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Residual stresses and fracture mechanics analysis of a crack in welds of high strength steels

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Abstract

This study presented the characteristics of residual stresses in welds of high strength steels (POSTEN60, POSTEN80) whose tensile strengths were 600 MPa and 800 MPa, respectively. Three-dimensional thermal elastic–plastic analyses were conducted to investigate the characteristics of welding residual stresses in welds of high strength steels through the thermal and mechanical properties at high temperatures obtained from the elevated temperature tensile tests. A finite element analysis method which can calculate the *J*-integral for a crack in a residual stress field was developed to evaluate the *J*-integral for a centre crack when mechanical stresses were applied in conjunction with residual stresses.

The results show that the volumetric changes associated with the austenite to martensite phase transformation during rapid cooling after welding of high strength steels significantly influence on the development of residual stresses in the weld fusion zone and heat-affected zone. For a centre crack in welds of high strength steels where only residual stresses are present, increased tensile strength of the steel, increased the *J*-integral values. The values of the *J*-integral for the case when mechanical stresses are applied in conjunction with residual stresses are larger than those for the case when only residual stresses are present.

Keywords: High strength steel; Martensite phase transformation; Residual stress relaxation; *J*-integral

1. Introduction

Because a weldment is heated locally by the welding heat source, temperatures in the vicinity of the weldment are not uniform but change with distance from the weld centerline. Due to the localized heating, complex thermal stresses are inevitably generated during welding. Residual stresses are stresses that remain in a

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material as a result of liquid-to-solid phase transformation associated with weld solidification and the subsequent non-uniform cooling of the weld altered by phase transformation (martensite transformation) in the solid state which most of ferrous b.c.c weld materials experience during rapid cooling after welding. It is well known that, in steel weldments, the solid-state transformation on cooling of austenite to martensite could have a major influence on the formation of residual stresses. The volumetric expansion due to phase transformation at a given location in the heat-affected zone (HAZ) or the fusion zone (FZ) depends on the volume fraction of martensite [1].

The effect of residual stress on structural integrity needs special consideration in the defect assessment of welded structures as residual stresses that develop in and around the welded joint are detrimental to the integrity and the service behavior of the welded part [2,3]. The combination of high tensile residual stresses in the region near the weld and operating stresses applied can promote failure by fracture or may change the susceptibility to failure modes, e.g. it can promote brittle cleavage failure rather than ductile tearing and also reduce the fatigue life, promote stress corrosion cracking during service. Consequently, it is very important to predict residual stress and its effect on structural failure behavior in the analysis of fracture mechanics of the structure.

In elastic materials, the linear stress intensity factor (K) may be used as a parameter to define the severity of a crack tip. The total value of the K due to residual stress and mechanical load can be obtained by superposition [4]. However, outside the linear elastic fracture mechanics K is no longer applicable and an appropriate elastic–plastic parameter must be used. Although most current defect assessment procedure adopt the J-integral [5] as the elastic–plastic fracture parameter, for a crack in the presence of residual stresses or the combination of residual and mechanical stresses, studies on a general path-independent J definition applicable in these situation appear to be lacking.

The objective of this study was to analyse the residual stress distribution in welds of high strength steels and to determine domain-independent values of the J-integral for a crack in welds. A finite element (FE) model which was able to estimate the effect of phase transformation on residual stress formation was developed. The effect of volumetric changes which is originated in the austenite → martensite transformation on the relaxation of residual stresses was investigated through the experimental study. Three-dimensional thermal elastic–plastic FEM analysis was conducted to reproduce the effect of phase transformation on the generation of residual stresses. The analysis included both the mechanical property changes depending on temperatures and the volumetric changes due to the phase transformation. Also, a finite element analysis method which can calculate the J-integral for a centre crack in a three-dimensional residual stress field generated by welding was developed using the modified J-integral definition. The situation when only residual stresses were present was examined in comparison to the case when mechanical stresses were applied in conjunction with residual stresses.

2. Experimental

The base materials used in this investigation were POSTEN60 and POSTEN80 steels, newly developed high strength steels for the use in bridges, pressure vessels and pipelines, and offshore construction, etc. The chemical compositions of POSTEN60 steel and POSTEN80 steel are shown in Table 1. The carbon equivalents (C_{eq}) of the steels can be calculated using the formula: $C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14$ are 0.40% and 0.46%, respectively. The engineering stress–strain curves, which are required input to FE code for thermal stress analysis, were determined by a conventional tensile coupon test for the temperature range from 20 (room temperature) to 800 °C (Fig. 1).

Residual stress measurements were carried out to investigate the extent of residual stress relaxation due to phase transformation in the FZ and HAZ of high strength steels through the saw cutting method. Rolled

Table 1
Chemical compositions of materials used (wt.%)

Materials	C	Si	Mn	P	S	SAL	Cr	Ni	Cu	V	Mo	B
POSTEN60	0.13	0.3	1.33	0.012	0.004	0.031	0.02	0.02	–	0.038	0.13	–
POSTEN80	0.07	0.3	0.91	0.015	0.004	–	0.45	0.9 + 7	0.02	0.038	0.45	0.0016