Experimental Research on the Factors Affecting Fusion Zone Size and Mechanical Properties in Crack Arrest by Current Detour and Joule Heating

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Abstract. When pulsed current passes through the specimen containing a crack, since the current cannot flow through the crack, the current has to detour around the crack tip, and the current density at the crack tip is excessively high. Owing to Joule heating, local melting occurs and a circle hole is formed at the crack tip. In this work, with 316 stainless steel as a specimen, the crack arrest experiment is performed on high pulsed current discharge device of type HCPD-I. The factors affecting the fusion zone size are studied. By making tensile test and fatigue test, relationships between the molten hole size and the crack arrest effect are derived. The experimental results indicate that the molten hole size is proportional to crack length and discharge parameter. The discharge parameter to the best effectiveness of crack arrest can be obtained.

1. Introduction
To remanufacturing blanks with remanufacturability (named after remanufacturing, it possesses the residual life which can complete a whole service cycle), advanced surface technology[1,2] is applied to recover the surface size and make the remanufactured components superior to the original ones or advanced manufacturing technique[3] is adopted to process the parts to satisfy the assembly requirements. In past, the remanufacturing blanks with cracks were considered as irreparable. The core parts of large mechanical equipment (such as engineering machinery, ship, airplane, large-scale compressor) are costly, highly value-added, complexly processed and possess high technological requirements. During processing of these parts with cracks, it is vital to arrest propagation of the cracks so as to guarantee effectiveness of the repair process to achieve the purpose of prolonging the life of products.

Retarding or arresting the crack growth can be achieved by reducing crack tip stress intensity[4], introducing residual compressive stress[5] and reducing crack tip stress concentrations[6]. Drilling stop-hole at the crack tip or in the direction of crack propagation is commonly used in practice. However, the effectiveness of crack arrest depends on the machining precision and the size of stop-hole. Yet, new stress concentration and fatigue cracks can initiate at edge of the stop-hole. In addition, drilling stop-hole is only suitable for surface cracks; it is not applicable to internal defects or embedded cracks.

During recent years, pulsed current is widely applied as a very promising non-equilibrium processing technology for practical solution, such as the modification of materials[7], refining the solidification structure[8], improving the fatigue of metals and healing damage [9].
As known, when a conductive metal containing a crack is subjected to pulsed current, since the current cannot flow through the crack, the current has to detour around the crack tip, and then the current density at crack tip increases significantly. The local temperature increases owing to Joule heating that initiates crack tip melting, a round molten hole is formed, and the curvature radius of the crack tip is increased. In this way, mechanical stress concentration can be reduced or even eliminated and large compressive stresses could be generated around the crack tip. This phenomenon causes prevention of crack growth. A brief review of the performed studies using Joule heating of pulse current for crack arrest is presented because this subject forms the basis of the presented work. The effects of electromagnetic fields produced by current pulses on the kinetics of crack growth were examined in the work of GOLOVIN[10]. The authors found out that when the current pulses were passed at appropriate time, the crack growth was prevented. The papers[11,12] reported that the temperature field and the stress field of the specimens containing two and three dimensional cracks were derived by the methods of integral transformation and complex variables functions. The pulsed current discharge experiments and mechanical tests on embedded crack and welded joints were reported in the work of FU[13,14]. In papers[15,16], the phase change zone and microstructure near the crack tip were analyzed after performing discharge experiments. It was found that the grain size was refined and toughness, hardness, and corrosion resistance were increased. These increases were good enough for retarding crack growth and improving the resistance to stress corrosion. A plate containing a crack, under high electric current, was analyzed based on thermo-electro-structural coupled theory. The temperature-dependent characteristic parameters[17] and phase change[18] were also considered in the works.

However, the factors affecting the fusion zone size and the relationship between the fusion zone size and the effectiveness of crack arrest have not been evaluated quantitatively. The technology of crack arrest by pulsed current has not been applied in modern industry. In the present work, the 316 stainless steel is put under investigation. The crack arrest experiments are performed on a high pulsed current discharge device of type HCPD-I. The size of fusion zone under various discharge parameters and geometries of specimens are quantified. By making tensile test and fatigue test, the effectiveness of crack arrest is analyzed, and the discharge parameter to the optimal effective of crack arrest is determined.

