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Fatigue crack propagation behavior of old puddle iron including crack closure effects

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Abstract

In this paper the fatigue crack growth behavior in structural components from the old 19th century structures (e.g. bridges) has been investigated. The delivered material for investigation was extracted from a beam made of puddled iron, commonly used in 19th century. The obtained results from several ancient railway metallic bridges (located in Lower Silesia, Poland) have shown the presence of microstructural degradation processes in puddled iron. In all analyzed materials (low carbon puddled iron) microstructure degradation processes were related to: the presence of numerous precipitations of carbides and nitrides (or the carbides–nitrides) of iron inside the ferrite grains, the presence of continuous precipitations of cementite at ferrite grain boundaries. In order to restore the initial state of the microstructure, all tests were carried out in two stages of heat treatment; as-received state and after normalization (950°C, 2h, cooled in air) state. The kinetic fatigue fracture diagrams (KFFD) have been obtained. The problem of crack closure has been involved in fatigue crack growth process during the experiments and its understanding is fundamental for the analysis of stress ratio effects on KFFD. In the paper, a few experimental and numerical techniques for the evaluation of the crack closure/opening forces based on the experimental data have been compared. The implemented algorithm in the numerical environment gives promising results in description of the kinetics of fatigue crack growth of the old puddled iron with consideration of crack closure effect.

Keywords: fatigue crack growth, puddle steel, crack closure effect, compliance method

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1. Introduction

In the 19th and early 20th century, two types of low-carbon steel were commonly used: the puddled (called wrought iron) and the mild steel. These two types of steel tend to degradative processes for at microstructure level. The microstructure degradation of these steels relies (a large generalization), among others, on degeneration of areas of perlite, the presence of precipitates carbides and nitrides within the grains and numerous separations of cementite at the borders of grains. These processes have been already described in Lesiuk et al. (2010), Pękalski (1998, 1999) and Rabiega (2007). These phenomena of microstructures degradation is more apparent in wrought (puddled) steels than in the old mild steel – similar to the modern types of steel. It has been estimated that in Poland in the 70s more than 10% of bridges constructed using puddled steel were still in operation (based on Madaj (2009)). As an another example, in France (based on Suresh (1998)) about 40% in weight of the metalic railway bridges currently in service are puddled iron hot riveted structures. On the other hand, in the literature the availability of real fatigue material data after 100. years operating time is not abundant. The results of complex low cycle fatigue data and fatigue crack growth rate results are available in works by De Jesus et al. (2011) and Correia (2010) with their useful form in numerical investigation of the old structures (Correia (2010)). Degradation of mechanical properties and cyclic properties have been considered in (works of Nykyforchyn et al. (2010) with the corrosion resistance data being addressed in papers by Zagórski (2004) and Zvirko (2014). Such data is necessary for further analysis of the future material behaviour. The materials for the pipelines, pressure vessels, oil trunks, off-shore structures, etc. have shown a similar tendency for degradation processes in a shorter time of exploitation. A number of existing structures erected at the turn of the 19th to 20th century, with the co-existence of a lack of material data in the literature, confirmed the need of investigation on the fatigue and fracture behaviour on such old materials. It is worth fulfilling the lack of description of fatigue crack growth rate in terms of the crack closure effect in mentioned ancient types of steel. Since the publication of the Elber's work (Elber (1970)), the problem of crack closure effect is a major topic in fracture mechanics and fatigue crack growth in terms of the mean load influence. As it is well known from the experimental practice, the R-ratio (K_{min}/K_{max}) strongly influences the unification process of description of the fatigue crack growth rate in a force driven approach. In many research works, it has been proved that the R-ratio effect is negligible if we consider the ΔK_{eff} as a crack driving force parameter in Kinetic Fatigue Fracture Diagram (KFFD):

$$\Delta K_{eff} = K_{\max} - K_{op}. \qquad (1)$$

Another group of authors (e.g. Xiong et al. (2008) indicates that the ΔK_{eff} does not always (not fully) consolidate the experimental data in one line. It seems that the crack driving force in this case should be much more complicated. Kujawski (2001) proposed the crack driving force according to the following relation:

