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Fatigue behavior of mechanical structures welded with different filler metal

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Abstract. This paper describes an investigation on the effect of using three different filler metals on fatigue behavior of mechanical structures welded. The welding is carried out on the steel A510AP used for the manufacture of gas cisterns and pipes. The welding process used is manual welding with coated electrodes and automatic arc welding. Compact tension CT50 specimen has been used. The three zones of welded joint; filler metal FM, heat affected zone HAZ and base metal BM have been investigated. The results show that the crack growth rate CGR is decreasing respectively in BM, FM and HAZ; however, this variation decreases when stress intensity factor SIF increases. For low values of SIF, the CGR is inferior in the over-matched filler metal of which the value of mismatch M is near unity, but for high values of M the CGR is superior, and the effect of the over-matching on CGR becomes negative. No deviation of the crack growth path has been noticed.

Keywords: yield stress; fatigue crack growth; stress intensity factor; crack growth path; overmatch; undermatch

1. Introduction

Safety of welded structures is a major issue in industrial activity. The cracks are usually the real cause of structural damage. Looking for ways and solutions to keep and preserve these structures is one of the most important priorities in the current state.

Welded joints are favourable areas for crack initiation. For the safety of welded structures, a study is very necessary. Making the right choice of the filler metal, knowing the behaviour of the crack and its crack growth rate leads us to predict the lifespan.

The choice of filler metal, the conditions and adequate welding processes have a very large influence on the quality of the welded joint (Nathan *et al*. 2015, Salleh *et al*. 2016, Magudeeswaran *et al*. 2014).

Several studies have discussed the factors affecting the behavior of welded joints, especially the effect of the heterogeneity of welded structures (Zhang *et al*. 2002, Burzić *et al*. 2014). The term heterogeneous welding refers to the junction of two materials which are hardly miscible with very

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Table 1 The chemicals compositions of A510AP steel and filler metals

Element (%)	C	S	Si	Mn	Ni	Cr	Mo	V
A510AP	0.162	0 .005	0.44	1.45	0.08	0.07	0.008	0,10
GMoSi	0.1	-	0.6	1.15	-	-	0.52	-
GCrMo1Si	0.1	-	0.6	1	-	1.2	0.52	-
G694M	0.09	-	0.52	1.57	1.4	0.3	0.25	0.09

different mechanical properties.

For this purpose the relationship between the yield strength of filler metal and the yield strength of the base metal termed as -*M*- designated by mismatching has an effect on the crack growth rate, crack propagation resistance and path deviation of crack (Nègre *et al*. 2004, Ravi *et al*. 2004a, Khurshid *et al*. 2012).

Several researchers have shown that fatigue crack initiated from the filler metal, deviate from its original propagation direction, after a stage of steady propagation, traverse into the heat affected zone, and then enters into the base metal (Zhang *et al*. 2002).

Some authors have tried to explain that this deviation is due to the difference in mechanical properties between the three zones of the welded joint, as the crack is moving from a harder microstructure to a softer microstructure (Lei *et al*. 1998). In the present study, no deviation of the crack growth path has been noticed.

Our study was conducted on A510AP steel, used for the manufacture of gas cisterns (liquefied petroleum gas (LPG)) and pipes. We have chosen three categories of filler metal to make a comparison and choose the most suitable material. A weld joint is obtained bymanual welding with coated electrodes, and automatic arc welding, manual welding with the coated electrode is used for the first pass and after inspection by radiography and Penetrant test procedure, and if the weld is good a second pass is made which is done by automatic arc welding. Compact tension (CT50) specimen has been used to evaluate the fatigue crack growth behavior. FM, HAZ and BM areas have been investigated.

The three categories of filler metal used, are (GMoSi noted FM1), (GCrMo1Si noted FM2) and (G694M noted FM3). The following Mechanical property characterization tests have been made: tensile testing, and fracture toughness. The chemical composition of A510AP steel and fillers metals are given in Table 1.

In addition, The tests of strength to the ductile mode of unstable cracking have been conducted to evaluate the J integral, these tests have been done at ambient air on specimens SENB10 type (bending three points of B×B section) taken in the transverse direction (TL) of the welding joint. The tests have been done for measurement of fracture toughness J_{IC} which represents the energy required to initiate crack growth, in order to make a comparison between the behavior of the three filler metals.

