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Crack Growth Rate in the Field of Residual Stresses in Welded Structures

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The presence of residual stresses in welded structures can significantly affect the material's resistance to fatigue under cyclic loading. The presence of tensile residual stresses adversely affects the fatigue crack growth rate by increasing it. The change of microstructure and material hardening as a result of the welding process also have negative impact on the crack growth. Accurate prediction and reliable assessment of the residual stress are important for the structural integrity as well as for the design of welded parts regarding residual life assessment. Although there are several techniques for the determination of residual stresses, the finite element method is one of the most convenient and useful ones. This paper presents a finite element modeling procedure to determine the crack growth behavior of butt welded joints under the subject of load for mode I.

Key words: **welded structure, butt welding, residual stresses, crack, crack growth, residual life assessment, finite element method.**

Introduction

THE finite element method can be used to simulate the welding process i.e. temperature field, residual stress fields and strain. The law of linear superposition elastic fracture mechanics is usually used to determine the fatigue crack growth in a residual stress field. The main objective is to determine the stress intensity factor due to residual stress after the welding process using a weighting function or the finite element method. The weighting function has been successfully used in the previous studies. However, the weighting function is limited to structures with simpler geometry. On the other hand, the finite element method has been successfully used to determine the crack growth rate in structures with complex geometry and loading.

Also, the finite element method is one of the most commonly used methods for the determination of the temperature field in the welding process as well as the residual stress field induced by the welding process. However, in the previous studies only a few papers discussed the development of efficient and reliable methods of the welding process simulation. Servette and Zhang [1] have compared the values of their works on the fatigue crack growth in the residual stress field obtained from various empirical crack growth laws such as Walker's equation, the Harter-T method and NASGRO equations using the finite element method. It turned out that the Harter-T method and NASGRO equations give better results than Walker's equation. However, in their works, they entered the values of residual stresses in the finite element model without simulating the welding process. Other authors such as Barsoum and his colleagues [2] have developed the finite element model for the analysis of a crack growth rate in the simulation of welding processes based on linear elastic fracture mechanics.

Generally, the welding process is a complex phenomenon that is a consequence of heat transfer, the transformation of material structure and its mechanical properties. On the basis of this complex approach, it is necessary to accurately simulate the welding process within numerical methods.

In this paper, we used a three-dimensional finite element model to simulate the welding process using the ANSYS software package. The process of welding is a combined thermo-mechanical process. The temperature field has a very strong influence on the stress field with the negligible inverse effect. The analysis carried out first is the transient thermal analysis. The analysis itself is based on the law of heat transfer with a moving heat source. The obtained values of the temperature fields are used as input values, i.e. load in a thermal mechanical analysis. The occurrence of residual stress is the final state of thermal stresses after the welding process and the cooling of the material to the room temperature.

Comparison of numerical and experimental values of residual stress

To verify the use of the finite element method stated in the previous section, the analysis of two butt-welded plates of a length of 600mm, width of 600mm and thickness of 6mm, is shown in Fig.1. The measurement of residual stress is derived from the strain gauges on the surface of the plate in two directions, perpendicular to the welding axis and along the welding axis. For conducting an adequate welding simulation process, a three-dimensional finite element model was used with the same parameters of the welding process as in the experiment.

The shape of the weld groove has a "V" shape, and the

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plates were welded in one pass. During the welding process, the following parameters of welding were applied: arc welding, welding current of 240 A, voltage of 30 V and welding speed of 5mm/sec. For the finite element model, we used SOLID70, an isoparametric element with eight nodes and one degree of freedom at each node (temperature). Four elements through the thickness and the whole plate model were used. Due to the symmetry of the model, the analysis can be carried out only with one half of the model. Both the thermal analysis and the mechanical analysis used the same finite element mesh. In the mechanical analysis, the finite element SOLID45 was used as well as appropriate boundary conditions. Since the heat flux has a large gradient in the vicinity of the welding zone, the finite element mesh was finer. In order to get accurate results of the welding process, the four elements were used through the thickness, 1.5mm, normal to the line of welding, 0.5mm, and the welding axis 5mm. Since the plates are free during the welding process, the mechanical analysis and boundary conditions were used to prevent the movement of the rigid plates. The material used in the welding process was S355, with its thermo-mechanical characteristics shown in Table 1.