$$\overline{K}* = K_{\max}{}^{m} (\Delta K^{+})^{1-m}. \qquad (2)$$

In this, ΔK^{+} represents a positive part of ΔK. Energy approaches are also an alternative with stronger physical meaning. In this case, Szata (2002, 2009) demonstrates the independency of the KFFD description from the R-ratio effect based on ΔH – energy parameter (proportional to the dissipated energy in each cycle of loading). However, the typical engineering practice is connected with a commonly used "force based" description of KFFD – based on ΔK or K_{max}. From the physical point of view, it is clear that the crack closure effect is a general term of many physical processes responsible for partial closure of fatigue crack, i.e.: plasticity induced crack closure (PICC), roughness crack closure (RICC) and oxidation surface crack closure (OSCC). Of course, there are only the main hypothesis of crack closure during the fatigue process. From the experimental point of view, there are a few exemplary techniques concerning the closure identification (Kaleta et al., (2000)):

- Direct methods : light microscopy, replica technique, interferometry, stereo photogrammetry of crack surface, digital image correlation;
- Potential drop methods;
- Ultrasonic methods;

- Compliance methods - Crack opening displacement extensometers, local strain gages in the vicinity of a crack tip, back face strain gages BFS, interferometric strain gages;
- Crack propagation - high R-ratio testing, special sequences of the variable amplitude cycling.

The most common experimental technique is the compliance method. The high resolution and high precision of filtering signal allows to record the "perfect" data for further signal analysis and processing.

2. The algorithm of implemented closure point identification

A few commonly used numerical examples of estimation of closure load (F_{cl}) from F-COD data record exist in the literature. The most commonly used technique is the 2% compliance offset ASTM method, as described in ASTM E647. However, many experimental and numerical works (i.e. Chung et al. (2009)) indicated that the obtained values of a load closure (F_{cl}) seem to be underestimated. The more efficient is the Linear-Quadratic Spline Method (LQSM) introduced in the work of Carman et al. (1988) and developed by Schijve 1991). The main idea of F_{cl} identification consists in division of the recorded F-COD curve into two parts: the linear one and nonlinear, simply treated as quadratic one – as it has been shown in Fig.1.

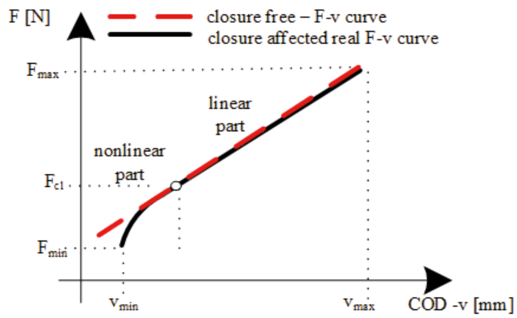

Fig. 1. Schematic decomposition of the recorded F-COD curve

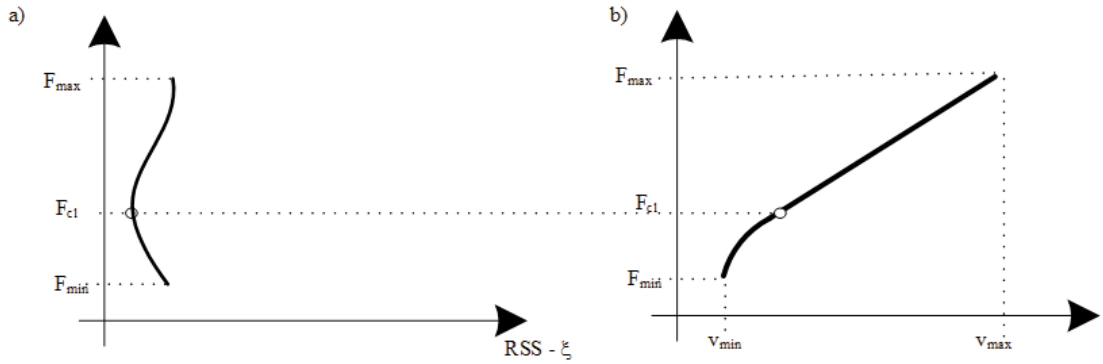

Fig. 2. Procedure of identification the closure load: a) Optimal value of F_{cl} corresponding to a minimal value of RSS – ξ, b) closure point on the recorded F-COD signal

