Engineering Failure Analysis 17 (2010) 1069–1076

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Impact behavior of different stainless steel weldments at low temperatures

O.H. Ibrahim [a,*], I.S. Ibrahim [b], T.A.F. Khalifa [c]

[a] Metallurgy Dept., Nuclear Research Centre, Atomic Energy Authority, Egypt
[b] Nuclear Safety Centre, Atomic Energy Authority, Egypt
[c] Shoubra Faculty of Engineering, Benha University, Egypt

ARTICLE INFO

Article history:
Received 2 November 2009
Received in revised form 20 December 2009
Accepted 20 December 2009
Available online 11 January 2010

Keywords:
Austenitic and duplex stainless steel weldments
Instrumented impact toughness
Ferrite content

ABSTRACT

A comparative study was made of the fracture behavior of austenitic and duplex stainless steel weldments at cryogenic temperatures by impact testing. The investigated materials were two austenitic (304L and 316L) and one duplex (2505) stainless steel weldments. Shielded metal arc welding (SMAW) and tungsten inert gas welding (TIG) were employed as joining techniques. Instrumented impact testing was performed between room and liquid nitrogen (−196 °C) test temperatures. The results showed a slight decrease in the impact energy of the 304L and 316L base metals with decreasing test temperature. However, their corresponding SMAW and TIG weld metals displayed much greater drop in their impact energy values. A remarkable decrease (higher than 95%) was observed for the duplex stainless steel base and weld metals impact energy with apparent ductile to brittle transition behavior. Examination of fracture surface of tested specimens revealed complete ductile fracture morphology for the austenitic base and weld metals characterized by wide and narrow deep and shallow dimples. On the contrary, the duplex stainless steel base and weld metals fracture surface displayed complete brittle fracture morphology with extended large and small stepped cleavage facets. The ductile and brittle fracture behavior of both austenitic and duplex stainless steels was supplemented by the instrumented load–time traces. The distinct variation in the behavior of the two stainless steel categories was discussed in light of the main parameters that control the deformation mechanisms of stainless steels at low temperatures; stacking fault energy, strain induced martensite transformation and delta ferrite phase deformation.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Austenitic stainless steels possess an unique combination of mechanical properties which makes them useful at cryogenic (very low) temperature applications. These applications encounter handling and storing liquefied natural gases as liquid oxygen and nitrogen with boiling temperatures of −183 and −196 °C respectively. At such cryogenic temperatures these steels have tensile strengths substantially higher than at ambient temperatures while their toughness is slightly degraded [1]. In addition, austenitic stainless steels are candidate structural material for future hydrogen energy transportation and storage systems. For the design and safety aspects of such systems, it is necessary to investigate the low temperature impact properties of weld metals of these steels since weld metals have higher susceptibility to embrittlement than their counterpart base metals [1]. Moreover, austenitic stainless steels weldments have been proposed for use as superconducting magnet structure for future fusion energy applications. Since these magnet structures experience large electromagnetic forces and

* Corresponding author.
E-mail address: omyma_essam@yahoo.com (O.H. Ibrahim).

1350-6307/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfailanal.2009.12.006

operate under cryogenic environment, the weld metal characteristics particularly low temperature toughness must be assured [2].

On the other hand, duplex stainless steels have found applications for pipelines of gas and oil, heat exchangers and pressure vessels. For pressure vessel applications duplex stainless steel provide high tensile yield strength and very strong work hardening capacity by virtue of the beneficial effect of the austenite phase. However, using duplex stainless steel in the pressure vessel field application has been restricted due to lack of technical experience concerning knowledge of fracture behavior. Since duplex stainless steels contain half as much of ferrite phase, and they have the readiness to undergo ductile to brittle transition, therefore, they have not found wide applications in cryogenic service. Nevertheless, assessment of their impact properties at low temperatures is a basic safety requirement.

The aim of the present investigation is to provide a comparison of low temperature impact behavior of austenitic (304L, 316L) and duplex (2205) stainless steel base metals along with their shielded metal arc welds (SMAW) and tungsten inert gas (TIG) welds.

