

INVESTIGATIONS TOWARDS J-R CURVES INDEPENDENCE OF THE SPECIMEN SIZE

A.Neimitz* and R.Molasy*

In the paper the stable crack growth is reconsidered. The proper physical interpretation of the quantities entering the crack growth equation is recalled. This interpretation has been used to propose modified procedure to determine the J-R curves which are independent of the specimen size. Two extreme cases are analysed as an example: small scale yielding and fully plastic case. General equations for modified J-R curves for both cases are proposed. Experimental results that confirm size independence of the modified J-R curves are presented.

INTRODUCTION

The problem of the stable crack growth in a ductile and semi-ductile materials has attracted attention of the researchers for several decades. However, the results obtained are not satisfactory. They would be if one could uniquely predict the moment of the beginning of the unstable crack growth for given geometry and size of the machine or structural element. The concept of the resistance curves has dominated others in seeking solution for this very basic but also practical problem. In this approach it has been assumed that the stable crack growth is an equilibrium process from the thermodynamic point of view. It means that at each moment of the crack extension the crack tip driving force is in equilibrium with the resistance to the crack growth force. Many fracture parameters have served as a crack tip driving force to construct the R-curves (stress intensity factor K , energy release rate G , crack tip opening displacement δ_T , crack tip opening angle, J -integral). Among others the J -integral has become the most often used in practical applications. However, it turned out that the J-R curves do not satisfy the very fundamental requirements. These curves are, in most cases, geometry and size dependent. Thus, the present paper is an attempt to answer the very fundamental questions. What is the reason of the J-R curves size and geometry dependence: the wrong structure of the crack growth equation or the incorrect methodology of the J-R curves determination? The answers to the above questions are not straight forward and they will be presented in the next sections.

* Kielce University of Technology, Al. Tysiaclecia P.P.7, 25-314 Kielce, Poland

CRACK GROWTH EQUATION

The answer to the first question formulated in the Introduction has already been given by Neimitz (1),(2). It will be repeated here very shortly. The crack growth equation assumes the following form

$$J_{ff} = D \dots\dots\dots(1)$$

where the J_{ff} is so called far field J-integral and it should be understood as an amount of energy delivered to the domains where it has been dissipated during the unit crack extension. It has been shown that this part of energy which is dissipated for plastic deformation, voids and microcrack nucleation and growth should be delivered to the system in the form of work of external forces. The energy which is dissipated for a new crack surfaces creation has its source in elastic energy that has been stored within the specimen. Formally, the J_{ff} can be computed utilising classical Rice's definition of the J-integral. However, in this case the contour of integration is not arbitrary. It must be drawn outside the dissipation zone. The D function in the Eq.(1) is so called dissipation function. Its graphical representation is the J-R curve (in fact it is the J_H -R curve). Since the dissipation function represents all dissipative processes taking place during the crack extension, the J-R curve must be size and geometry dependent. For example, dissipation due to plastic deformation depends on the volume of the domain where plastic deformation takes place. In turn, this volume depends on the size and geometry of the specimen.

The answer to the first question from the Introduction is positive. It means that for the stable crack growth the equilibrium type crack growth equation is correct. However, the physical meaning of the quantities entering it should be reinterpreted. They should be understood as a global quantities. Strictly speaking, J_H is not „crack tip driving force” because it drives all dissipative processes during the crack growth. J_H is not path independent and it is not the strength of the HRR field in front of the crack when it is growing. Its interpretation as an energy released during the crack growth is correct. However, in this case the energy is released not only into the crack tip but to the whole zone of dissipation as well.

The answer to the second question from the introduction is not unique. The methodology of the J-R curve determination is correct but such a curves are size and geometry dependent. Thus, the practical engineering application of the J-R curves in their „classical” definition is certainly limited. In the next section a new concept of the modified J-R curves determination will be presented. It will be shown that such a curves are size independent, at least for tested material.

MODIFICATION OF THE J-R CURVES

Let us assume that dissipation processes are dominated by plastic deformation and process zone formation (voids and microcracks nucleation and growth as well as new crack surface creation). In principle, the amount of energy dissipated in all dissipative processes should be computed from the analysis at the microscopic level. However, such an analysis could be very complex, involving many new assumptions, simplifications, and not necessarily well defined material parameters. Thus, we propose a very simple approach. We assume that

amount of energy dissipated by plastic deformation is equal to the product of plastic zone volume V_{pl} and specific energy of plastic deformation ξ . The volume of plastic zone is certainly dependent on the specimen size and geometry in contrast to specific energy ξ which may be assumed geometry and size independent. Similar assumptions have been made computing the energy dissipated within the process zone. It is equal to the product of process zone volume V_{pz} and specific energy of process zone formation χ . The total energy dissipated and stored during the process of crack growth under external loading can be written in the form:

$$A = \xi V_{pl} + \chi V_{pz} + A_{el} \dots \dots \dots (2)$$

where A_{el} is amount of elastic energy stored within the loaded specimen. In this paper we will concentrate on two extreme situations: small scale yielding in front of the crack and totally yielded material along uncracked ligament in front of the crack. In the first case we assume that the volume of the plastic zone is equal to:

$$V_{pl}^{(ss)} = \alpha_1 B r_p^2 \dots \dots \dots (3)$$

where α_1 is a constant, B is specimen thickness, r_p is the length of the plastic zone which can be easily computed from the simple formulas known in fracture mechanics. In the second case we assume that the volume of the plastic zone is equal to:

$$V_{pl}^{(ty)} = \alpha_2 B b_0^2 \dots \dots \dots (4)$$

where α_2 is a constant and b_0 is the length of the uncracked ligament in front of the crack. In both cases we assume the volume of the process zone equal to:

$$V_{pz} = B \Delta a h(\Delta a / b_0) \dots \dots \dots (5)$$

where $h(\Delta a / b_0)$ is the width of the process zone and Δa is actual crack length extension. We will recall now the well known Rice's formula to determine experimentally the value of the J-integral

$$J = \frac{\eta A}{b_0 B} \dots \dots \dots (6)$$

where η is specimen geometry factor (e.g. for three point bending $\eta = 2$), A is an area under force- displacement curve. It denotes the same quantity that was defined in Eq(2).

By very simple algebraic manipulation over Eq.(2) (multiplying both sides by η , dividing both sides by V_{pl} , introducing (3) or (4) and (5), utilising (6)) one can obtain the following relations:

$$\frac{J_{pl}}{r_p^2} = \alpha_{ss} + \beta_{ss} f_{ss}(\Delta a / b_0) \dots \dots \dots (7)$$

for small scale yielding where J_{pl} is a „plastic” part of the J-integral

$$\frac{J_{pl}}{b_0} = \alpha_{ty} + \beta_{ty} f_{ty}(\Delta a / b_0) \dots \dots \dots (8)$$

for totally yielded unbroken ligament in front of the crack. The constants $\alpha_{ss}, \dots, \beta_{ty}$ and functions $f(\Delta a/b_0)$ should be determined experimentally. We will approximate functions $f(\Delta a/b_0)$ in the form of the power function.

EXPERIMENTAL ANALYSIS

To verify above theory the experimental program has been performed. Three point bend specimens with side grooves have been machined and precracked from two different steels (40HMNA and 18G2A according to Polish standards). Chemical composition and mechanical properties of these steels are listed in Tables (1) and (2).

Table 1. Chemical composition

Material	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Al
40HMNA	0.45	0.72	0.37	0.015	0.014		0.74	1.51	0.17	
18G2A	0.18	1.41	0.38	0.020	0.010	<0.05	<0.05	<0.05	<0.05	<0.02

Table 2. Mechanical properties

Material	σ_y MPa	σ_m MPa	A5 %	Z %	n
40HMNA (S)	1265	1787	7.2	28	0.027
18G2A	383	573	32	68	0.086

The specimens have been machined to provide the following dimensions: $B \in (8-20)$ mm, width $W = 20, 30$ mm, length $L = 4W$, initial relative crack length $a_0/W \in (0.37-0.73)$. Tests were carried out on the MTS testing machine, fully computerised. The crack growth has been measured with the help of potential drop and compliance change techniques.

Results: „Classical” J-R curves for various specimen sizes are shown in the Figs(1a)-(3a). Modified curves are presented in the Figs (1b)-(3b). One may see that they are size independent. Modified J_{pl} -R curves can be represented by the following equations

$$\frac{J_{pl}}{b_0} = 1.25 + 219.54 \left(\frac{\Delta a}{b_0} \right)^{0.31} \dots \dots \dots (9)$$

for fully plastic case and

$$\frac{J_{pl}}{r_p^2} = 4.41 + 1498.45 \left(\frac{\Delta a}{b_0} \right)^{0.64}, \dots\dots\dots(10)$$

for small scale yielding. Very similar formulas can be written for J-R curves ($J=J_{pl}+J_{el}$). They are also independent of the specimen size. For plastic materials (18G2A) the equation is almost the same. For small scale yielding (40HMNA) the coefficient α_{ss} is equal to 2.76, $\beta_{ss} = 1551.4$, the exponent is equal to 0.31

Conclusions. It was shown that proper modification of the J-R curves leads to the results that are specimen size independent. However, Eqs (9) and (10) may not be geometry independent since coefficients $\alpha_{ss}, \dots, \beta_{ss}$ are functions of η, α_1 and α_2 . Nevertheless, these quantities can be computed.

The size independence of the modified J-R curves for tested materials was observed if J/b_0 or J/r_p^2 was plotted as a function of normalised crack extension $\Delta a/b_0$ only. They are not specimen size independent if they are functions of Δa .