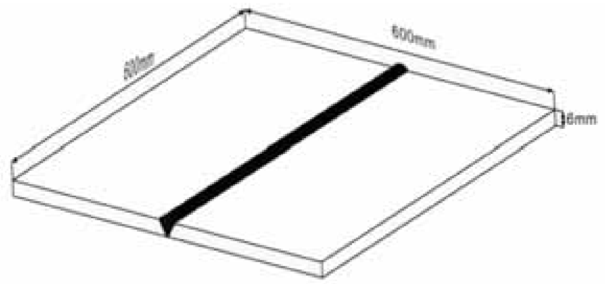

Figure 1 Geometry of the welded plates

Table 1. Thermo-mechanical properties of material S355

Temperature (°C)	Specific heat (J/kg°C)	Thermal conductivity (W/m°C)	Density (kg/m^3)	Tensile Strength (MPa)	Coefficient of thermal expansion (10-5/°C)	Young modulus (GPa)	Poisson coefficient
0	405	45	7880	245	1.20	210	0.3
100	480	44	7880	230	1.20	200	0.3
200	520	42	7800	220	1.20	200	0.3
400	650	38	7760	185	1.20	170	0.3
600	800	30	7600	90	1.20	80	0.3
800	920	18	7520	30	1.20	35	0.3
1000	920	18	7390	25	1.20	20	0.3
1200	920	18	7300	20	1.20	15	0.3
1400	920	18	7250	10	1.20	10	0.3
1550	920	18	7180	5	1.20	10	0.3

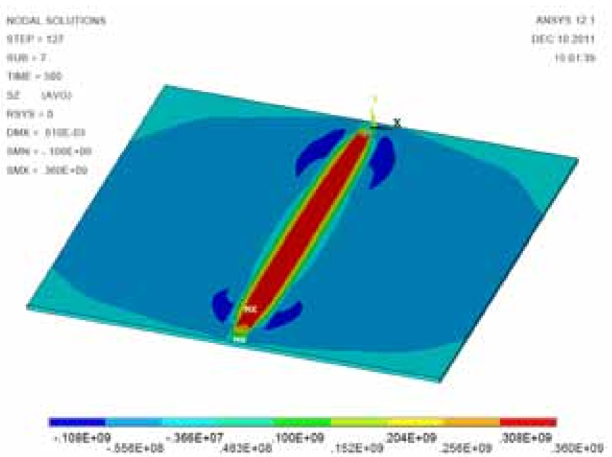

Figure 2 Distribution of the longitudinal residual stress perpendicular to the weld line

In the analysis conducted by the finite element method, we took the same thermo-physical and thermo-mechanical properties of the base and filler materials. It was also taken into account in the analysis that the materials behave elastically-plastically i.e. ideally, von Misses model hardening materials.

Fig.2 shows the distribution of the longitudinal residual stress perpendicular to the weld line while in Fig.3 the distribution of the residual von Misses stress is along the welding line.

The residual stress values are shown as the function of distance from the axis of the welding. Based on the obtained values, the maximum value of tensile residual stresses occurs at the root weld while the maximum value of residual stresses in pressure occurs on the upper surface of the welded plates. Fig.4 shows the values of the residual stresses along the line of the welding. In Fig.5, the distribution of the residual stress along the line of the welding is shown.

The obtained values of residual stresses after welding processes are normalized by the stress at the yield point of the base material (Sx/Sy and Sz/Sy) and are shown in Figures 2 and 3. The values and distribution of residual stresses using the finite element method and experiments are close as it can be seen in Figures 6 and 7.