2. Tensile test

Tensile tests have been conducted at the laboratory of the national company of the petroleum big works in Algeria GTP, for the determination of the conventional and rational features of traction, the tests have been done at ambient temperature on appropriated specimens in accordance with the AFNOR A03-151 and A03-351 norms. Five samples were made for each zone of the

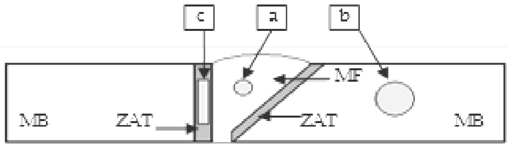
Table 2 Mechanical properties of A510AP steel and filler metals

Materials	Mechanical properties					
	Re (N/mm^2)	*Rm* (N/mm^2)	*A* (%)	*k*	*n*	*M* mismatching
A510AP	380	400	20	980	0,401	
GMoSi (FM1)	460	560	22	836	0,302	1.2
GCrMo1Si (FM2)	305	450	20	1009	0,508	0.8
G694M (FM3)	570	706	22	970	0.3	1.5

weld joint. The test specimens used for the traction test are:

Cylindrical specimens with a circular cross-section
- 6 mm pour (Weld Metal FM -a-)
- 10 mm pour (Base Metal BM -b-)

Prismatic specimens (heat affected zone HAZ -c-)



All the tests have been performed on electro-hydraulic universal machine with IBERTEST control with at a dynamic load capacity of 40 Kn and 33 kN.

The test speeds depend on the material and are chosen in accordance with standard ASTM E8M. In the elastic domain and until the upper flow limit is reached, this speed must be maintained as constant as possible and must be located within the limits corresponding to the rate of loading (2-20 MPa s^{-1}) for elasticity modulus of the material. In the plastic domain and until the elasticity conventional limit is reached, the test speed must be between 0.1 and 3 mm/min.

The results obtained are summarized in Table 2.

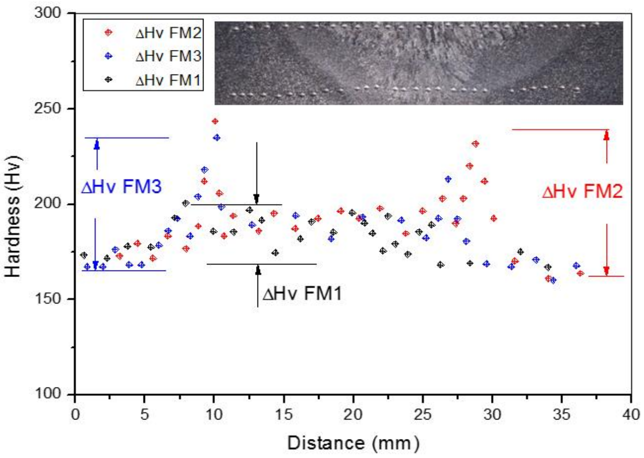


Fig. 1 Hardness profile in the weld joint

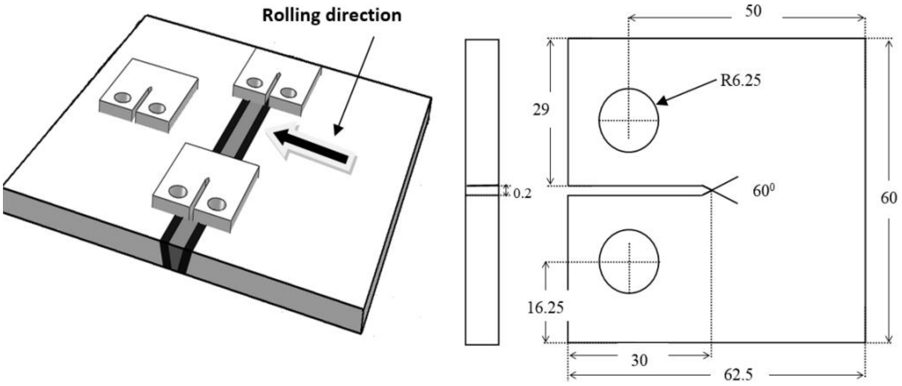


Fig. 2 Schematic representation of the notch and dimensions of specimens CT50 in mm

3. Hardness measurement (*Hv*)

Metallographic examination and measure of hardness have been carried out on a SHIMADZU (JIS-HMV-2251) system in order to determine the hardness profile in the weld joint. These hardness tests are used to determine if the variations of hardness in the welded joint were regular or on the contrary it they present hardenings. The obtained results are represented in Fig. 1. The obtained measures show welded specimens hardness with the filler metal (FM2 and FM3). In the other hand in the other case, there is regular uniform hardness for welded specimens with the filler metal FM1 because it presents a lower (ΔHv min) which is recommended (Haušild *et al*. 2005).