2. Experimental methods

2.1. Specimen Preparation

The material investigated is austenite 316 stainless steel with 1.8 mm in thickness. The chemical compositions of the test material determined using EDS (energy dispersive spectrometer) are listed in table 1, and the mechanical properties of it are plotted in table 2. In this paper, the main purpose is to investigate the effect of current detour and Joule heating at the crack tip. In this regard, the slit can be substituted for a crack. The configuration of specimen is shown in figure 1. A unilateral slit is prepared by wire-electrode cutting in the center of longer side that penetrates throughout the thickness. The root radius of the crack tip is \( r=0.1 \text{mm} \). The crack lengths are \( a=10,12.5 \) and 20 mm, respectively, for the three specimens.

| C  | Si  | Mn  | Fe  | Ni  | Cr  | Mo  |
|----|-----|-----|-----|-----|-----|-----|
| 7.03 | 0.53 | 1.10 | 63.14 | 9.62 | 16.40 | 2.18 |

Table 1. Chemical composition of the 316 stainless steel (wt.%).

| Tensile strength/ MPa | Yield stress/ MPa | Elongation/ % | Reduction of area/ % |
|-----------------------|------------------|---------------|---------------------|
| 620                   | 310              | 30            | 40                  |

Table 2. Mechanical properties of the 316 stainless steel.
2.2. Discharge experiment

The crack arrest experiments were performed under ambient on a self-made high pulsed current discharge device of type HCPD-I, as shown in figure 2a. It is composed of electric governor, high-tension transformer, rectifying silicon stack, current limiting resistor, high-tension switch, capacitors and load. The basis parameters are as follows:

1. There are ten capacitors (MWF12kV-20μf) and the energy storage capacity of each is 1 kJ;
2. The discharge voltage is 4kV-10kV and continuously adjustable;
3. The peak current of discharge is 250 kA;
4. The pulse periodic time is 40μs-100μs.

![Figure 1. Configuration of specimen.](image)

In this study, two factors affecting the fusion zone size: discharge parameters (voltage $U$ and capacitance $C$) and geometry of specimen $a/W$ (the ratio is the slit length versus the specimen width) were investigated. The various discharge parameters were respectively fed to the specimens. Each specimen was only treated once by one pulse. The pulsed current was applied into the specimen through two copper electrodes, as shown in figure 2b. In the discharge process, local fusion and eruption occurred at the crack tip because of Joule heating accompanied by sparks and intense sound. As a result, a small hole was formed and the crack tip became blunt. With increase of discharge parameter and crack length, the current and heat concentration ahead of crack tip was larger and the melting process gets more intense.

![Figure 2. The discharge device and process (a) discharge device (b) discharge process.](image)

2.3. Morphology and microstructure observation

After the discharge treatment, the metallographic sample was cut from the position corresponding to the fusion zone of specimen and the geometry of the sample was 10mm×10mm as illustrated in figure 1. The surface was polished with emery papers of grain number from #200 to #1500 and was finished up to a mirror plane by buffing with diamond powder of 1 μm grain diameter. The sample was etched by solution containing 17% nitric acid, 50% hydrochloric acid and 33% glycerin. The optical metalloscope was used to observe the morphology and microstructure around the crack tip, and the diameters of molten holes were measured. The attained data were worked upon to obtain the average value.
2.4. Mechanical property test
Owing to the larger range of fusion zone size, the tensile test and fatigue test were conducted on specimens with \( a=20\text{mm} \) \((a/W=0.8)\) treated by various discharge parameters. When the specimen fractured, the tensile strength, displacement corresponding to the tensile strength and cycles were recorded to analyze the mechanical properties of specimen so as to assess the effectiveness of crack arrest.