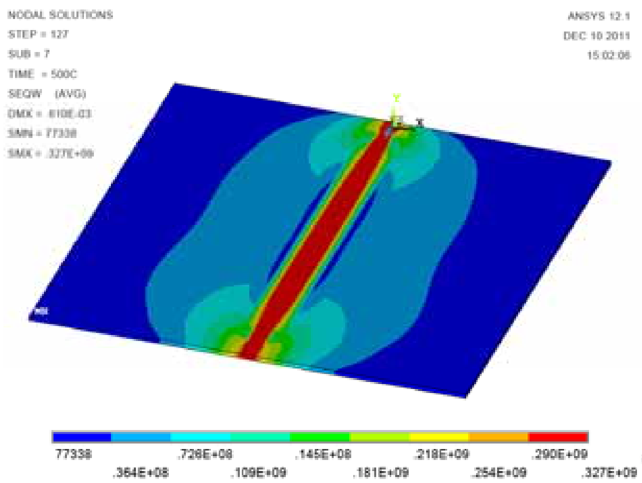

Figure 3 Distribution of the residual von Misses stress along the welding line

Crack growth rate in welded joints using the finite element method

The main task in the analysis of the crack growth rate in the field of residual stresses in welded structures is to determine the stress intensity factors. There are several methods to determine the stress intensity factors: extrapolation of crack tip moving, a modified technique of virtual crack closure and the J-integral. In the method of extrapolation of crack tip moving, it was presumed that the displacements and stresses near the crack tip have asymptotic behavior, so the fracture mechanics parameters were calculated at the top of the crack. This method is essentially simple, but does not guarantee the accuracy of the results. The virtual crack closure technique easily enables determining the parameters of fracture mechanics based on strain energy. The J-integral method also defines the parameters of fracture mechanics based on strain energy and surface integrals.

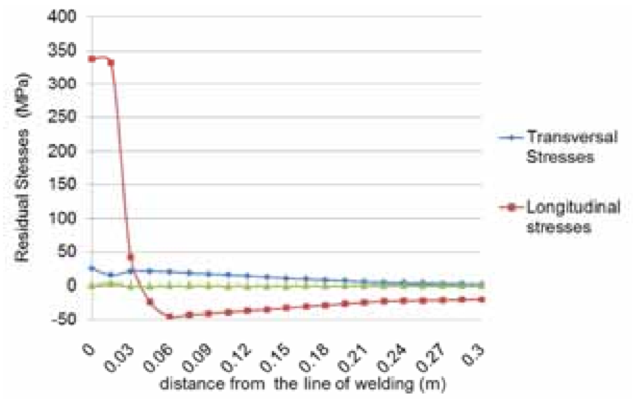

Figure 4 The distribution of the residual stress normal to the line of the welding

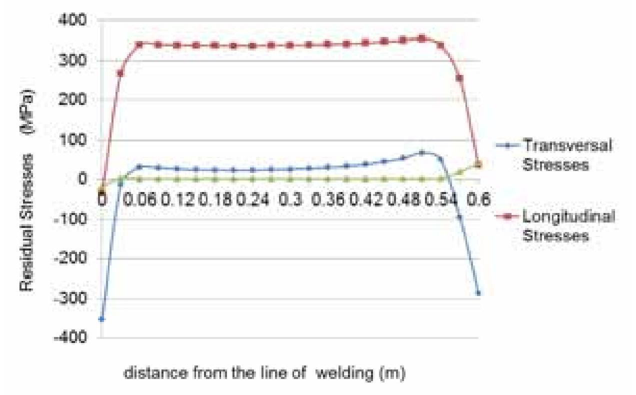

Figure 5 The distribution of the residual stress along the line of the welding

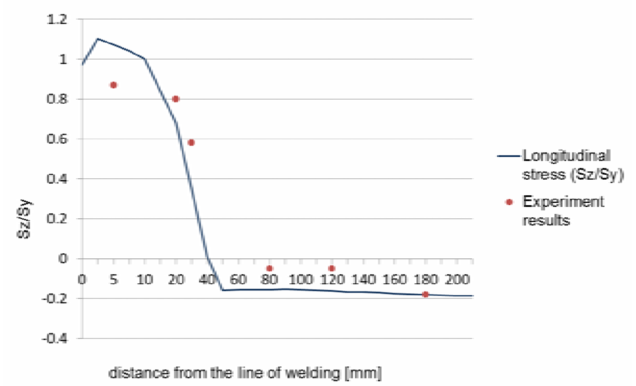

Figure 6 Comparison of the residual stress values obtained by the experiment and the finite element along the line of welding