2. Experimental

The chemical composition of the investigated materials is presented in Tables 1 and 2. The 304L, 316L austenitic and 2205 duplex stainless steels were subjected to solution heat treatment at 1050 and 1150 °C, respectively for 1 h and then water quenched. Welding procedures included shielded metal arc welding (SMAW) and tungsten inert gas welding (TIG). Instrumented impact tests were conducted on impact specimens of the investigated material with dimensions of $55 \times 10 \times 4.5$ mm from room temperature to −196 °C. The impact machine total capacity was 300 J with a hammer velocity of 5.1 m/s. The ferrite content was determined using digital ferritometer apparatus.

3. Results and discussion

Fig. 1 shows the microstructure of the investigated materials. Fig. 1a presents the microstructure of the 304L base metal in the as received and solution treated condition. As can be seen the microstructure contains equiaxed grains with about 30 μm grain size along with well defined annealing twins. The 304L SMAW and TIG weld metals are shown in Fig. 1b and c they display discontinuous network of vermicular ferrite structure. The main observation is that the ferrite structure is finer in the case of the TIG weld metal (Fig. 1c). Fig. 1d presents the microstructure of the 316L base metal in the as received and solution treated condition. As can be seen the microstructure contains equiaxed grains with about 30 μm grain size. The 316L SMAW and TIG weld metals are shown in Fig. 1e and f and they display globular ferrite structure with a finer morphology in the case of the TIG weld metal (Fig. 1f). Fig. 1g presents the microstructure of the duplex base metal in the as received and solution treated condition. The microstructure contains a mixture of elongated and equiaxed grains with about 5 μm grain size of ferrite and austenite phases. The duplex SMAW and TIG weld metals are shown in Figs. 1h and i and they display acicular ferrite structure. Again the ferrite morphology is finer in the case of the TIG weld metal (Fig. 1i). The observed finer ferrite structure morphology of the TIG weld metal condition as compared to that of the SMAW condition can be related to the less heat input content provided during the welding process.

The effect of test temperature on the impact properties of the investigated materials was evaluated between room temperature and liquid nitrogen temperature (−196 °C). The results are presented in Table 3 and Fig. 2. As can be seen, both 304L and 316L base metal conditions showed very little decrease in their impact energy. This was associated with the ductile fracture morphology characterized by wide and deep dimples at −196 °C test temperatures (Fig. 4a and d). This was supported by the load–time traces which displayed full ductile behavior features (Fig. 3a and d). The 304L and 316L (SMAW and TIG) weld metals exhibited larger drop in the impact energy, with decrease in the test temperatures (Table 3). The main obser-

Table 1
Chemical composition of base metals.

Element	C	Mn	Si	Ni	Cr	Mo
304L	0.022	1.14	0.69	10.1	17.7	–
316L	0.020	1.50	0.40	10.0	17.0	2.10
Duplex (2205)	0.020	1.50	0.40	6.0	23.0	3.00

Table 2
Chemical composition of weld metal fillers.

Element	C	Mn	Si	Ni	Cr	Mo
AWS E 308L	0.030	0.50	0.90	10.43	18.94	0.30
AWS E 316L	0.020	1.80	0.07	11.7	18.70	2.70
ER 2209 Duplex	0.030	1.50	0.90	9.50	23.0	3.00