To investigate the tensile strength and plasticity of the specimen untreated and treated by different discharge parameters, the tensile tests at ambient temperature were performed on AO LAN DESL-5T universal material test machine. The tensile speed was 1.0 mm / min. The tests stopped when the specimen fractured. The tensile strength \( \sigma_b \) and the displacement \( d \) corresponding to tensile strength were recorded.

The tensile fatigue tests were performed in an atmosphere under sine load conditions using electro-hydraulic servo testing machine SHIMADZU EHF-U. All of tests were run at a stress ratio of \( R=10 \), a maximum force of \( F_{\text{max}}=200\text{N} \) and the frequency of \( f=20\text{Hz} \). The load cycle number \( N \) was recorded when the specimen fractured.

3. Results and discussion

3.1. Morphology and microstructure around crack tip after discharge
In this section, the specimen with \( a=20\text{mm}\) \((a/W=0.8)\) treated by discharge parameter 180μf-7,000V is investigated. Figure 3 shows the microstructure around crack tip after discharge. As shown in figure 3(a), after performing crack arrest, the shape of the crack tip becomes obtuse and smooth. There are no serrated convexes or concaves, neither are there any secondary cracks. As the current cannot flow through the crack, the current has to detour around the crack tip, which causes the current density to increase excessively because of Joule heating. This results in local melting at the crack tip. The partition around the crack tip is distinct. As shown in figure 3(b), it is the edge of the molten hole covered by fusion metal (white-bright layer). The microstructure of area A is very fine. That is because pulsed current increases the degree of supercooling of fusion metal, reduces crystallization and refines solidification structure[19]. Figure 3(c) shows area B located outside the white-bright layer. Color change is visible, which means the local temperature is higher in this region. It does not reach the fusion point but does reach the austenitic phase change temperature. Area B is actually the heat affected zone (HAZ). The rapid heating increases the nucleation rate. After discharge, the growth of nucleated grains is restrained by the surrounding cool matrix. This, consequentially, results in formation of fine acicular austenite. The original microstructure in area C remains unchanged during discharge as shown in figure 3(d). The reason is that the effect of detour and Joule heating is weak over there and, thus, the temperature of matrix stays low. It is the characteristic that the non-defected part of component remains unchanged. The boundaries around areas A, B, and C are clearly detectable and they show a huge temperature gradient around the crack tip. At the instant of pulse current passing through the specimen, the temperature around the crack tip increases sharply and it initiates melting. On the other hand, the matrix remains almost at the room temperature. The expansion of the fusion zone and the HAZ with high temperature is restricted by the surrounding matrix which is at low temperature. Therefore, a huge compressive stress, which is a superposition of phase transition stress and thermal stress, is formed around the crack tip. This is beneficial for suppressing generation of new microcracks and preventing crack growth.
3.2. Fusion zone size versus discharge parameter
The specimen geometry in this section is the same as that described in figure 1 and the crack lengths are $a=10$, $12.5$ and $20$ mm, respectively, for the three specimens. The various discharge parameters are fed to the shorter sides. Figure 4 shows the diameter of molten hole versus discharge parameter on specimen with $a/W=0.5$. When the discharge parameter is smaller, no obvious melting occurs at the crack tip and the radius of curvature of crack tip is $0.1$ mm as before performing discharge. But a snuff colored HAZ is observed around crack tip. When the discharge parameter is large enough, the crack tip begins to melting and a circular hole is formed. With increase in discharge parameter, input energy increases so that the melting process gets more severe and diameter of molten hole becomes larger.

When the voltage $U$ increases, the size of molten hole becomes larger. Figure 5 shows the average diameter of molten hole under different discharge voltage at $C=180\mu F$. With the increase of capacitance, the diameter of molten hole also becomes larger. The average diameter of molten hole under different capacitance at $U=10000V$ is shown in figure 6.
With the increase of voltage and capacitance, the current flowed through the specimen increases. Furthermore, owing to high current density around crack tip, Joule heating increases significantly. Therefore, the diameter of molten hole can be adjusted by the discharge parameter.

