Part Repair using a Hybrid Manufacturing System

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ABSTRACT

Nowadays, part repair technology is gaining more interest from military and industries due to the benefit of cost reducing as well as time and energy saving. Traditionally, part repair is done in the repair department using welding process. The limitations of the traditional welding process are becoming more and more noticeable when the accuracy and reliability are required. Part repair process has been developed utilizing a hybrid manufacturing system, in which the laser aided deposition and CNC cutting processes are integrated. Part repair software is developed in order to facilitate the users. The system and the software elevate the repair process to the next level, in which the accuracy, reliability, and efficiency can be achieved. The concept of repair process is presented in this paper. Verification and experimental results are also discussed.

INTRODUCTION

Part repair technologies have been employed in many military and industrial applications such as torpedo shell, die, mold, and turbine blade repairing. Damages can occur during the operations or the handlings. As shown in Figure 1, defects or damages can be categorized into 4 main categories: crack, worn out surface, corroded surface, and broken parts. (Wang et al., 2002)

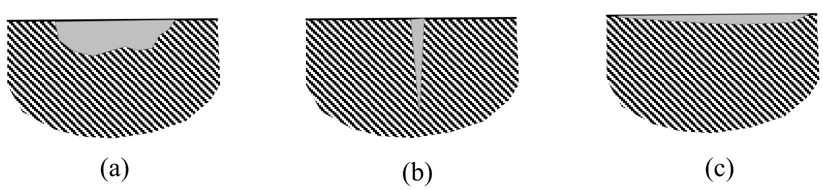


Figure 1: Damages (a) Pit (b) Cracks (c) Worn-out

The sizes of the damages are used to classify the types of damages. The damage is classified as a crack if the width is tiny but the depth and the length of the damage are relatively large. Heat stress induces cracks in dies or molds. Cracks in ship steel are caused by fatigue. If the width and length of the damage are large compared to the depth, the damage is defined as a worn-out surface. Worn out surfaces are typically seen in parts with movements such as shafts. Corroded surfaces usually occur on parts in extreme environment, inserts of molds and torpedo shells for example.

Common processes used in part repair process are Gas Tungsten Arc Welding (GTAW) and Tungsten Inert Gag (TIG) welding. These traditional repair processes contains five basic steps as the follows. (Sammons, 1999) (a) The damaged part is cleaned and identified the defects. Grease and other impurities need to be removed. (b) The damaged part is then pre-heated. (c) Filler is added via the welding process. (d) After welding, part is then rested to relieve from expansion due to the heat. (e) Post-heat is then applied to relieve the stress.

There are some limitations of the welding process in part repair. The welding process cannot achieve high accuracy and reliability. The deformation of the repaired part is usually large. The bonding between the filler and the damaged part is always poor. More importantly, some of the metal materials are not weldable.

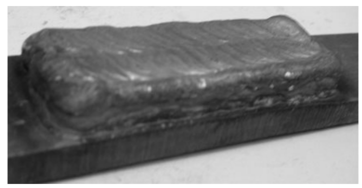


Figure 2: Sample piece using welding process

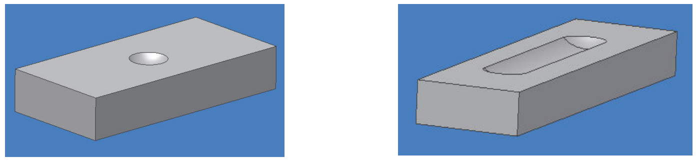
A cold repair process called Metalock process has been used. This process avoids the stress due to the heat. Holes are drilled along the cracks and then tapped and filled with studs. The repaired pieces are not fused to a single piece. This method also requires highly skilled technicians.

Laser welding process is another method which has been used in part repair. Laser welding process possesses advantages over the conventional welding process. The heat-affected zone is relatively small compared to welding. Thus, the deformation and stress are relatively small. Laser welding process can be used with virtually any kinds of materials including unweldable materials. The time required for repairing is significantly reduced. The accuracy and repeatability can be achieved. However, this process limits itself to repairing cracks only due to the nature of the process.