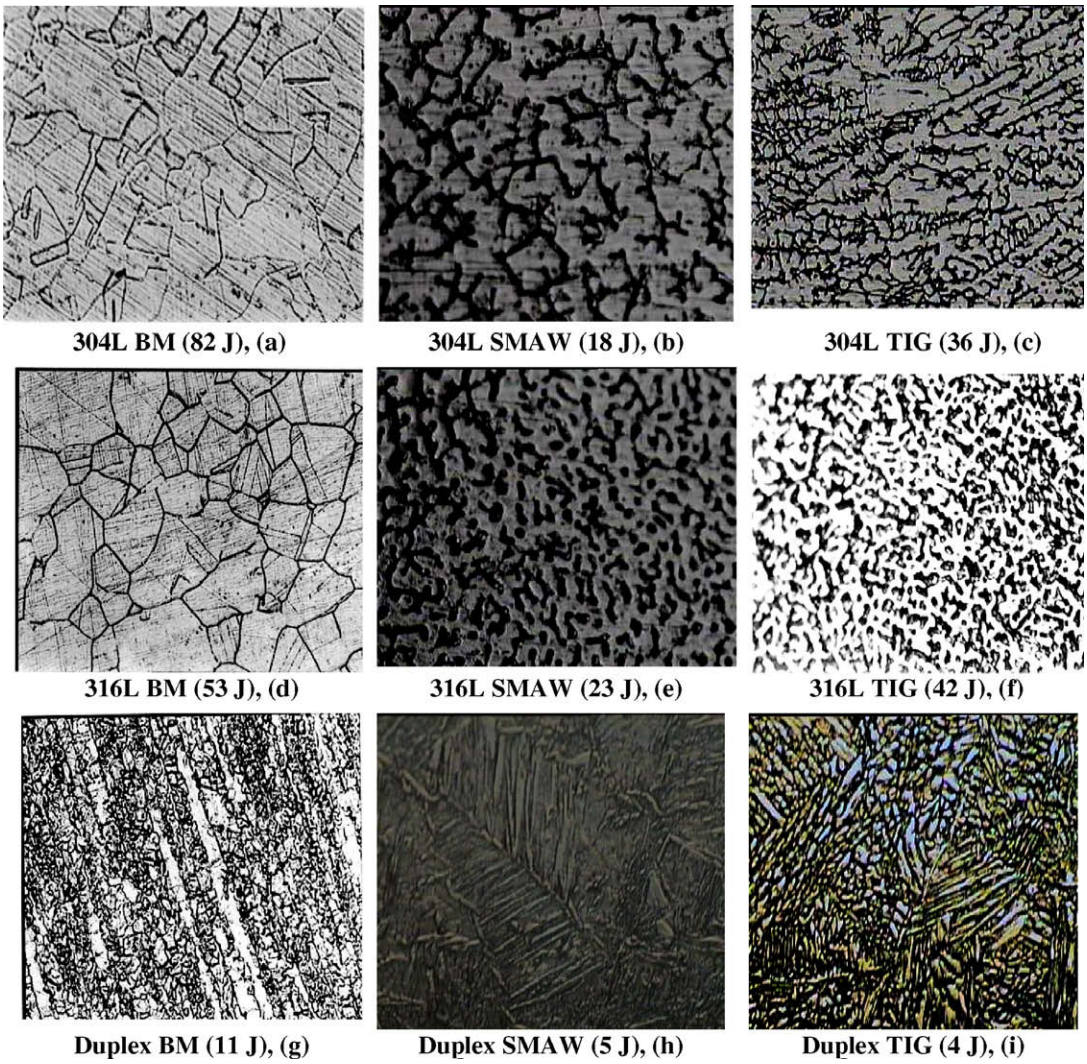

Fig. 1. Microstructure of the investigated materials.

Table 3
Effect of test temperature on impact energy of investigated materials.

Type	Base metal					SMAW					TIG				
	A.R	−50	−100	−150	−196	AW	−50	−100	−150	−196	AW	−50	−100	−150	−196
304L	85	84	83	83	82	40	30	26	22	18	72	68	60	56	36
316L	63	62	59	55	53	32	32	33	32	23	55	54	52	48	42
Duplex	107	65	48	28	11	48	15	7	6	5	75	11	9	6	4

vation was that the 304L weld metal experienced much higher amount of drop than 316L weld metal, for both the SMAW and TIG weld conditions. The percentage drop in the impact energy (between room temperature and −196 °C) of the SMAW weld condition was 45% for the 304L weld metal against 28% for the 316L weld metal. This is to be compared with 50% and 23% in the case of the TIG weld condition. However, the two types of the weld conditions, for the 304L and 316L steels, maintained fully ductile fracture behavior, at −196 °C, as indicated by the fracture surface morphology (Fig. 4 b, c, e and f), as well as the load–time traces (Fig. 3b, c, e and f) features. It should be noticed that the dimple size observed in the weld metal fractographs is much finer than those of the base metals which indicates lower impact energy values.