4. Fatigue test

Fatigue crack tests have been conducted on compact tension specimens (CT50) 7 mm thickness compliant with standardASTM-E-647. The tests have been performed at the University of Sidi Bel Abbes, on electro-hydraulic machine controlled -INSTRON-, with a capacity of 100 kN in static and 50 kN in dynamic, and carried out in ambient air with a stress ratio of 0.1 and frequency of 25 Hz for all specimens. We have three specimens for each filler metal, the same for base metal and HAZ. The specimens used have been mechanically polished with emery paper and were oriented in the transverse direction (TL) of the weld joint.

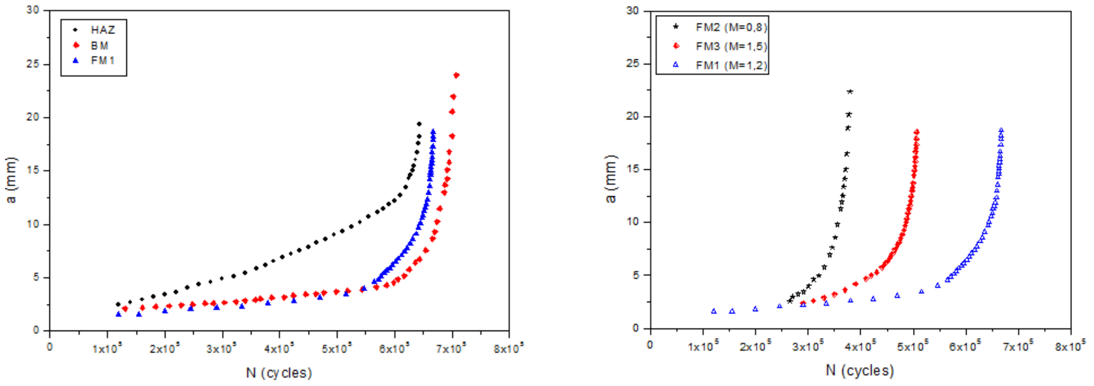
The shape and dimensions of specimens are shown in Fig. 2.

During the fatigue test, for FM1 we observed that, after several cycles, the crack did not propagate, so we resulted in the technique of localpre-compression method of ligament of the specimen (standard A03-180) to relax the stresses residuals. After this method, the crack propagated.

5. Results and discussion

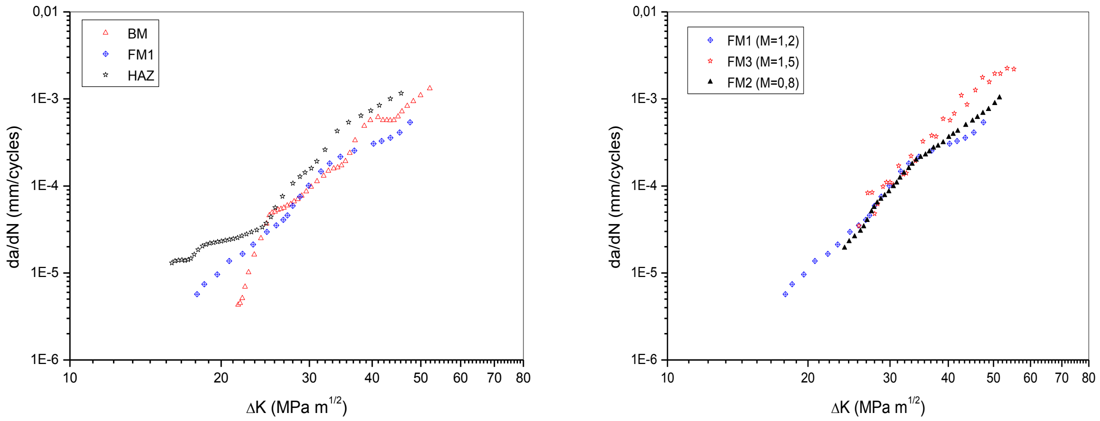
5.1 Crack growth tests

Fatigue crack growth tests have been carried out in the speed range between 4.10^{-5} and 2.10^{-2} mm/cycle, in ambient air with a stress ratio of 0.1. Fig. 3 shows the relation of crack length with the number of cycles of the weld joint. The relationship of fatigue crack growth rate and stress



