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Repair of cracks in metals: A review

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Abstract

Cracks are surface or subsurface fissures that develop in a material. Propagation energy derived from mechanical, thermal, chemical, and metallurgical effects, or a combination of these may influence crack initiation and growth. Various types of cracks exist in metals and can be categorised as cooling, solidification, centreline, crater, grinding, pickling, heat treatment, machining tears, plating, fatigue, creep, stress corrosion and hydrogen cracks. Cracks can grow and lead to complete fracture of the component posing significant threats to component life and may lead to serious injuries or loss of life. Brittle fracture in metals occurs with little or no visible warning. Discovery of any cracks warrants immediate interventions to arrest the cracks before they propagate to the point of fracture. Several crack detection and repair methods in metals have been developed, characterised and validated through research. This paper reviews the repair techniques of cracks in metals.

Keywords: Cracks; crack repair techniques; metals

1. Introduction

Historically, the cracking of the Tsar Bell while it was in the casting pit during a fire in 1737 confirms the position that metal cracking has been a long standing problem in the metal industry [1]. However, during those ancient days, metal cracking was rarely scientifically studied and not so controllable. According to Hart [2], it was not until World War II that recognition of metal cracks as an engineering concern became prominent when the costs that emanated from hydrogen cracks related failures (in terms of

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fabrication, repairs, loss of plant, injuries and irreplaceable loss of human life) led to the need for extensive global scientific study of cracks in metals. The studies included crack detection, crack propagation, crack classification and crack repair techniques. The author further reported that in 1973, Britain recorded annual costs of £180 million for the repair of cracks on welded assemblies. The United States of America estimated annual costs for failure due to fracture to be around $119 billion [3]. Failure by fracture (cracking) is highly intolerable since it violates safety requirements and is a primary threat to the integrity and performance of machinery and mechanical structures [1]. To-date, a number of metal crack detection techniques have been developed and these include, examination through human senses, liquid penetration method, ultrasonic testing, radiographic imaging, magnetic particle inspection and eddy current testing, which are all non-destructive testing techniques (NDT) [4]. Various types of cracks exist in metals and the common categories include cooling, hot, solidification, centreline, crater, liquidation (hot tearing), grinding, pickling, heat treatment (quenching), machining tears, plating, fatigue, creep, stress corrosion, and hydrogen cracks [4, 5].

Several techniques have been developed for the repair of cracks. These have been applied to a range of crack sizes, both macro and micro cracks. Hammer peening, grinding, vee-and-weld, doublers or splice plates [4], pulsed electron beam irradiation [6], carbon fibre reinforced polymer (CFRP) patches [7], stop-hole technique [8], bonded composite patches [9], crack stitching [10, 11, 12, 13] and laser additive crack cladding [14, 15] have been extensively studied. The aim of the present paper is to review the commonly used crack repair techniques in metals.

Nomenclature

D	stop hole diameter
σ_y	yield stress of the material
S_r	nominal stress range where at the crack tip
a	half-crack length

2. Common crack repair techniques in metals

Dexter et al [4] defined fracture as rupture in tension or rapid extension of a crack which leads to gross deformation, loss of function or serviceability, or complete separation of the component. When fracture critical cracks are detected in mechanical components and structures, several methods are employed to arrest or stop them from further growth or propagation. The choice of the repair technique or a combination to be used depends on many factors which include the nature of the crack, crack position, crack orientation, crack size, crack accessibility, component application, expected repair precision, availability of tools, metal type, component thickness and the required expertise. The commonly employed techniques will be reviewed in this section.

2.1 Metal crack stitching

Metal crack stitching is a mechanical crack repair technique which uses a combination of interlocking series of stitching pins and locks [10, 11, 12, 13]. The locks are reported to be installed across the joint line at intervals along the crack length. This technique was reported to produce gas and liquid tight joints which restores the metal to its original strength without further need to weld the joint. The authors concurred that the technique offers a number of advantages which include dampening and absorbing compression stresses, spreading tensile strains and dissipating the load away from the crack, maintaining the original alignment of the repaired surfaces, on-site repairs with minimum equipment dismantling, minimum downtime, cost effective and being of worldwide recognition. It was further reported that metal crack stitching is commonly used on cast iron but has also been successfully applied to other machinable metals such as ductile iron, steel, aluminium and bronze castings. The technique is said to bear, “metal locking, metal surgery, cold welding, stitch welding and crack patching” as its other names [11].