REFERENCES

- (1) Neimitz, A. „Crack Growth Equations”, Proceedings of IUTAM Symposium on „Constitutive Relation in High/Very High Strain Rates”. Edited by K.Kawata and J.Shiori, Springer, 1996, pp.92-104.
- (2) Neimitz, A. ”Evolution Equations of Stable and Unstable Crack Propagation”, Proceedings of ICF7, „Advances in Fracture Research”, Edited by B.L.Karihaloo et al, Pergamon, 1997, Vol.4, pp.1803-1809

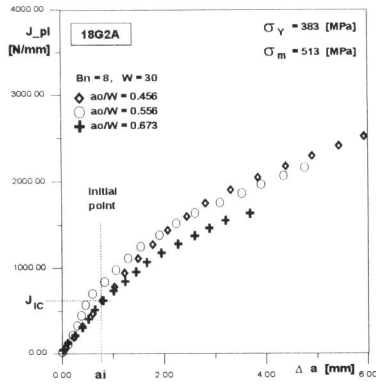


Figure 1a. Classical J_{pl} -R curve for 18G2A steel for three different initial crack lengths. The fully plastic case. $B_n = 8\text{mm}$.

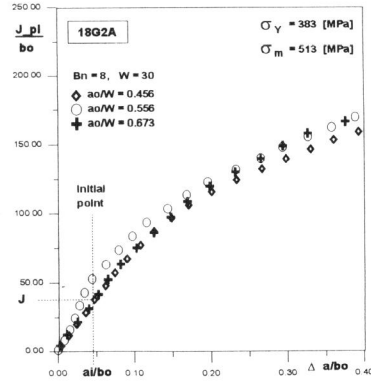


Figure 1b. Modified J_{pl} -R curve for 18G2A steel for three different initial crack lengths. The fully plastic case. $B_n = 8\text{mm}$.

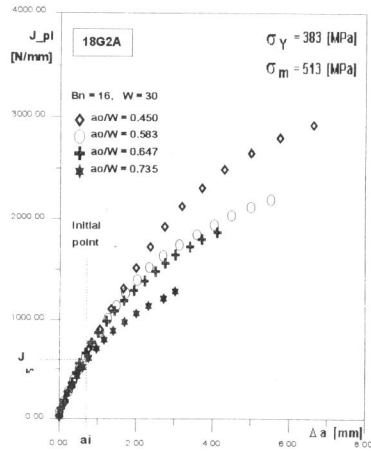


Figure 2a. Classical J_{pl} - R curve for 18G2A steel for four different initial crack lengths. The fully plastic case. $B_n=16$ mm.

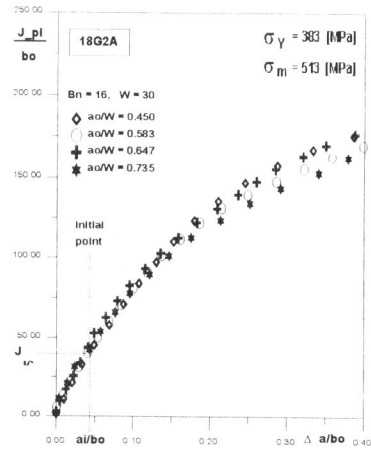


Figure 2b. Modified J_{pl} - R curve for 18G2A steel for four different initial crack lengths. The fully plastic case. $B_n=16$ mm.

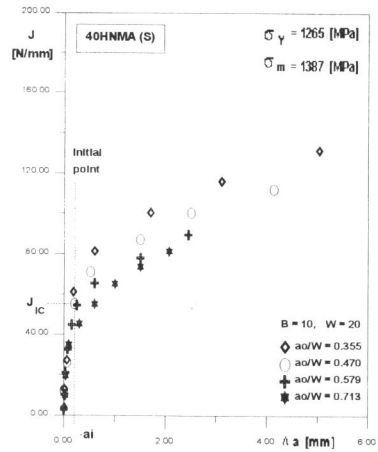


Figure 3a. Classical J - R curve for 40HMNA steel for four different initial crack lengths. The small scale yielding case. $B_n=10$ mm.

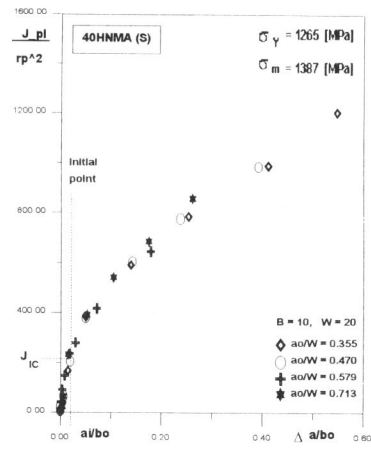


Figure 3b. Modified J - R curve for 40HMNA steel for four different initial crack lengths. The small scale yielding case. $B_n=10$ mm.