(a) Three zones of weld joint (b) Three category of fillers metals

Fig. 3 Crack length vs. a number of cycles



(a) Three zones of weld joint (b) Three category of fillers metals

Fig. 4 Crack growth rate vs. number of cycles

intensity factor is shown in Fig. 4.

We can notice that the curves take a quasi-rectilinear form on most of the explored domain, which may be presented by the PARIS law (Paris and Erdogan 1963, Paris *et al*. 1961).

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

C: constant depends on material and the environment,
m: Paris exponent are given in Table 3,
ΔK: Stress intensity factor SIF,

As shown in Figs. 4(a)-(b), the values of SIF vary from 21 to 52 MPa$\sqrt{m}$ in the base metal, from 17 to 45 MPa$\sqrt{m}$ in the heat affected zone and from 18 to 48 in the fusion zone of FM1. For the other filler metals, the values of SIF vary from 25 to 51 in the fusion zone of FM2 and from 2 8 to 50 in the fusion zone of FM3. In Fig. 4(a), for the three zones of the weld joint of FM1, it is

Table 3 (*C*, *m*), paris law parameters and ΔK range

Designation	PARIS LAW	ΔK MPa$\sqrt{m}$
BM	$da/dN = 3{,}69e^{-11}\Delta K^{4{,}39}$	21 to 52
HAZ	$da/dN = 6{,}38e^{-11}\Delta K^{4{,}09}$	17 to 45
FM1	$da/dN = 5{,}91e^{-10}\Delta K^{3{,}54}$	18 to 48
FM2	$da/dN = 1{,}62e^{-12}\Delta K^{5{,}19}$	25 to 51
FM3	$da/dN = 5{,}01e^{-12}\Delta K^{5{,}90}$	28 to 50

noted that between the value 17 and 25 MPa$\sqrt{m}$of SIF, the crack growth is yet unstable.

For the same value about 22 MPa$\sqrt{m}$, the base metal is more resistant to cracking compared with the other zones, the CGR is greater in the heat affected zone. Beyond the value 25 MPa$\sqrt{m}$ of SIF where the crack growth becomes stable, the difference between the CGR decreases, the fusion zone of FM1 is more or less resistant to cracking compared with the other zones (BM and HAZ). The CGR of the fusion zone is often greater than that of the base metal at room temperature. However, this observation contradicts those of previous researchers, who have found that fatigue crack growth rates were lower in the fusion zone and heat affected zone than in the base metal (Akita *et al*. 2006 and Itatani *et al*. 1994). It has also been observed that the fusion zone often exhibits better fatigue resistance (i.e., lower crack growth rates) compared to the base metal (Pickard *et al*. 1975).

In Fig. 4(b), by comparing the behavior of the three fusion zone of FM1, FM2, and FM3 it is noted that the crack growth started about the value 18 MPa$\sqrt{m}$ for FM1, while for FM2 and FM3 the crack growth started about the value 25 MPa$\sqrt{m}$. May be one can explain this behavior by the higher residual stresses in FM2 and FM3, and this prevented the initiation of crack, as compressive residual stresses increase fatigue strength. It was found that the tensile residual stresses increased the fatigue crack growth rate and compressive stresses reduced it (Stacey and Webster 1988). Compressive welding residual stresses decreased the total SIF value (K_{tot}), and the crack growth rate (Božić *et al*. 2013).

For FM1 we resulted in the technique of local pre-compression method of ligament of the specimen (standard A03-180) to relax the stresses residuals, then the crack starts to propagate better than other fillers.

The stresses occur during solidification stress of the weld metal or due to variations in compactness metallurgical phases appearing in the zone near of the weld. The crack growth rate is disturbed by the existing residual stress field therein.