In contrast, the duplex stainless steel base and weld metals behavior was much different. The duplex stainless steel base metal impact energy decreased gradually with the decrease in test temperature featuring ductile to brittle transition behavior (Table 3 and Fig. 2). The duplex stainless steel base metal maintained adequate amount of ductile fracture until −50 °C

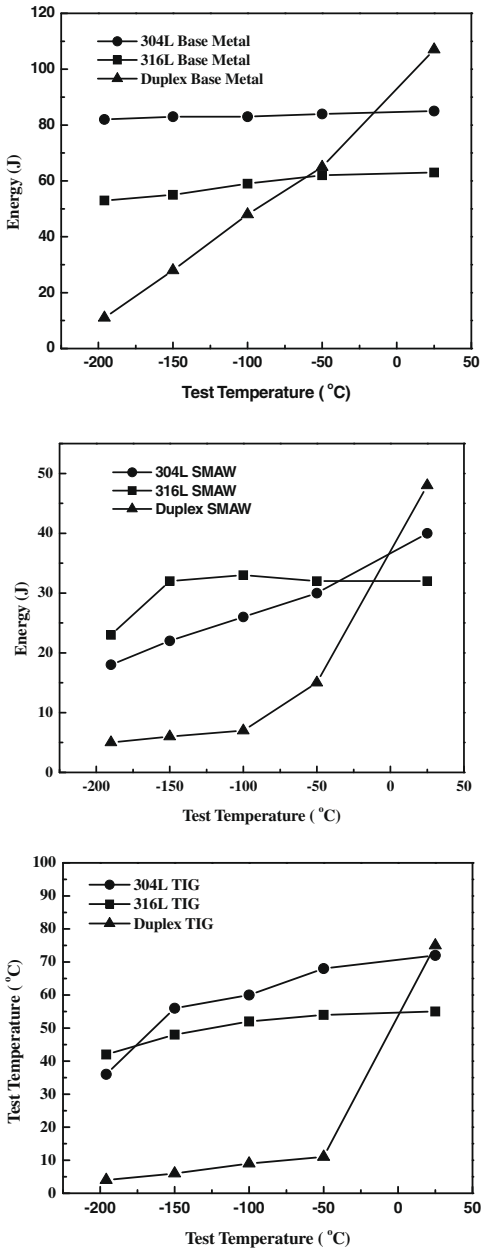

Fig. 2. Effect of test temperature on impact energy of investigated materials.

test temperature. Lower test temperatures −100, −150 and −196 °C resulted in complete brittle fracture. Figs. 4g and 3g show cleavage facets and diminished load–time trace, which are indication of brittle fracture for the base metal. The duplex stainless steel SMAW and TIG weld metals displayed total brittle fracture behavior as early as −50 °C test temperature with a greater drop in the impact energy (Table 3). This was assessed by the fracture surface examination which revealed large and small flat cleavage facets (Fig. 4h and i) as well as diminished load–time traces (Fig. 3h and i).

There are two main parameters that control the deformation mechanism of austenitic and duplex stainless steels. These are: first, generation of stacking faults during deformation which depends on the magnitude of the stacking fault energy. The second parameter is the formation of strain induced martensite during deformation which increases with the decrease in deformation temperature. The stacking fault energy is determined by the steel chemical composition and it has been reported to be of 18 and 78 kJ/m^2 for the 304L and 316L base metals, respectively [3]. On the other hand, the temperature at which martensite is formed during deformation has been reported to be 40 °C and 12 °C for 304L base metal and its 308L weld metal, respectively. The corresponding values for 316L base metal and its 316L weld metal were −15 and −40 °C,

