance to pitting. E_{pit} values of base material and FSS welds made by the addition of 2 g Al (2.4 wt.%), 2 g Cu (0.18 wt.%) and filler material (ER 430) addition without Cu and Al in as-weld and post-weld annealed conditions are presented in Table 8. From the results it is observed that the joints fabricated by the addition of 2 g Cu (0.18 wt.%) in post-weld annealed condition exhibit higher pitting corrosion resistance. Enhanced pitting resistance corresponding to post-weld annealed condition could be due to reduced segregation, formation of tempered martensite and some retained austenite [18].

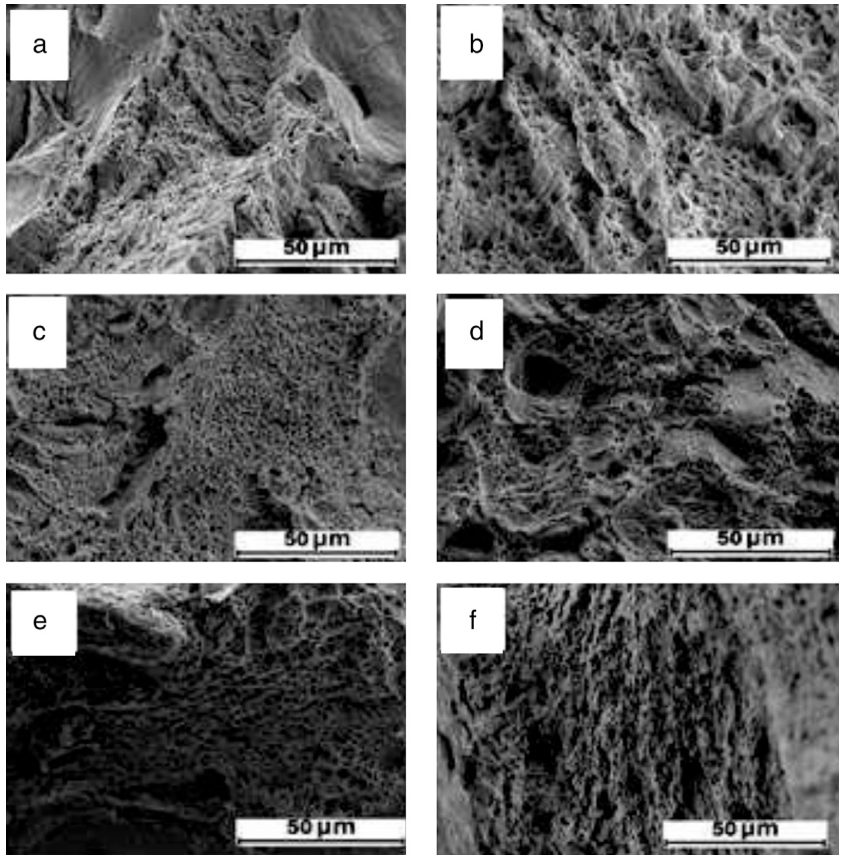


Fig. 14 – Fractographs of tensile (a–c) and impact specimens (d–f) of ferritic stainless steel weldments in post-weld annealed condition. (a) 1 g Cu (0.1 wt.%) addition; (b) 2 g Cu (0.18 wt.%) addition; (c) 3 g Cu (0.25 wt.%) addition; (d) 1 g Cu (0.1 wt.%) addition; (e) 2 g Cu (0.18 wt.%) addition; (f) 3 g Cu (0.25 wt.%) addition.

4. Conclusions

The influence of copper and aluminium addition in the range from 1 g Cu (0.1 wt.%) to 3 g Cu (0.25 wt.%), 1 g Al (1.7 wt.%) to 3 g Al (6.2 wt.%) and filler material (ER 430) addition without Cu and Al on mechanical properties and corrosion behaviour of AISI 430 ferritic stainless steel welds were analyzed in detail and the following conclusions are derived.

- The ferritic stainless steel joints fabricated by the addition of 2 g Al (2.4 wt.%) in post-weld annealed condition resulted in better tensile properties (ultimate tensile strength, yield strength and elongation %) compared to all other joints. This is due to the fine grain microstructure and also formation of precipitates such as Al_4C_3 and Al_2O_3 which are believed to be responsible for grain refinement in the weld zone.
- There is a marginal improvement in the ductility of ferritic stainless steel weldments by the addition of 2 g Cu (0.18 wt.%) in post-weld annealed condition compared to all other joints and base metal. This is attributed to the formation of fine dimples in the weld zone of the ferritic stainless steel joints.
- The FSS welds made by the addition of 3 g Cu (0.25 wt.%) in as-weld condition resulted in increased hardness. This could be due to the precipitation hardening effect of copper.
- Post-weld annealed FSS welds made by the addition of 2 g Cu (0.18 wt.%) showed relatively better pitting corrosion resistance. This is due to reduced segregation, formation of tempered martensite and some retained austenite.

Conflicts of interest

The authors declare no conflicts of interest.

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