Between value 25 and 40 MPa$\sqrt{m}$ of SIF, the difference between CGR is almost nothing, beyond the value 40 MPa$\sqrt{m}$, the CGR of the fusion zone of FM1 is the lowest; the effect of the over-matched filler metal FM1 (M = 1.2) is beneficial relative to the under-matched filler metal FM2 (M = 0.8), in contrast to the over-matched filler metal FM3 (M = 1.5) has a highest crack growth rate; this confirms that the right choice of filler metal is one that presents a mismatching nearest of the unity, for high values of (M) the effect of the over -matching becomes negative. We can observe that this Mis-match ratio is inversely proportional with fatigue crack growth exponent (m). Ravi *et al*. (2004b), but this is verified when mis-match M does not exceed the high values such as our case M = 1.5.

In this work, no crack path deviation was noted in all tests, which is encouraging for the choice of filler metal. Some authors (Inal *et al*. 2000) have shown that beyond of some value of SIF, Crack growth is generally accompanied by a crack deviation from its original plane towards the base metal. This deviation is due to different mechanical characteristics of weld joint zones, as the crack moves from a harder microstructure to a softer microstructure.

5.2 Evolution of energy settings

At different levels of SIF, the test frequency is reduced to 0.02 Hz. and we represent the crack opening δ depending on the load P. This energy is determined by a numerical integration of cycles (P, δ) of Fig. 5, its expression is obtained by calculating the area of the loop obtained by

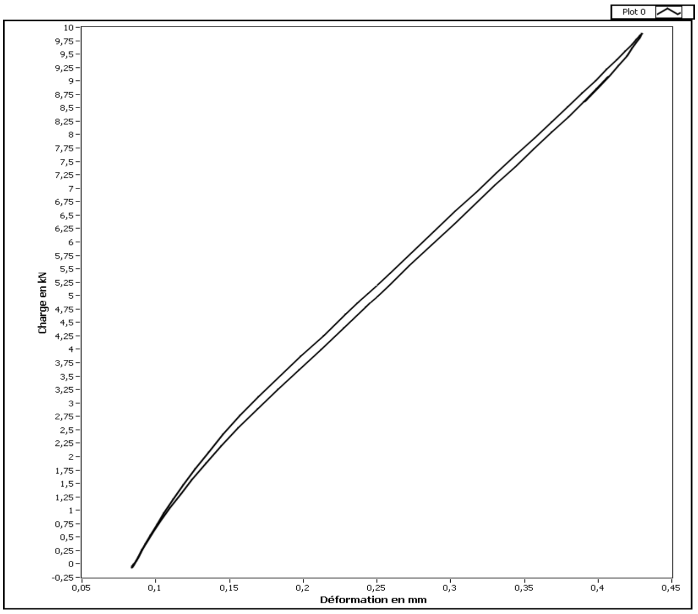
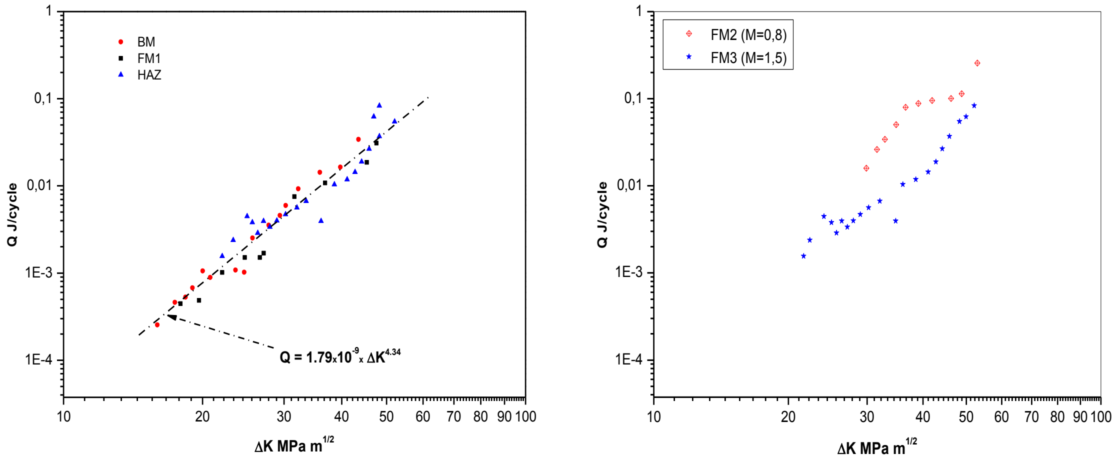


Fig. 5 Hysteretic energy (load P according to the crack opening δ)



(a) Three zones of weld joint (b) Three category of fillers metals

Fig. 6 Evolution of energy hysteretic vs. ΔK (SIF) acquisition and processing using a program written in LABVIEW.