After crack detection, the crack is procedurally repaired. The basic process begins with positioning, realigning, and firmly holding the cracked surfaces together using special fixtures and clamps [12]. Holes are then drilled across the line of fracture to the tool depth of the casting using special jigs. Locks are then installed into the apertures to a depth of 80% of the casting or metal wall thickness [13] and pinned into a tight metal-to-metal condition, which become integral with the parent metal. Holes are then drilled along the crack line. They are then tapped and filled with overlapping studs (stitching pins), resulting in a joint that has pressure-tight strength and original casting rigidity. Each stitching pin has a break-off groove above its shoulder that allows the head to twist off when it reaches the proper torque [13]. After this, pneumatic chisels and grinders can be used for smoothening the repaired surface. The minimum spacing between the locks for maximum strength was reported to be equal to one half of the length of the locks being used. The application of the technique was reported to extend from plant and machinery, ship engines, marine gearboxes, to power presses and petro-chemical refineries.

2.2 Vee-and-weld

According to Dexter et al [4], Vee-and-weld has for long been a method of weld repair for long and through-thickness metal cracks. The authors reported that material is removed along the crack length, through three-quarter the thickness of the section that is cracked in the shape of a V. The V-shaped groove is then filled with weld metal. The authors recommended air arc gouging, and grinding as the preferred methods of material removal. They however discouraged the use of a disc grinder to remove the cracked material as the crack can become blurred (or smeared) as more material is removed, increasing the possibility of hiding or masking the crack path that will leave an embedded flaw within the repair weld. Air-arc gouging was recommended as it opens up the crack making the crack path easy to identify and follow. It was further stated that vee-and-weld repairs are most effective when used to repair a cracked weld detail, not cracks in unwelded base metal. The reliability of this repair method depends highly on how skilled the welder is if it is not automated. The authors concluded that repairs can be made using the shielded metal arc welding (SMAW), flux-cored arc welding (FCAW), or gas metal arc welding (GMAW) process depending on availability and site conditions.

2.3 Stop-hole technique

According to Dexter et al [4], the stop-hole technique is the most commonly used repair method for fatigue cracks. It requires a hole of sufficient diameter to be drilled at the crack tip, completely removing the sharp notch at the tip of the crack for successful arrest of the crack. The authors suggested the use of larger holes (50.8 to 101.6 mm) as long as it does not compromise the strength and stiffness of the structure or connection and to the comfort of the customer. A minimum practical hole diameter of 25.4 mm was also recommended. The procedure was described to begin with identifying the crack tip using the recommended crack detection method and mark it out with a centre punch. Magnetic particle and liquid penetrant techniques were proposed and are the easiest and the most widely used detection techniques. The drill can either be cantered over the crack tip or such that its trailing edge touches and removes the crack tip. The authors cautioned that care needs to be taken not to miss the crack tip to ensure that the crack would not continue to propagate. It was further reported that the hole size to be drilled will then be calculated using Equation 1 and in case of edge cracks, the hole size predicted by equation 1 will be increased by 25%. In equation 1, D is the hole diameter, S_r is the nominal stress range where the crack tip is located, a is the half-crack length and σ_y is the yield strength of the material.

$$D = \frac{S_r \pi a}{55 \sigma_y} \geq 25.4\, mm \qquad \text{(for } \sigma_y \text{ in MPa and a in mm)} \qquad (1)$$

It was further reported that bushes or bolts may be plugged into the holes for favourable compressive stresses around the entire hole, an idea which was criticised by some engineers arguing that it hides crack reinitiating during inspection. Cold expansion of the hole was reported as another way to introduce the beneficial compressive residual stress around the hole by hitting with a hammer a tapered mandrel slightly larger than the hole forcing it through the hole, plastically deforming the hole thus creating a compressive stress field around it that will prevent the hole from further propagation. The authors concluded by asserting that flame-cut holes should never be used to remove crack tips as they introduce a gouged surface condition that may initiate new fatigue cracks.