The follows summarize the applications of part repair processes. In a work done by Camp and Bergan (Camp and Bergan, 2000), torpedo parts are repaired using laser aided repair process. Motor shafts (Wang and Zhuang, 1996; Vuorista, 2002) and Ship steel (Brown, 1999) are repaired using laser aided repair processes. The corroded and worn-out dies and molds are fixed in the work done by Roy and Francoeur (Roy and Francoeur, 2005) as well as the work done by Skzek and Lowney. (Skzek and Lowney, 2000) Laser welding is used to repair the corroded steam generator tubes in nuclear plants (Wowczuk, Miller, and Bruck, 1990) Turbine blades are repaired using laser cladding process. (Sexton, et al., 2002; Richter, Orban, and Nowotny, 2004) It is criticized in the work done by Wang et al. (Wang et al., 2002) that the process planning for these repair processes are application specific.

SYSTEMS AND REPAIR OPTIONS

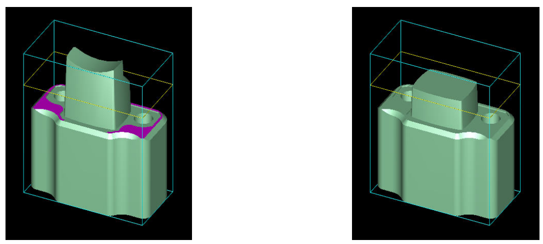
The repairs are done in a multi-axis hybrid manufacturing systems in which the laser deposition and the machining processes are integrated. The repair software provides some options in order to match the damages. The three basic options include ball-end circular hole, ball-end slot, and entire cutting plane. Ball-end mill is used for cutting the hole and the slot in the first two options which are designed to repair parts with pits and cracks. (Figure 3)



(a) (b)

Figure 3: Repair options (a) Ball-end circular hole (b) Ball-end slot

Flat-end mill is used to perform cutting in the third option which is designed for repairing parts with worn-out or corroded surfaces as well as broken parts (Figure 4).



(a) (b)

Figure 4: (a) entire cutting plane option (b) part after removing damaged portion

MACHINING AND DEPOSITION PATHS

The machining paths for ball-end-circular-hole option and ball-end slot option are simply done by linear interpolation (G01). Contour-parallel curves are used as the deposition paths for these 2 options. The contour-parallel curves are also used as the machining and deposition paths for entire-cutting-plane option. However, the track width of the cutting paths is different from that of the deposition paths. Also, the layer height of deposition is usually smaller than the depth of cut.

The curve offsetting has been studied extensively. There are many approaches to construct the offset paths for the 2D contours. These methods can be categorized into 3 groups: Pair-wise Offset (Choi and Park, 1999), Pixel-based (Choi and Kim, 1997), and Voronoi approaches (Ruan et al., 2002; Ruan, Eiamsa-ard and Liou, in print; Held, 1991; Held, Lukas, and Andor, 1994; Eiamsa-ard et al., 2003; Kao, and Prinz, 1998; Kao, 1999). Some of the earlier work (Choi, and Park, 1999; Choi, and Kim, 1997; Held, Lukas, and Andor, 1994; Eiamsa-ard et al., 2003) reported that their algorithms can be successfully used with arbitrary shapes. In general, the offset curves can be defined using Minkowski operations described below.

Minkowski operations (sum and subtraction)

Minkowski operations have been used in the areas of image processing and robotics path planning. Minkowski Sum and Minkowski Subtraction are known as dilation and erosion respectively in the area of image processing.

Let A and B be sets as shown in Figure 5. $A \oplus B$, the Minkowski Sum of set A and set B, denotes the sum or the addition of the two sets. Minkowski Sum is defined as the follow:

$$A \oplus B = \{a+b: a \in A \text{ and } b \in B\} \tag{1}$$

It is common to write A+b instead of $\{a+b: a \in A\}$. Thus, $A \oplus B$ can also be defined as:

$$A \oplus B = \bigcup \{A+b: b \in B\} = \bigcup_{b \in B} \{A+b\} \tag{2}$$

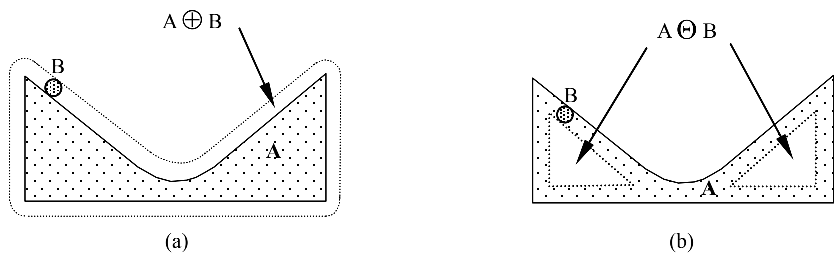


Figure 5: (a) Minkowski sum $A \oplus B$ (b) Minkowski subtraction $A \Theta B$

Similarly, the Minkowski Subtraction ($A \Theta B$) is defined as:

$$A \Theta B = \bigcap \{A+b: b \in B\} = \bigcap_{b \in B} \{A+b\} \tag{3}$$

Interior, Closure, and Boundary operations

Let X be a closed set. (i.e. $X = \{x: x \in X\}$). The interior of set X is the union of all open sets within X, denoted as int(X). Note that int(X) is necessary an open set. The closure of set X, denoted as cl(X), is the intersection of all close sets containing X. cl(X) is necessary to be closed. The boundary of set X, denoted as $\partial(X)$, is its closure minus its interior.

$$\partial(X) = cl(X) - int(X) \tag{4}$$

Offset paths

Let R be the target region in which the coverage paths are planned; T be the virtual tool shown as a planar disk in Figure 6. Also, at iteration i, let O_i be a set in which the distance from the contour to any points in the set is larger or equal to a fixed distance d_i. (d_i = i * D where D = diameter of the tool or laser diameter - overlap) The boundary of set R, shown in Figure 4 as $\partial(R)$, is the contour boundary of the target region.

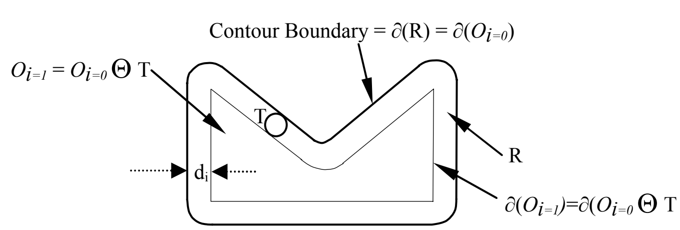


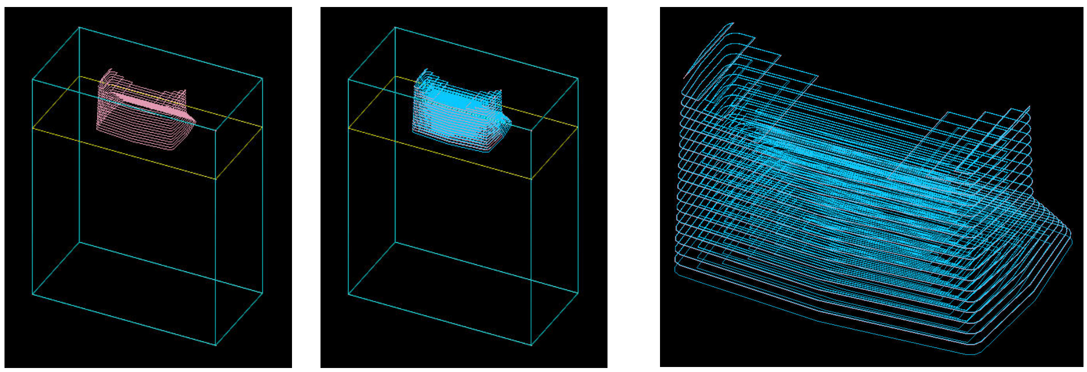
Figure 6: Relationship between offset curve and Minkowski subtraction ($O_{i=0} \Theta$ T).

At iteration i, the set O_i is equivalent to the Minkowski Subtraction of the set O_{i-1} and the tool area (T). (Figure 6) The deposition paths $\partial(O_i)$ is defined as:

$$\partial(O_i) = \partial(O_{i-1} \Theta \mathrm{T}) = \partial\left(\bigcap\nolimits_{t \in T} O_{i-1} + t\right) \tag{6}$$

DEPOSITION PATH GENERATION

The paths for deposition were generated in the software written in Visual C++ using ACIS 3D toolkit. Layer height was set at 0.03 inch. The track width was set to be 0.1 inch with 50% overlap. The contour-parallel was used. The results are shown in Figure 7. The deposition paths were then sent to a postprocessor to generate the NC codes.