Fig. 6 shows the evolution of the hysteretic energy Q dissipated during a cycle according to SIF with a stress ratio of 0.1.

We note that hysteretic energy has the same trend for the different cases of Mismatching and that for the same level of SIF, the hysteretic energy is greater in the under-matched specimens than those over-matched specimens. However, the difference between the hysteretic energy decreases when SIF increases.

5.3 Evolution of specific energy

Fig. 7 shows the evolution of specific energy U versus ΔK spent per cycle for a load ratio R = 0.1. This energy is given by the following relationship (Itatani *et al*. 1994).

$$U = \frac{area\ of\ the\ loop(p.\delta)}{2B\left(\frac{da}{dN}\right)} \quad \text{or} \quad U = \frac{Q}{2B\left(\frac{da}{dN}\right)} \tag{2}$$

We noticed that this specific energy U is almost constant relative to SIF for different zones of the weld joint with average values of 2.106 J/m^2.

These results are consistent with the work of other researchers (Akita *et al*. 2006, Itatani *et al*. 1994, Pickard *et al*. 1975), where they consider that the hysteresis work is mainly dissipated in the plastic zone, and in the case where the closure phenomena are important, it is conceivable that a part of the energy U is dissipated in the zone within the plasticized wake along the crack front. They found also that beyond the SIF value called ΔKcr, the U value is constant and independent of the ratio R and the environment.

5.4 Toughness testing J_{IC}

The tests of strength to the ductile mode of unstable cracking have been achieved on a servo-hydraulic machine. These tests have been done at ambient air on SENB10 type specimens

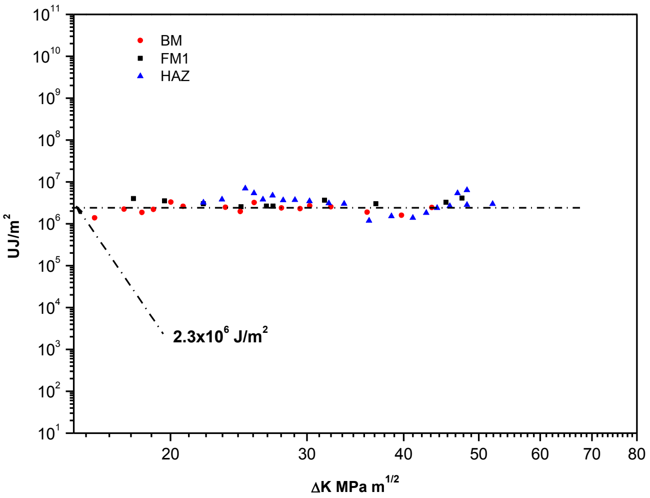


Fig. 7 Evolution of specific energy vs. ΔK (SIF)

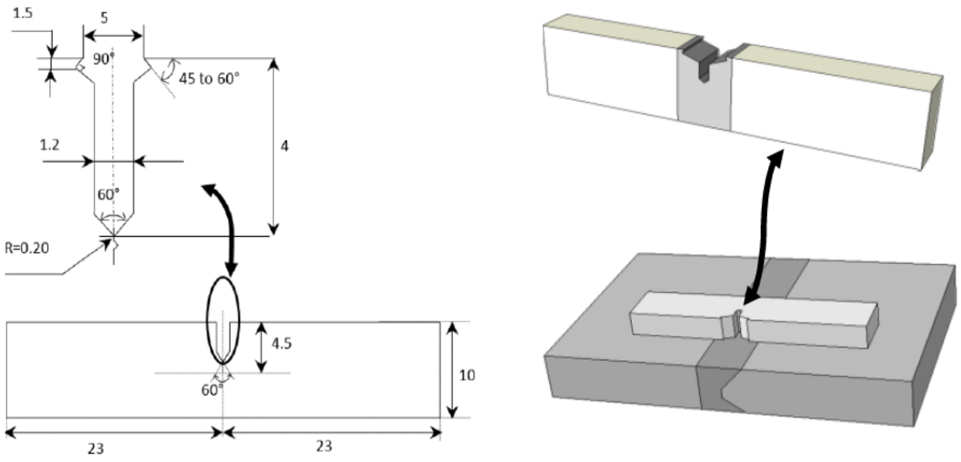


Fig. 8 Schematic representation of the notch and dimensions of the specimen SENB in mm