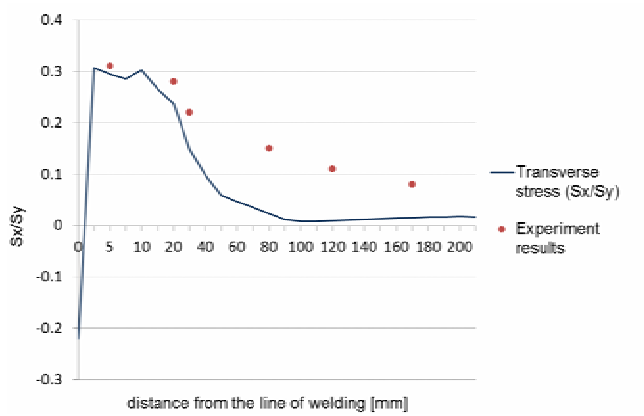

Figure 7 Comparison of the residual stress values obtained by the experiment and the finite element perpendicular to the welding line

In this paper, we used the J-integral method for determining the stress intensity factors based on the energy released in the field of residual stresses due to the welding process. Note that the J-integral is no longer independent of the path around the crack tip, and many authors have devoted their research to this problem [3]. Based on the research by various authors [4, 5], the J-integral has been modified [6], which eliminates the dependence of the J-integral path. In this paper, we used a modified J-integral for determining the stress intensity factors for mode I in the field of residual stress after welding.

The influence of residual stress fields on the cack growth

The effect of residual stresses on the crack growth rate can be determined on the basis of the principle of superposition of linear elastic fracture mechanics and the effective stress intensity factor, K_{eff}:

$$K_{eff} = K_{applied} + K_{residual} \tag{1}$$

Due to the availability of material constants of fracture mechanics in the function of ΔK_{eff}, the crack growth ratio can be described in the Paris Eq. 2:

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^m \tag{2}$$

Under cyclic load, the values of ΔK_{eff} and R_{eff} are determined by the following equation:

$$\begin{aligned}\Delta K_{eff} &= \left(K_{applied}^{\max} + K_{residual}\right) - \left(K_{applied}^{\min} + K_{residual}\right) = \\ &= K_{applied}^{\max} + K_{applied}^{\min} = \Delta K_{applied}\end{aligned} \tag{3}$$

$$R_{eff} = \frac{K_{eff}^{\min}}{K_{eff}^{\max}} = \left(\frac{K_{applied}^{\min} + K_{residual}}{K_{applied}^{\max} + K_{residual}}\right) \tag{4}$$

Based on Eqs.3 and 4, the effective range of the stress intensity factor remains constant when we analyze residual stresses. However, the relationship of the effective stress intensity factor continues to change as the top of the crack spreads through the residual stress field for a constant stress ratio and therefore results in the change in the mean stress at the top of the crack. Therefore, the crack growth in the residual stress field is necessary to include the ratio of effective stresses relative to the range of stresses [2,13]:

$$\frac{da}{dN} = \frac{C\left(\Delta K_{eff}\right)^m}{\left(1 - R_{eff}\right)}$$

Based on Eqs.3, 4 and 5, for the calculation of the crack growth in welded joints, it is necessary to know the values of the stress intensity factors of the external loads applied $K_{applied}$, and the fields of residual stresses $K_{residual}$. It is not necessary to calculate the total value of the stress intensity factors due to the external load and the residual stress fields due to welding [7].

Determination of the crack growth in butt welded joints under the effect of mode I loading

The authors carried out a three-dimensional finite element analysis in this paper in order to determine the crack growth velocity in welded joints under the effect of external load for mode I [8, 9]. For the analysis, we used the model of welded plates with the geometry shown in Fig.1, and the material properties in Table 1. The material constants in the Paris equation had the following values: $m = 3$ and $C = 3x10^{-13}$ mm /cycle. In the zone of the welded joint, a more refined finite element mesh, isoparametric one, with twenty nodes, was used. In order to determine the parameters of fracture mechanics, i.e. the stress intensity factor in the analysis, a crack extending throughout the thickness was introduced in the middle of the welded joint. The adopted crack length for a plate of the given geometry is 2a = 5 mm (Fig.8). For different values of the external tension load, the values of the J-integral around the crack tip were calculated. The obtained values of the J-integral were calculated on the basis of linear elastic fracture mechanics and the properties of the integral independent of the path around the crack tip. Fig.9 shows the value of the J-integral around the crack tip for different values only from the external mechanical load for mode I. In the analysis, the tension in the range of 80 MPa to 160 MPa was taken as the values of external loads. For each external load value, the values of the J-integral were calculated for different paths around the crack tip. On the basis of Fig.9, we conclude that the values of the J-integral are independent of the path around the crack tip for all values of the load applied in the analysis [10].