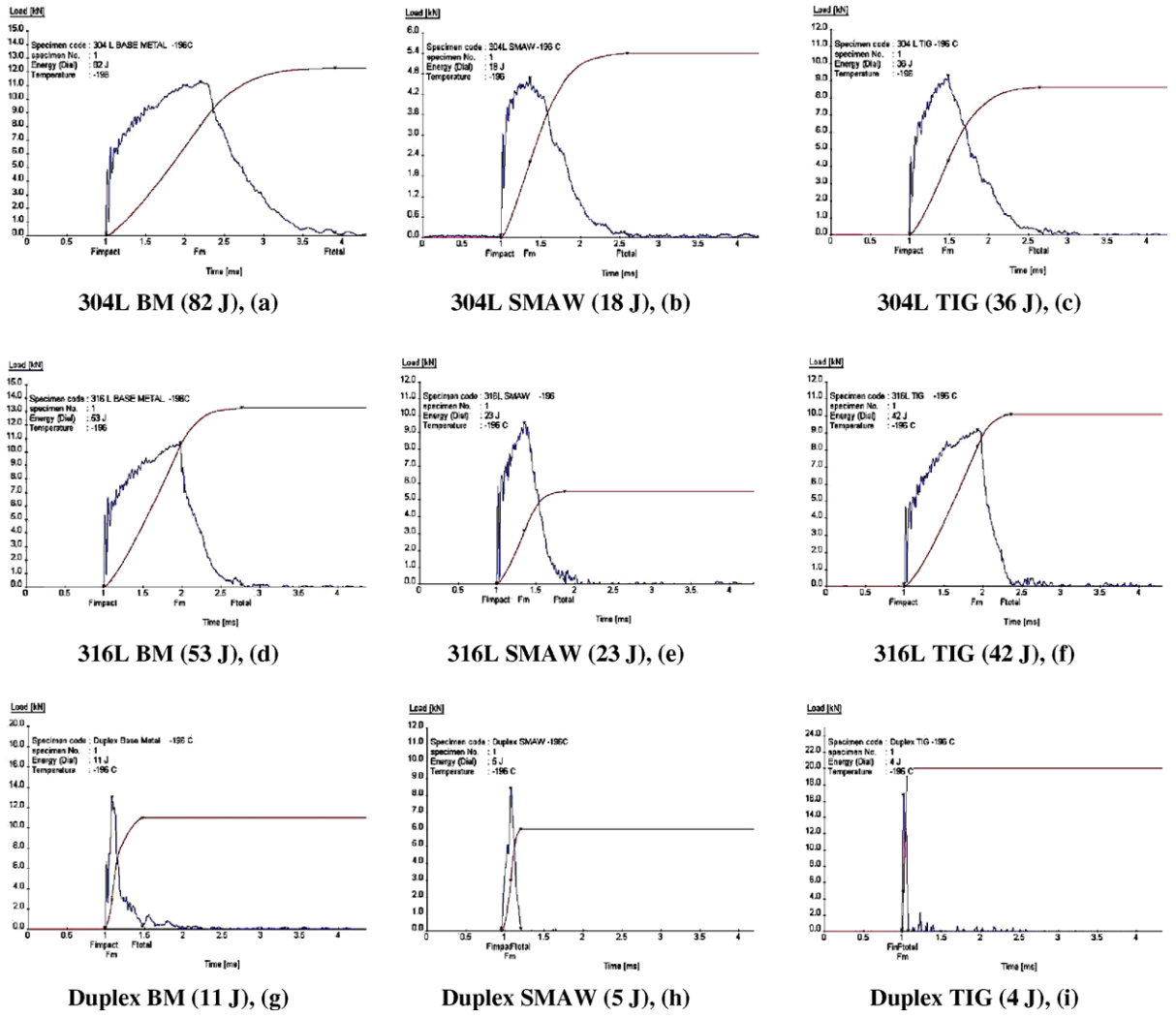

Fig. 3. Instrumented impact test load–time traces of investigated materials tested at −196 °C.

respectively. The corresponding values for the duplex stainless steel base and weld metals were −54 and −95 °C, respectively [4].

Another parameter that could contribute to the deformation mechanism of austenitic and duplex stainless steels particularly at cryogenic temperatures is the amount of delta ferrite phase contained in their microstructure. The measurement of delta ferrite content of the investigated stainless steel weldments (Table 4) showed that the 304L base metal had higher ferrite content than the 316L base metal (5.6% vs. 1.6%). However, their counterpart SMAW and TIG weld metals revealed higher delta ferrite content. After testing at −196 °C the ferrite percent values of the 304L base metal, SMAW and TIG weld metals increased from 5.6% to 24.5%, from 7.7% to 27.5% and from 9.3% to 16.7%, respectively. The 316L base metal, SMAW and TIG weld metals increased from 1.6% to 16.5%, from 9.7% to 17.4% and from 6.2% to 9.5%, respectively. This can account for the relatively higher amount of drop of the 304L SMAW and TIG weld metals impact energy at −196 °C than that of the 316L weld metals. The observed less amount of drop of the 304L base metal at −196 °C than that of the 316L base metal, despite the higher ferrite percent of the 304L base metal at −196 °C, can be attributed to the role played by its lower stacking fault energy in accommodating the plastic deformation and thus obscuring the effect of deformation induced martensite. As regards the duplex stainless steel, its ferrite content remained almost unchanged after testing at −196 °C (Table 4). This could be attributed to the negligible amount of plastic deformation exerted at −196 °C and accordingly no transformation of austenite to deformation induced martensite would take place.