3.3. **Fusion zone size versus a/W**

In this section, the dimensions L, W and r is kept constant. The slit length a is used as a variable. Figure 5 and 6 also shows the diameter of molten hole D versus a/W under different voltage and capacitance, respectively. Larger diameter of molten hole is obtained when a/W is larger. This phenomenon is due to the higher concentration of the electric current at the crack tip. On the contrary, the specimen with smaller a/W can get the smaller size of molten hole. When the discharge parameter is the same, the molten hole appears first on the specimen with larger a/W. It can be concluded that the crack tip cannot melt when the crack length relative to specimen width was too small unless higher current is subjected to specimen. The results are in agreement with the numerical simulation results [15].

3.4. **Melting area size versus mechanical properties**

The specimen with a=20mm (a/W=0.8) was used in this section. The tensile strength σ delineating displacement corresponding to tensile strength and fatigue life N were used to analyze the relationship between diameter of molten hole and mechanical properties. When the diameter of molten hole is D=1.18mm, the maximum tensile strength is σb=582.84 MPa, increased by 1.12% in comparison with original specimen. Figure 7 shows the diameter of molten hole is less than 2mm, the tensile strength of specimen changes slightly; the diameter of molten hole is larger than 2mm, the strength of specimen is significantly weakened, and the tensile strength decreases sharply when the diameter of molten hole increases. On the other hand, after treated by pulsed current, the strength of the specimen could be increased due to the refined microstructure and the high-density dislocation around the crack tip[20].

Figure 8 exhibits when the diameter of molten hole is D=1.43mm, the displacement corresponding to tensile strength is d=12.436mm, increased by 36.86% compared with that of non-discharge specimen. The result indicates that the appropriate size of molten hole can improve the elongation and plasticity of the specimen. In terms of the room temperature tensile behavior, coarse phase provides low elongation to failure. After treated by pulsed current, the microstructure around crack tip becomes very fine and more homogeneous (as shown in figure 3c) and has the best plasticity[21]. In addition, the directionally drift electrons can generate an electron wind when pulsed current is passing through the specimen. It can enhance the mobility of dislocation and annihilate the point defects, thus can prevent the formation of microcracks[22]. On macroscopic aspect, the specimen deforms in the tensile direction, which results in the significant improvement in plasticity[23].
Figure 7. Diameter of molten versus tensile strength.

Figure 8. Diameter of molten hole versus displacement of max force.

Figure 9. Diameter of molten hole versus fatigue life.

Thus, it can be concluded that when the size of molten hole is too small or too large, it cannot prevent the crack propagation, but also weakens the strength of specimen. The better effectiveness of crack arrest can be obtained by choosing the optimal discharge parameter. The proper discharge parameter can be determined by experiments combined with numerical simulation.

4. Conclusion
In this study, the factors affecting the fusion zone size and the relationship between diameter of molten hole and the effectiveness of crack arrest by current detour and Joule heating effect are investigated. The main results are summarized as follows:
(1) The previous experimental and analysis results show that current detour and Joule heat release by pulsed current can effectively prevent the crack propagation and prolong the service life of component.

(2) The main factors affecting the fusion zone size are discharge parameter (voltage and capacitance) and geometry of specimen (the length of crack). The diameter of molten hole is proportional to the discharge parameter and a/W.

(3) The specimen with a/W=0.8 is as example. The mechanical properties comprehensively considered, under the discharge parameter 180µF-7,000V, the diameter of molten hole is D=1.18mm and the crack arrest effect is the best, the tensile strength increased by 1.12%, the displacement corresponding to tensile strength increased by 26.19% and the fatigue life prolonged by 41.6%.

(4) The diameter of molten hole with better crack arrest effect can be obtained by adjusting the discharge parameter. The tensile strength, plasticity and fatigue life would be improved. If the model of the relationship between the fusion zone size and discharge parameter and geometry of component can be established, the technology of crack arrest using pulsed current can be applied in remanufacturing.

5. Reference

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