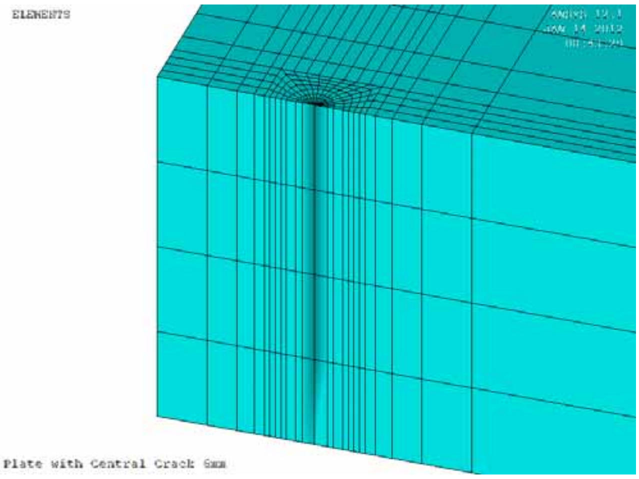

Figure 8 Singular finite elements around the crack tip

The crack that was introduced in the analysis, of the length of 2a = 5 mm, has a central position, perpendicular to the weld line and extends throughout the thickness. The presence of residual stresses across the thickness leads to the conclusion that during its growth, the crack has the same geometry throughout the thickness. Also, the crack growth is perpendicular to the external load, which includes the determination of the stress intensity factor mode I.

The size of the models that we have taken in the analysis satisfies the size of the plastic zone around the crack tip as it does not exceed 1/5 of the model under the influence of external load and residual stress after welding.

To determine the ratio of the crack growth in the weld joint, Eq.5 was used, where certain values of the stress intensity factors are due to external loads $K_{applied}$, and the fields of residual stresses $K_{ressidual}$. Fig.10 shows the function of the crack growth rate for a constant load ratio (R = 0) and the crack growth rate for external mechanical loading and residual stresses due to the welding process. It is obvious that, when there are welding residual stresses, the crack growth rate is significantly higher than when it is present in mechanical loading only.

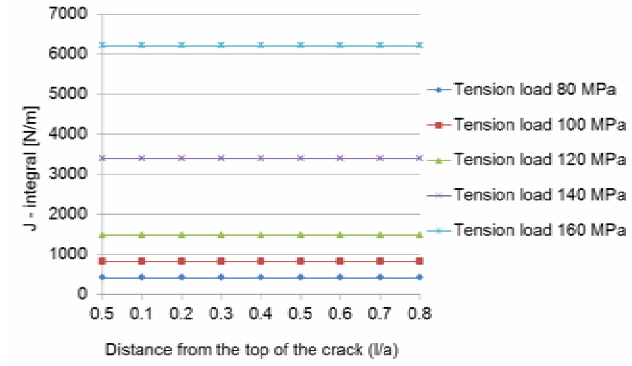

Figure 9 The values of the J-integral for different values of the external tension load

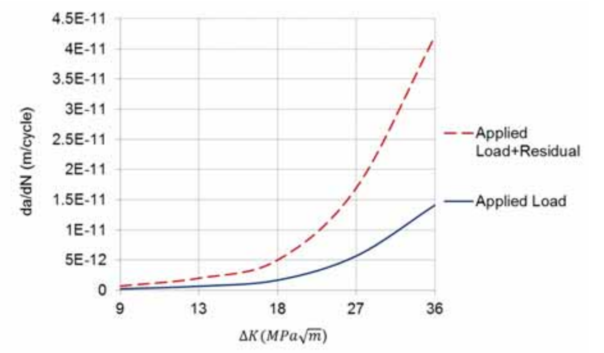

Figure 10 The crack growth ratio in the function of the stress intensity factor for the constant stress ratio (R = 0)