In light of the abovementioned results, it can be seen that the deformation mechanism of austenitic and duplex stainless steels is a product of many parameters that include generation of stacking faults, strain included martensite transformation and ferrite phase deformation. At −196 °C all the investigated materials are metastable and undergo partial transformation to martensite during deformation. Evidence of martensitic transformation has been detected in the crack tip plastic zone of

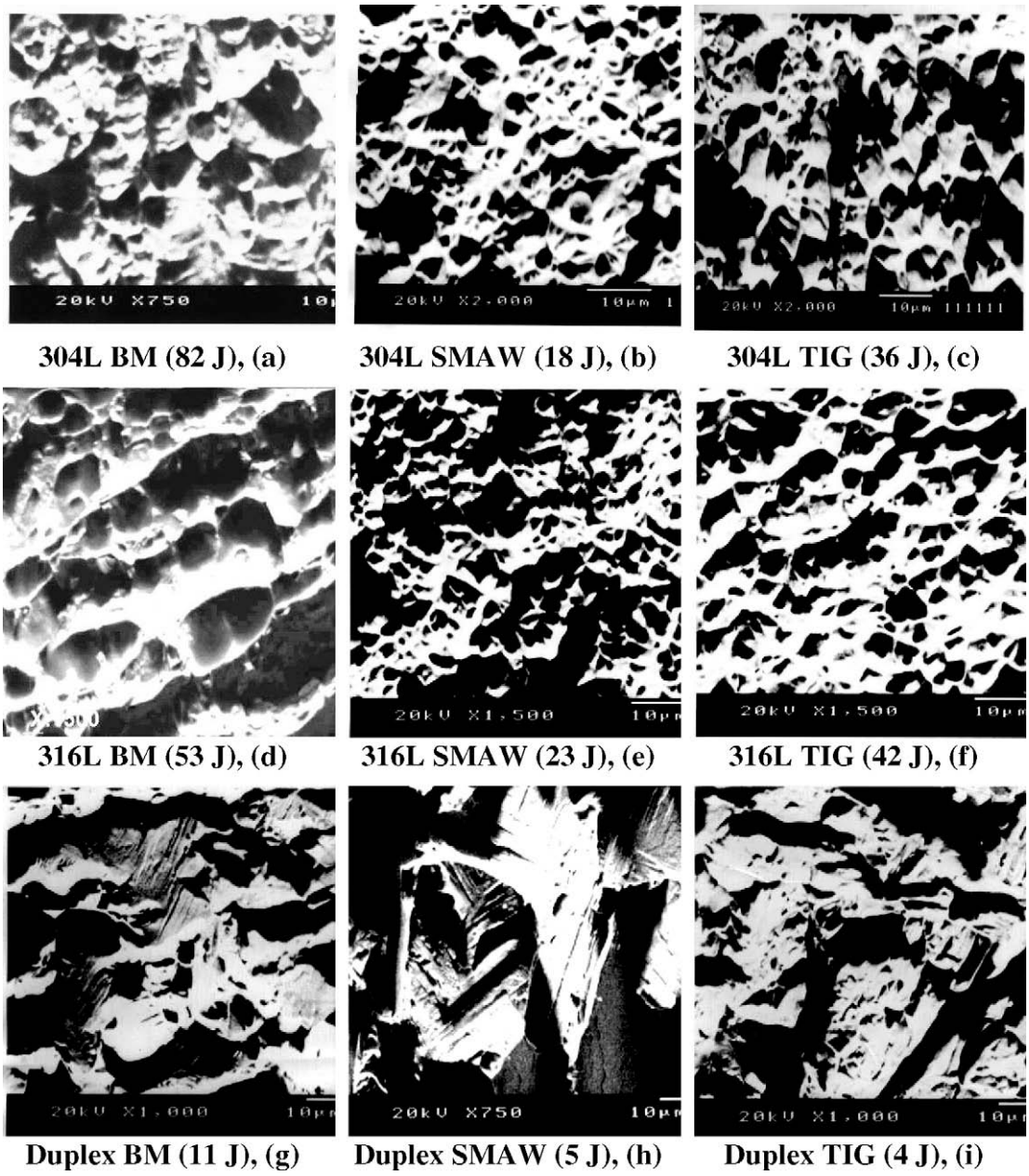

Fig. 4. Fracture surface of investigated materials tested at −196 °C.

Table 4
Average ferrite number of the investigated materials.

Type	Base metal		SMAW		TIG	
	RT	−196 °C	RT	−196 °C	RT	−196 °C
304L	5.6	24.5	7.7	27.5	9.3	16.7
316L	1.6	16.5	9.7	17.4	6.2	9.5
Duplex St. St.	49.5	51.6	42.8	43.1	45.4	47.3

austenitic and duplex stainless steels impact specimens at cryogenic temperatures as low as liquid nitrogen [5]. The vast majority of austenitic stainless steels base metals do not exhibit a ductile to brittle transition phenomenon but they tend to show decreased fracture resistance at cryogenic temperatures. This can be ascribed to the dominance of stacking fault

generation over the formation of strain induced martensite and the relatively little content of the delta ferrite phase originally present in their microstructure. The observed decrease in impact energy of austenitic stainless steel weld metals (SMAW and TIG) is a verification of the role played by their higher ferrite content in affecting the deformation process.

At cryogenic temperature, welds typically exhibit higher strength and lower toughness than their base metal counterparts. The inferior weld metal toughness is associated with high non metallic inclusion and delta ferrite content and higher strength level [6]. Delta ferrite phase undergoes a ductile to brittle transition with decreasing test temperature. However, since the investigated austenitic stainless steel weld metals fracture surface displayed ductile dimple rupture features at room temperature and even at −196 °C, it can then be concluded that the austenite matrix has restricted the cleavage fracture mechanism that could have been formed around the deformed delta ferrite phase.