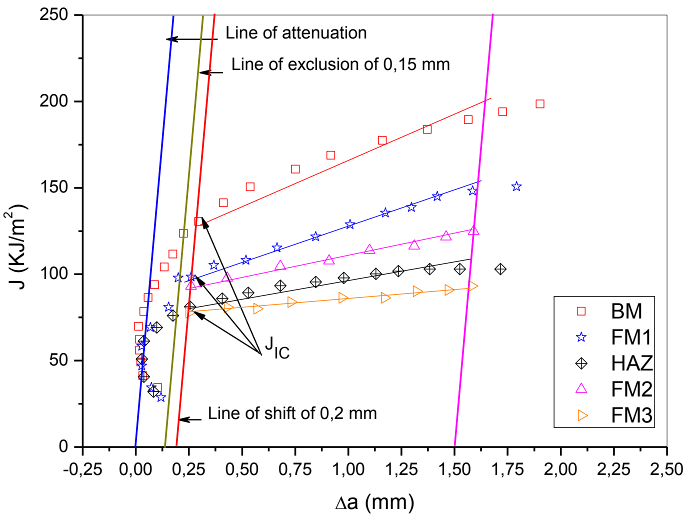


Fig. 9 Evolution of the integral J vs. Crack length

specimens are shown in Fig. 8.

The Fig. 9 represents the evolution of the J integral in relation to the extension of the crack (Δa). Only the data points located between the 0.2 mm and 1.5 mm exclusion lines are considered valid. The value of J_{IC} is determined to the point where the curve intersects the line of shift of 0.2 mm (as per ASTM E813-2002).

Between 0.00-0.25 of Δa, the J integral has are verse trend, crack growth is yet unstable because of closure phenomena. After a few instants, the stress relaxed and the crack propagates.

The remarks that one can make to the exam of these curves are the following:

For the value of mismatch (M) near of unity, the lowest values of the parameter $J_{0.2}$ obtained are observed for the under-matched filler metal FM2, and on the other hand, the highest values are observed for the over-matched filler metal FM1.

6. Conclusions

The present investigation was carried out to study the effect of mis-match on fatigue crack growth behaviour and fatigue life of A510AP steel weld joint obtained by automatic welding process with coated electrodes. From this investigation, following conclusions have been obtained:

The fatigue crack growth behaviour and fatigue life of the welded joints are influenced by mis-match ratio. We observed that Mis-match ratio is inversely proportional with fatigue crack growth exponent (m), and the same is verified when mis-match M does not exceed the high values such as our case $M = 1.5$.

Beyond the value 40 MPa$\sqrt{m}$ of SIF (stress intensity factor), The crack growth rate of the fusion zone of FM1 is the lowest; the effect of the over-matched filler metal FM1 ($M = 1.2$) is beneficial relative to the under-matched filler metal FM2 ($M = 0.8$), in contrast to the over-matched filler metal FM3 ($M = 1.5$) has a highest crack growth rate, this confirms that the right choice of filler metal is one that presents a mismatching nearest of the unity. For high values of (M) like our cases $M = 1.5$ the effect of the over -matching becomesnegative.

No crack path deviation was noted in all tests, which is encouraging for the choice of filler metal.

As we have noticed above, for the same level of SIF, the hysteretic energy is greater in the under-matched specimens than those over-matched specimens. However, the difference between the hysteretic energy decreases when SIF increases.

As regards the specific energy U, We noticed that this specific energy U is almost constant relative to SIF for different zones of the weld joint with average values of 2.106 J/m^2.

For the value of mismatch near of unity, the lowest values of the parameter $J_{0.2}$ obtained are observed for the under-matched filler metal FM2, on the other hand, the highest values are observed for the over-matched filler metal FM1.

For the over-matched filler metal FM3, the value of $J_{0.2}$ integral obtained is the lowest, the same remark already mentioned above for crack growth rate, the effect of the over -matching becomes negative.

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