$$\hat{v}_L(F) = A_0 + A_1 F \tag{3}$$

$$\hat{v}_Q(F) = B_0 + B_1 F + B_2 F^2 \tag{4}$$

In this figure,
$\hat{v}_L(F) -$ estimated linear function of a linear regime of the recorded hysteresis loop,
$\hat{v}_Q(F) -$ estimated quadratic function of a non-linear regime of the recorded hysteresis loop.
From linear regression the constants A_0 and A_1 will be easily obtained. The values B_0, B_1, B_2 are unknown and they should respect the following conditions from the common F_k – knee value identification:

$$\hat{v}_Q(F) = \hat{v}_L(F) \tag{5}$$

$$\frac{d(\hat{v}_Q(F))}{dF} = \hat{v}_L(F) \text{ (for } F=F_k) \tag{6}$$

According to the above conditions, we obtain:

$$\begin{aligned} B_1 + 2B_2 F_k &= A_0 + A_1 F_k \\ B_0 + B_1 F_k + B_2 F_k^2 &= A_0 + A_1 F_k \end{aligned} \tag{7}$$

The constants B_0, B_1, B_2 should be optimal from the mathematical point of view. In order to validity their optimal values, we can find the mentioned constants minimalizing the residual sum of squares ξ (RSS) defined as:

$$\xi = \frac{1}{(v_{\max} - v_{\min})^2} \cdot \sum_{i=1}^{N} \begin{Bmatrix} (\hat{v}_Q(F_i) - v_i)^2 \text{ for } P_i < P_k \\ (\hat{v}_L(F_i) - v_i)^2 \text{ for } P_i \geq P_k \end{Bmatrix} \tag{8}$$

The value of F_k which corresponds to the minimal value ξ will be treated as closure load F_{cl}. V_{max} and V_{min} are the maximal and minimal values of COD during each cycle of loading. The described method is easy to automatization during the experiment with a guarantee of the optimal value F_{cl} corresponding to the minimal ξ. However, if the raw data are strongly influenced by the noise (or wrong tuning of the recorded signals) in that case, the algorithm may choose a wrong value of identified closure load point.

Table 1. Chemical composition of analyzed steel

Chemical element	C [%]	Mn [%]	Si [%]	P [%]	S [%]
PP – steel (1863)	0.08	0.025	0.15	0.245	0.015
RS – steel 1850-1900	0.06	0.1	0.17	0.198	0.025
BC– steel 1850-1900	0.09	0.2	0.02	0.03	0.03
Typical puddle iron based on Czapliński et al. (2009)	<0.08	<0.4	N/A	<0.6	variable
Typical mild 19th century rimmed steel based on Czapliński et al. (2009)	0.02-0.15	0.2-0.5	Variable	0.03-0.06	0.02-0.15

3. Material investigation and experimental results

Three parts of an ancient steel structure from a railway civil engineering infrastructure were obtained for investigation. The PP steel are the parts of the restored viaduct in Brochocin (Low Silesia District, Poland), BC and RS steels are the parts of the ancient infrastructure of the Main Railway Station in Wroclaw.