Ayatollahi et al [8], numerically studied fatigue life extension by crack repair in 6061-T651 aluminium alloy using the stop-hole technique. The authors used ANSYS Parametric Design Language (APDL) code under mode-I and mode-II loading conditions. The results obtained indicated that a hole drilled at the crack tip turns the crack into a notch reducing the crack tip stress singularity hence enhancing the fatigue life of the repaired structure. The authors concurred with Dexter et al [4], when they numerically discovered that larger stop-hole diameters resulted in extended fatigue lives. It was further numerically revealed in their studies that the presence of stop holes notably diminished the stress concentration around the crack tip. It was reported that the comparisons made between the experimental and computational results obtained were in close agreement, which proved that the numerical model developed in the study successfully predicted the fatigue life extension caused by the stop-hole method and can be extended to other cracked metal alloys.

2.4 Bonded crack patches

These can be in the form of bonded composite patches, carbon fibre reinforced polymer (CFRP) patches or doublers or splice plates [4, 7, 9, 16, 17]. Khan et al [9] investigated the arresting of crack growth emanating from v-notch under stepped variable fatigue loading using bonded composite patches. In the investigation, the authors studied the effect of the cyclic variable amplitude loading (CVAL) on the fatigue life of Al 7075-T6 made samples. The results did not show significant improvement of the fatigue life of cracked specimens repaired with bonded composite patches for increasing fatigue blocks and vice versa. The authors reported that the repair technique reduces the stress field near the crack by bridging the stresses between the cracked plate and the composite patch which leads to retardation or complete stoppage of the crack growth. The repair of cracked components by an adhesively bonded composite patch has gained acceptance in aerospace structures [18]. The technique was found to be effective when optimally used.

Emdad, and Al-Mahaidi [7] studied the effect of pre-stressed carbon fibre reinforced polymers (CFRP) patches on crack growth of centre-notched steel plates. The authors found that multi-layers of CFRP increased the fatigue life of the plate up to 30% and showed an increase in the cracked life of between 6.5 times and 10 times as also reported by Srilakshmi et al [17]. Increases in pre-stressed patches lowered the crack growth rates thus increasing the crack life of the specimen. The pre-stressing technique proved to be effective and the authors recommended that the correct use of pre-stressing in general can lead to increased fatigue life of cracked members by applying a compressive force to the crack edges. The authors further indicated that the compressive force will impose artificial crack closure on the flawed structure arresting its further growth. It was postulated that the method cannot be used for double-sided repairs due to limited access and the use of the pre-stress force on one side can cause significant bending moments to the member leading to unforeseen failure as also cautioned by Ahn and Basu [19].

Doublers or splice plates can be used to repair through-thickness cracks by adding them to either increase a cross-section or provide continuity at a cracked cross-section which in turn reduces stress ranges and can be added after the repair is made [4]. However, alignment problems have been reported to affect this technique.

2.5 Laser additive crack cladding

Laser Additive Technology (LAT), uses a laser beam to locally melt the filler powder and the target material surface [20, 21]. Parts are built in a layer-by-layer fashion by focussing the laser and powder source across the substrate [22]. Shielding gas assisted powder is delivered through an integrated powder delivery system and the heat generated by the melt pool as well as the laser beam causes the powder to melt and bond with the substrate as it solidifies [23, 24]. In comparison to its conventional counterparts, LAT offers advantages of small heat affected zone (HAZ) and a small weld dilution zone (WDZ) which protects both the mechanical and metallurgical properties of the welded substrates [25, 26]. LAT is widely used for free form fabrication, materials processing, manufacturing, maintenance and repair of high value and critical parts [20, 21].

Graf et al [14] investigated laser additive repair of cracks in stainless steel and titanium alloys. The cracks were removed by milling into V-grooves, U-grooves and open top U-grooves of 10 mm depth for comparison of the results obtained. The cracked regions were cut open into three grooves, to the root or tip of the crack in order to remove the crack and rebuilt by laser cladding. The experimental study was performed using a TRUMPF TruDisk 2.0 kW Yb:Yag laser with a 3-jet powder nozzle positioned within a 5-axis machine, helium 5.0 carrier gas and argon 5.0 shielding gas, at a local inert gas atmosphere with less than 50 ppm oxygen and spherical powder grain size of 45-125 μm with the deposition parameters shown in Table 1 and Table 2.