Conclusion

The authors have presented computation procedure in this paper in order to determine the ratio of the fatigue crack growth in butt welded plates for mode I fracture mechanics loading conditions. The influence of residual stresses on the crack growth rate was analyzed by determining the stress intensity factor and the modified J-integral, which is based on the law of superposition of linear elastic fracture mechanics. The J-integral values obtained in the analysis of residual stress fields show that the estimated values are independent for different paths around the crack tip (Fig.9). Finally, after performing the analysis of the crack growth rate, it was shown that the influence of residual stress significantly reduces the residual life of structures to fatigue. In the case of the given geometry, load and the presence of residual stresses, the remaining life is reduced to 70% compared to the structure without the presence of residual stress, Fig.10.

Acknowledgments

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Brzina širenja prskotine u polju zaostalih napona kod zavarenih konstrukcija

Prisustvo zaostalih napona u zavarenim konstrukcijama može značajno uticati na otpornost materijala na zamor pod dejstvom cikličnog opterećenja. Prisustvo zaostalih napona na zatezanje povećava brzinu širenja prskotine. Promena mikrostrukture i otvrdnjavanje materijala kao rezultat procesa zavarivanja takođe ima negativan uticaj na brzinu širenja prskotine. Tačno i precizno određivanje zaostalih napona su važni za integritet struktura kao i za projektovanje zavarenih delova sa aspekta preostalog veka. Iako postoji nekoliko tehnika za određivanje zaostalih napona, metoda konačnih elemenata je jedna od najčešće korišćenih. Ovaj rad predstavlja postupak modelovanja metodom konačnih elemenata radi određivanja ponašanja širenja naprsline kod sučeono zavarenih spojeva pod opterećenjem za mod II.

Ključne reči: **zavarena konstrukcija, sučeono zavarivanje, zaostali naponi, prskotina, rast prskotine, procena veka trajanja, metoda konačnih elemenata.**

Скорость роста трещины в области остаточных напряжений в сварных конструкциях

Наличие остаточных напряжений в сварных конструкциях может существенно повлиять на устойчивость материала на усталость во время циклического нагружения. Наличие остаточных напряжений при растяжении увеличивает скорость роста трещины. Изменение микроструктуры и упрочнение материала в результате процесса сварки также оказывает отрицательное влияние на скорость роста трещины. Точное и акуратное определение остаточных напряжений важны для целостности структуры, а также и для проектирования сварных компонентов с точки зрения остаточного ресурса. Хотя существует несколько методов для определения остаточных напряжений, метод конечных элементов является одним из наиболее часто используемых. Эта статья представляет собой моделирование процессов с использованием метода конечных элементов для определения поведения распространения трещин в стыковых сварных соединениях под нагрузкой для режима II.

Ключевые слова: **сварная конструкция, стыковая сварка, остаточные напряжения, трещина, рост трещины, оценка жизненного цикла, метод конечных элементов.**

La vitesse de la croissance de fracture dans le champ des charges résiduelles chez les constructions soudées

La présence des charges résiduelles dans les constructions soudées peut affecter beaucoup la résistance des matériaux à la fatigue sous l'effet de la charge cyclique. La présence des charges résiduelles chez la tension augmente la vitesse de la croissance de fracture. Le changement de la micro structure et le durcissement des matériaux comme le résultat du processus de soudage a l'influence négative sur la vitesse de croissance de fracture. Une définition précise et exacte des charges résiduelles est importante pour l'intégrité des structures ainsi que pour la conception des pièces soudées en ce qui concerne la durée de vie. Bien qu'il existe plusieurs techniques pour la détermination des charges résiduelles la méthode des éléments finis est l'une des plus appliquées. Ce papier présente le processus du modelage par la méthode des éléments finis dans le but de déterminer le comportement de la croissance de fracture chez les joints soudés sous la charge pour le mode 1.

Mots clés: **construction soudée, soudage en bout, charges résiduelles, fracture, croissance de fracture, estimation de la durée de vie, méthode des éléments finis.**