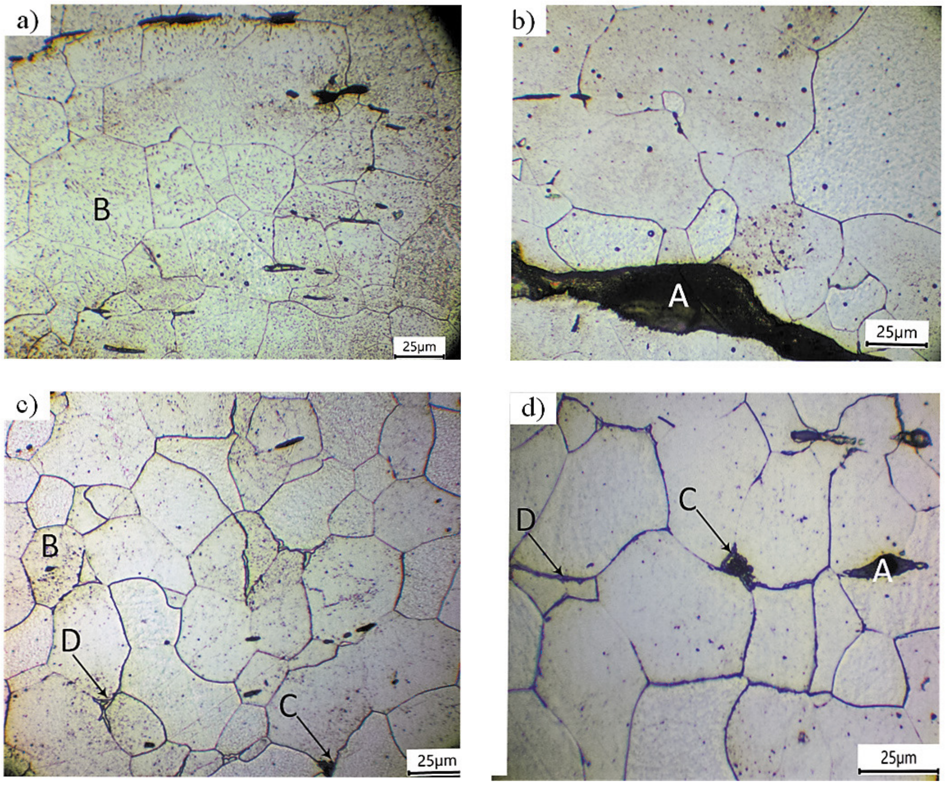

Fig. 3. Microstructure of the investigated steel a) PP steel in post operated state, light microscopy, etched 3%HNO_3, b) PP steel in normalized state, light microscopy, etched 3%HNO_3, c) BC steel in post operated state, light microscopy, etched 3%HNO_3, d) BC steel in normalized state, light microscopy, etched 3%HNO_3

The chemical composition obtained by means of gravimetric method and spectroscopy for investigated materials indicates that the PP and RS steels are puddle iron and the BC steel seems to be the old mild steel. This fact confirms the microstructure of investigated steels shown in Fig. 3. The microstructure of RS steel is described in Lesiuk et al. (2015). In Fig. 3, A indicates the non-metallic inclusion (mainly silicates), B represents brittle separations inside ferrite grains, C – pearlite areas, D a thick envelope of the Fe_3C_{III} on the grain boundaries. It should be noted that the microstructure of the PP steel is more degenerated than BC one. In each case, the normalization process have changed the microstructure of investigated steels. However, not all degradation processes have been removed. The basic mechanical properties (static tensile test results and CVN – Charpy energy) have been collected in Tab. 2.

In order to evaluate the fatigue crack growth resistance, the tests were performed using two types of CT specimens: W=38 mm, t=6 mm for the PP and BC steels, and W=48 mm, t=12 mm for the RS steel. The area of interest was a near threshold region, of the FCGR curve. In order to evaluate the ΔK_{th} region the ΔK-control decreasing test was performed (keeping constant R=0.1 & f=12Hz). During the experiments the signal of the force, COD & displacement were registered. The automated algorithm (LQ spline method) allowed to perform the closure load point evaluation during each cycle. The crack length was monitored by the compliance method and periodically controlled and corrected using low-magnification stereoscopic microscope with digital camera. The mechanical notch was prepared by the electro discharging machine and the specimen were pre-cracked to the 1.3-1.5mm long pre-cracks. The initial length (notch + pre-cracked fatigue crack) of a normalized crack length (a/W) ranged from 0.2 to 0.25. The load shedding during the ΔK decreasing test was kept on the level of the normalized gradient C=-0.078 mm^{-1}.

Two types of fatigue crack growth rate curves were obtained with the ΔK as a crack driving force and ΔK_{eff}. All the experimental data have been shown in Fig. 4 (wrought iron/puddled steel) and in Fig. 5 (mild steel). As it was expected, all the experimental results tend to one curve in case of the ΔK_{eff}, i.e. crack driving force parameter for each material type.