The results presented above showed that neither the austenitic stainless steel base nor weld metals had exhibited temperature-sensitive fracture mechanism. Both tested materials followed only ductile mode of fracture all the way down to the lowest testing temperature. The apparent comparatively lower impact energy values for the austenitic weld metals to those of austenitic base metals can be attributed to the formation of delta ferrite, in their microstructure during the welding process. Furthermore, the formation of delta ferrite may promote creation of martensite, upon cooling, because martensite phase is likely to start in areas with similar lattice structure; i.e. BCC structure [7]. However, it seems that the lowest testing temperature used in the present investigation (−196 °C), was not low enough to trigger cleavage fracture in the delta ferrite or martensite phases which have readiness for ductile to brittle transition mechanism. In this way, the whole fracture process is governed by the ductile fracture of the dominating austenite phase. For example, austenitic stainless steel castings and welds which possess dual-phase structure (austenite + certain amount of ferrite phase) are likely to show a mixture of ductile fibrous and brittle cleavage fracture morphology at liquid helium test temperature (−269 °C). The ferrite cleaves at this very low temperature whereas the surrounding austenite remains ductile. The ferrite cleavage may take over the fracture process if it is present in sufficient quantity or favorably distributed. At such very low temperatures, when the ferrite phase percent is 15% and higher continuous ferrite path is established through the ductile austenite and the toughness is governed essentially by the facture resistance of the ferrite alone. At lower percentages of ferrite phase the overall toughness is some average of both austenite and ferrite [2].

As shown above, the duplex stainless steel base and weld metals demonstrated ductile to brittle transition feature (Fig. 2). The ductile to brittle transition temperature (DBTT) was determined at half the value of the total impact energy against the test temperature. The determined DBTT values were −75 °C for the duplex base metal and −25 °C for both the SAMW and TIG duplex weld metals. This indicates that the duplex stainless steel weld metals are more prone to brittle fracture at cryogenic temperatures than their counterpart base metals.