Table 1. Welding parameters for the Ti6Al4V V, U and U-groove with angled side walls [14]

Welding parameters	(a)	(b)
Welding velocity (m/min)	0.5	1.0
Laser power (kW)	2.0	1.0
Laser spot diameter on surface (mm)	2.2	1.0
Powder mass flow (g/min)	9.4	3.8

Table 2. Welding parameters for the CrNi-Steel [14]

Welding parameters	V-groove 1	U and V-groove 2
Welding velocity (m/min)	0.5	1.0
Laser power (kW)	1.0	1.0
Laser spot diameter on surface (mm)	2.2	2.2
Powder mass flow (g/min)	4.0	8.0

The parameters were alternated among the three grooves and for both metals, the V-grooves and the narrow U-groove with open top angle side walls enabled better powder delivery accessibility. The repairs made for the V-grooves were subjected to X-ray testing and they showed good side-wall fusion. The cross-section of the narrow U-shaped groove showed lack of side wall fusion defects because of lack of vertical side wall laser irradiation as the laser beam could not be adjusted to be perpendicular to the side-walls. Top surface powder impedance on the upper lip of the groove was also reported to be a major challenge due to inaccessibility, causing irregularities in the powder stream close to the groove side-walls. The authors recommended wider grooves or inclined side-walls as necessary for the successful use of the technique. It was then concluded that the narrow U-grooves (cracks) could not be successfully repaired using LAT. Rottwinkel et al [15] used laser crack cladding process for the repair of V-groove shaped cracks in single-crystal (SX) turbine blades. The repaired samples were examined by scanning electron microscope (SEM)-analysis and were found to have cracks and the repair attempts were reportedly unsuccessful. There are very few published works on the repair of cracks through LAT and those that attempted are very recent.

2.6 Pulsed electron beam irradiation

Murray and Clare [6], studied the repair of Electrical Discharge machining (EDM) induced surface cracks by pulsed electron beam (EB) irradiation.The authors used low energy irradiation and few shots to investigate the physical mechanism of crack repair and the obtained results indicated trends in crack reduction and ultimately their elimination. Under the lowest EB cathode voltage of 15 kV and with 5 and 10 shots, there was evidence of partial crack resealing. According to the authors, the circular nature of the seal suggested flow across the crack when molten then contraction upon rapid quenching, solidifying a few joints where surface tension of the melt resisted the force of contraction. Cracks induced by the EDM process were entirely eliminated from the surface, and up to a depth of 4.5 μm of the new re-melted parts with an increased voltage of 25 and 35 kV after 20 shots at 25 and 35 kV. The study showed that pulsed electron beam irradiation has potential for the improvement of fatigue life and corrosive attack due to surface crack elimination. However, the process seems to be limited to cracks of micron dimensions.

2.7 Grinding

Grinding can be used to totally remove portions of a detail containing small cracks, particularly cracks at the edges of flanges or other plates [4]. The authors further stated that the gouge created by grinding should be tapered with a 2.5:1 slope and finish grinding should be performed parallel to the applied cyclic stresses. To achieve this, the authors asserted that, sparks from the grinding operation should fly in the direction of the primary stress. It was also further affirmed that small micro-cracks form at the weld toe as the weld pool cools to ambient temperature and contracts and under cyclic loading these micro-cracks begin to propagate and become small fatigue cracks. Grinding them off has been found to be effective at shaping the weld, at the same time killing crack paths thereby enhancing fatigue strength by reducing the associated stress concentration factor. The authors reported that welds reshaped with a burr grinder have been found to have a 50% larger allowable fatigue design stress range over their untreated counterparts.

2.8 Hammer peening

According to Dexter et al [4], shallow surface cracks of up to 3 mm deep can be repaired by hammer peening. The authors asserted that the application of the technique to cracked welds in service restores the remaining fatigue life to the original new weld. It was further reported that these treatments when optimally applied can result in fatigue resistance that is at least one fatigue category greater than the original detail. This can be best applied to cracks of micron dimensions and does not show significant fatigue life improvement on macro cracked welds.

3. Conclusion

Repair of cracks in metals was reviewed and various repair methods that are currently in use at both general practical purpose and high value and critical application levels have been discussed. It has been noted that computational studies are playing a key role in improving understanding of the effect of most crack repair techniques on the mechanical performance of repaired components. The recent introduction and use of laser additive technology for crack repairs has also been studied as it shows significant potential for crack repair. Limited recent works on this technique have been published and therefore is an interesting research area.

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