Design and Production Engineering Department

Fracture Evaluation of Steel Joints Made by Different Welding Processes

A Thesis submitted in partial fulfillment
of the requirements of the degree of
PhD in Mechanical Engineering
(Design &Production Engineering Department)

By
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Statement

This thesis is submitted in partial fulfillment of the requirements of Ph.D. Degree in Mechanical Engineering, specialization (Production Engineering), Ain Shams University.
The author carried out the work included in this thesis, at the laboratories of Central Metallurgical Research & Development Institute (CMRDI) and the laboratories of Kader Factory for Developed Industries (K.F.D.I.), Arab Organization for Industrialization (A.O.I.).
No part of this thesis has been submitted for a degree or qualification at any other scientific entity.

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Abstract

Steel sheets joining can be done by many welding techniques which have advantages and disadvantages. Selection of one among them to fabricate specific structure is delicate and most of the time depends on theoretical and practical experience.
In this investigation the fracture mechanics science was used to study the behavior during fracture of joints made by different welding techniques.

Fracture resistance of low alloying element low carbon steel sheet welded joints had been evaluated by Essential Work of Fracture (EWF) testing method. Testing was done on DENT specimens which were prepared by EDM using 0.3 mm wire diameter.

More than thirty two notched specimens with different notch lengths had been tested and the Specific Essential Work of Fracture (w_e) was evaluated and interpreted by different models. The results were presented and analyzed to make evaluation and assessment processes. Also features of the fracture surface were evaluated using SEM microscopy for comparison as well as the energy consumption of the different welding processes.

The EWF gave results which are matched with the results of tension test, micro hardness test for as received material and all type of welds, also it gave matched results with the power consumption of the different weldments. The weldment of GTAW gave higher Essential Work for Fracture (higher fracture energy) if it is compared to that of FSW and GMAW.

The SEM micrographs for the fracture surface of the as received material, GTAW and FSW weldments tensile test specimens assure those fractures are mixed brittle ductile types but differ in their tendency for fracture while for GMAW the fracture type is ductile which in turn interpreting the tension test results and micro hardness results for weldments.

FSW has the lowest value of energy consumption to fulfill the welded joint if it is compared to GTAW and GMAW.

Keywords:
Fracture toughness, Essential Work of Fracture (*EWF*)*, Double Notch Edge Tensile (DENT), Electrical Discharge Machining (EDM), The Specific Essential Work of Fracture* (w_e)*, Gas Metal Arc Welding* (*GMAW*)*, Gas Tungsten Arc Welding* (*GTAW*)*, Friction Stir Welding* (*FSW*)*, Mode 1 Fracture Toughness* (K_{1c})*, Scanning Electron Microscopy (SEM).*

Thesis Summary

It is usually accepted that the welded metallic structure serves its primary functions but with some defects ranges in size for example hair cracks. There are many standards to accept welded joints according to many approval references. Most of these standards are supplied to traditional welding processes like GTAW, GMAW. Friction stir welding (FSW) in general is relatively new welding technique which produces sound weldments. Considering many applications of friction stir welding, there is a great need to fracture toughness appropriate assessment procedure for welded joints made by this new technology. The most familiar procedures and tests which are used to evaluate fracture toughness are as follow:

- Plain fracture toughness (K_{1C})
- Crack Opening Displacement (COD)
- J Integral
- And other standards tests like ASTM (E399)

To measure K_{1C} this requires higher thicknesses and this is not found in the case of welding small thin sheets of steel. In this work a nonstandard test procedure have been used to evaluate fracture toughness, it depends on concept of the essential work of fracture (EWF). More than thirty two notched specimens were prepared using EDM wire cutting with a wire diameter of 0.3 mm and tensioned using the a universal testing machine.

The obtained results of the specific essential work of fracture (w_e) were interpreted using the estimated values of J_c for Mai model and the estimated values of w_e for Wells method to evaluate the validation of the test. GTAW and GMAW showed a remarkable deviation, on the other hand FSW showed lower deviation if compared to GTAW and GMAW.

However, the weldment of GTAW gave higher essential work for fracture than that of FSW and GMAW. These results matched the properties of the fracture surface that had been investigated using SEM microscope as well as the energy consumption of the different welding processes which proofed that FSW has the

lowest value of energy consumption compared to GTAW and GMAW.

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Nomenclature

AC	Alternating current
ASTM	American Standard for Testing of Material
ASS	Austenitic stainless steel
a	Notch length (it represents crack depth)
BW	Butt weld
BM	Base metal
CE	Carbon equivalent
CTOD	Crack Tip Opening Displacement
COD	Crack Opening Displacement
DC	Direct current
DCEP	Direct current electrode positive
DCEN	Direct current electrode negative
DT	Destructive test
DENT	Double Edge Notched Specimens
EDS	Energy Dispersive Spectroscopic Analysis
EWF	Essential work for fracture method
FSW	Friction Stir Welding
FCAW	Flux Cored Arc Welding
F	Compressive force
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat affected zone
h	Height of tool pin (mm)
J_c	The critical J-integral value
K	Strength coefficient
K_{IC}	Fracture toughness mode 1
LHF	Low hydrogen ferritic steel
L	Nominal ligament length
MMA	Manual Metal Arc welding
MAG	Metal Active Gas
MIG	Metal Inert Gas
NDT	Nondestructive test
n	Strain hardening exponent
PA	Horizontal welding position

P_f	Power consumed in friction
P_P	Power consumed in plastic deformation
SMAW	Shielded Metal Arc Welding
SEM	Scanning Electron Microscope
TMAZ	Thermo-mechanical affected zone
TWI	The Welding Institute
t	Specimen thickness
UV	Ultra violet
U	Total Work of Fracture
v	Tool traverse speed (mm/min.)
v_o	Welding speed (mm/min)
r_o	Radius of tool shoulder (mm)
r_p	Plastic zone size
r_i	Radius of the pin (mm)
WZ	Weld zone
WPS	Welding procedure specifications
W_f ,U	Total work for fracture
W_e	Essential work for fracture
W_P	Non-essential work for fracture
w_f	Specific total work for fracture
w_e	Specific essential work for fracture
w_P	Specific non-essential work for fracture
μ	Coefficient of friction
ω	Rotational speed of the tool (rev. /min.)
σ_e	Effective stress (power law stress)
ε_e	Effective strain (power law strain)
β	Shape factor
α ,m	Material constants (Ramberg-Osgood parameters)
σ_o	The yield stress of the material
ε_o	The strain corresponding to yield strength
δc	Critical crack opening displacement

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