The observed ductile to brittle transition behavior of the duplex stainless steel base and weld metals can be associated with the high ferrite phase content (50%) in their microstructure. Since ferrite is of a body centered cubic (BCC) structure, its yield strength is a function of temperature i.e. increases as the temperature is lowered due to increased lattice friction stress and pinning of mobile dislocations with interstitial atoms (carbon and nitrogen). On the other side, the cleavage fracture stress of ferrite is not a function of temperature and is only varied by microstructural parameters as grain size and dislocation density [8].

At room temperature, the cleavage fracture stress of ferrite is much higher than its yield strength and consequently plastic deformation prevails and ductile behavior is verified. As temperature decreases, and at a certain low temperature, lower than room temperature, the yield strength of ferrite becomes higher than its cleavage fracture stress. At this stage, a transition from ductile fracture through plastic deformation to brittle fracture by cleavage takes place. Since the austenite phase of the duplex stainless steel is of a face centered cubic (FCC) structure, neither of its yield or fracture stress would be a function of temperature. Accordingly, the ductile to brittle transition process of base and weld metals would be governed by the deformation characteristics of the ferrite phase [9,10].

4. Conclusions

The present investigation provided a comparison of the impact behavior, at test temperatures between room and liquid nitrogen (−196 °C), of austenitic (304L, 316L) and duplex (2205) stainless steel base and SMAW and TIG weld metals. The main conclusions are:

1. The 304L and 316L base metals exhibit little decrease in impact energy while their counterpart SMAW and TIG weld metals display greater drop, with decreasing test temperatures. Both base and weld metals maintained ductile fracture behavior even at liquid nitrogen test temperature.
2. The duplex stainless steel base and weld metals demonstrate ductile to brittle transition behavior with remarkable decrease in their impact energy with decreasing test temperature.
3. The instrumented load–time traces are indication of the ductile and brittle fracture behavior of both austenitic and duplex stainless steels, respectively.
4. The fracture surface morphology, at −196 °C test temperature, of austenitic base and weld metals show wide and small deep dimples characteristic of ductile fracture, while the duplex base and weld metals show stepped and large cleavage facets characteristic of brittle fracture.

5. The fracture process of austenitic and duplex stainless steels at low temperature is a product of a competition of many mechanisms that include: generation of stacking faults, formation of deformation induced martensite and ferrite phase deformation characteristics.

Acknowledgment

The authors gratefully acknowledge the technical assistance and providing of the welding facilities by Prof. Dr. A.A. Sadek, Central Metallurgical Research and Development Institute (CMRDI), Cairo, Egypt.

References

[1] George E, editor. Steel heat treatment, metallurgy and technologies. Totten, New York: CRC Taylor & Francis; 2007.
[2] Sa JW, Kim HK, Choi CH. Mechanical characteristics of austenitic stainless steel weldments at cryogenic temperature. In: Twenty first IEEE/NPS symposium on fusion engineering; 2005.
[3] Honeycombe RW. Steels, microstructure and properties. London: Edward Arnold; 1995.
[4] Straffelini G, Molnari A, Bonollo F, Tiziani A. Effects of aging on impact behavior of different stainless steel weldments. Mater Sci Technol 2001;17:391.
[5] Mills WJ. Effect of temperature on the charpy impact and CTOD values of type 304 stainless steel pipeline for LNG transmission. Int Met Rev 1997:42.
[6] Chan JW. Small punch testing for determining the cryogenic fracture properties of 304 and 316 austenitic stainless steels. Adv Cryogenic Eng 1992;55:38.
[7] Michler T. Toughness and hydrogen compatibility of austenitic stainless steel welds at cryogenic temperature. Int J Hydrogen Energy 2007;32:4081.
[8] Han G, Fukuyama S, Yokogawa K. Tensile behavior of duplex stainless steel at low temperatures. Mater Sci Technol 1999;15:909.
[9] Kacar R, Acarer M. Microstructure–property relationship in welded duplex stainless steels. Mater Sci Eng A 2003;363:290.
[10] Sieurin H, Sandstom R. Fracture toughness of a welded duplex stainless steel. Eng Fract Mech 2006;73:377.