Table 2. Basic mechanical properties of investigated steels

	Yield Strength YTS [MPa]	Ultimate Tensile Strength UTS [MPa]	Young Modulus E [GPa]	Elongation at break K [%]	Reduction in area Z [%]	CVN +20°C [J]	CVN -40°C [J]
PP – steel (1863?)	286.5	359.7	191	15.3	33.9	N/A	N/A
RS – steel 1850-1900	272	369	189	15.5	23.7	28.8	9.6
BC– steel 1850-1900	311	395.7	213	28.3	53.5	85	N/A
Typical values for puddled steel (Czaplinski et. al)	220-280	330-400	170-200	<25	N/A	Variable	Variable
Typical values for 19th century mild steel (Czaplinski et. al)	250-300	340-450	200-220	25-35	N/A	Variable	Variable

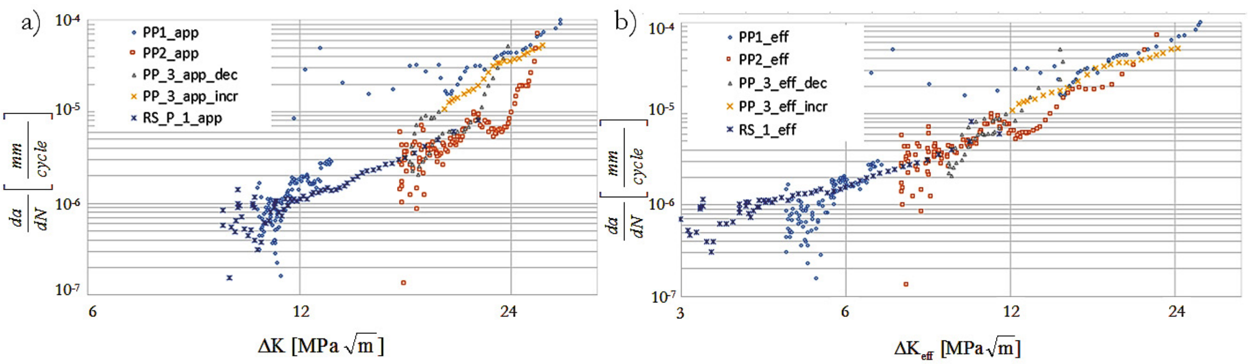

Fig. 4. Fatigue crack growth curves for puddle steel; a) based on ΔK, b) based on ΔK_{eff}.

Comparing the Fig.4 and Fig. 5, it seems that puddle iron is more sensitive to the crack closure effect. A significant influence of loading history is noticeable in the specimen No 3 (the PP steel). This specimen was loaded in the range ΔK=20 MPa $m^{0.5}$ to ΔK=10 MPa $m^{0.5}$ using ΔK decreasing method and then the specimen was loaded in the same range of ΔK, i.e it forms ΔK=10 MPa $m^{0.5}$ to the ΔK=20 MPa $m^{0.5}$ using the ΔK increasing test. As it is noticeable, the curves are not coincident in case of the ΔK description. In case of the ΔK_{eff} ,the curves tend to one line.

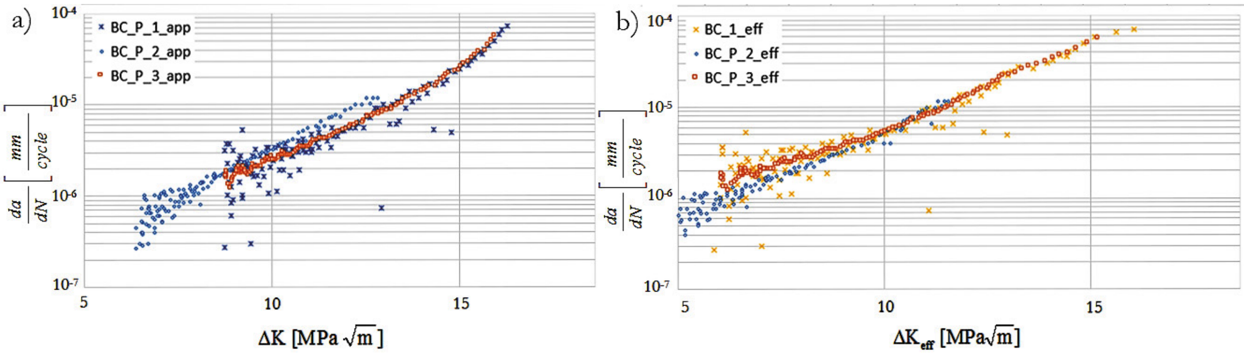

Fig. 5. Fatigue crack growth curves for mild 19th century steel; a) based on ΔK, b) based on ΔK_{eff}.

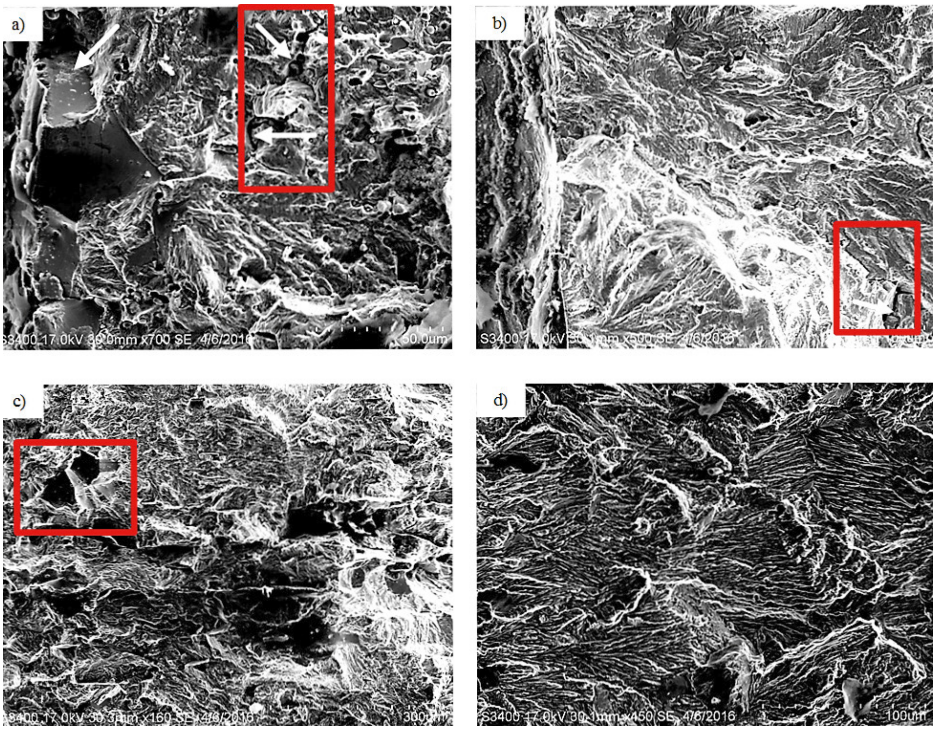

Fig. 6. Fatigue crack surfaces – crack growth direction from left to right – SEM analysis: a) PP steel – fatigue crack surface near mechanical notch; b) BC steel – fatigue crack surface near mechanical notch; c) PP steel – fatigue crack surface view in 3 mm distance from the mechanical notch tip – ΔK=21.2 MPam$^{0.5}$; d) BC steel – fatigue crack surface view in 6 mm distance from the mechanical notch tip – ΔK=15.8 MPam$^{0.5}$.

4. Summary and conclusions

The 19th century ancient types of steel were tested (2 puddle iron and 1 mild steel). The investigation of materials and microstructure observations have confirmed the presence of microstructural degradation processes. All kinds of steel were mechanically tested in the post operated state. The kinetic fatigue fracture diagrams were obtained. For all types of puddle iron materials, the differences of kinetics of fatigue crack growth were observed. The mechanism of multi-origin crack propagation and inhomogeneity in this type of steel are probably the main reason of data scattering in experimental results (in comparison to the mild steel or modern low carbon homogeneity steel). In the literature, there was a lack of FCG experimental data for such type of steel with considerations of the crack closure effect. According to the analysis of experimental results, it should be concluded that the crack closure effect plays the important role in fatigue fracture of puddled steel. In case of the mild steel, the crack closure effect is much lower. The main cause of such differences can be explained by the fractographic analysis. The nature of fatigue crack growth mechanism seems to be different from SEM images of the crack surface – compare the Fig. 6 (a and b) and Fig. 6 (c and d). The inhomogeneity of puddle iron causes a brittle manner of propagation supported by brittle separations on the grain boundaries (marked by a red frame in Fig. 6c). In each type of steel, the secondary cracks caused by nonmetallic inclusions were observed (indicate by arrows). Finally, the FCGR diagrams based on the ΔK_{eff} have shown significantly lower level of data scattering. In the future works it is worth to identifying the main mechanism (PICC or RICC) of crack closure in puddle iron. The implementation of crack closure effect in case of the puddled steel is a promising approach for the modeling the kinetics of fatigue crack growth rate in terms of energy approach.

Acknowledgements

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