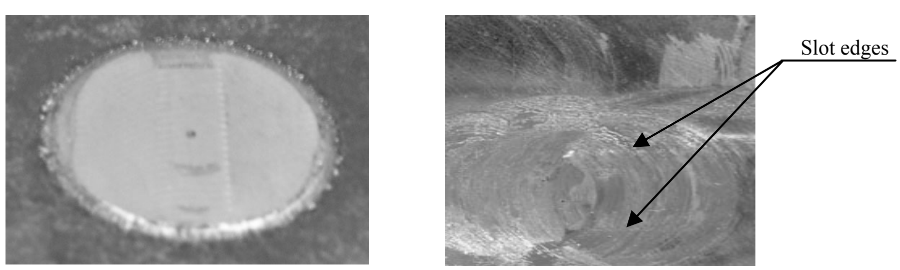


(a) (b) (c)

Figure 7: (a) Slices (b) Deposition paths (c) Deposition paths (close up)

EXPERIMENTS

The laser used was NUVONYX 1K max diode laser. The laser processing parameters for cladding steel H13 powder were 600W with a stand off distance from the nozzle to the top of the clad of 0.87 inch. The powder feed rate for H13 powder was 6g/min. The NC code was set to move the nozzle up 0.03 inch after each layer. The travel speed of the nozzle was 40 inches/minute. The first two repair options, Ball-end circular hole and Ball-end slot, were tested. The results are shown in Figure 8.



(a) (b)

Figure 8: (a) Ball-end circular hole (b) Ball-end slot

Experiments were done for the third repair option as well. The result of the repaired part is shown in Figure 9.

Figure 9: Part after repairing

BENDING TESTS

The interfacial strength is determined from four-point bend test. (Figure 10) The four-point flexture test is based on the storage of elastic energy on bending. Interfacial cracks propagate when the strain energy release rate equals to the critical energy release rate (G_c) of the interfacial failure. Four-point bend test has been used to analyze the interface between the substrate and the cladding produced by laser processing.

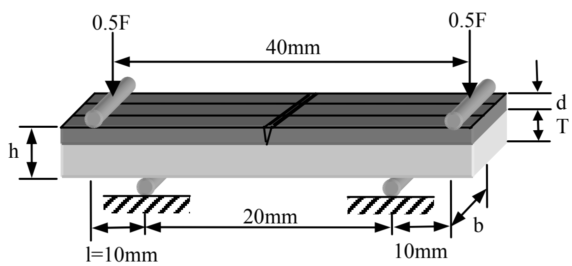


Figure 10: Bending test set up

Ashcroft et al. [21] calculated the critical energy release rate (interfacial energy) for thick claddings. Several critical parameters has been added into his calculation such as the thickness of the substrate, width of the substrate, and the thickness of the cladding itself as shown below.

$$G_c = (18 \cdot E_f \cdot d \cdot F^2 \cdot l^2 / b^2 \cdot T^6 \cdot E_s^2)(T^2 + d^2/3) \quad (7)$$

Where

E_f = Modulus of elasticity of cladding

d = Thickness of cladding

F = Critical load corresponding to de-lamination

l = Distance between the inner and outer rollers

b = Width of the substrate

T = Thickness of the substrate

E_s = Modulus of elasticity of substrate

The 50x6x1 mm specimens are cut out from the deposition. A center pre-crack is made on the specimen in order to induce symmetrical cracks along the clad-substrate interface.

The specimen is then loaded in four-point flexture on an Instron TT-B Universal Testing machine until a new crack propagates through entire cladding. The interfacial fracture energy of laser cladding tool steel specimen is compared to the tool steel weld specimen of the exact same dimension. Result is shown in the following table.

Table 1: Interfacial Fracture Energy or Bond Strength comparison between Laser cladding and welding processes

Properties	Notation	Laser cladding	Welding
Modulus of Elasticity of cladding (Pa)	E_f	2.10E+11	2.07E+11
Thickness of cladding (m)	d	2.00E-03	2.00E-03
Critical load of de-lamination (N)	F_c	11556	11428
Distance between inner and outer rollers (m)	l	1.00E-02	1.00E-02
Width of substrate (m)	b	6.00E-03	6.00E-03
Thickness of substrate (m)	T	8.00E-03	8.00E-03
Modulus of Elasticity of substrate (Pa)	E_s	2.10E+11	2.10E+11
Interfacial Fracture Energy (J/m^2)	G_c	15848.59	15278.02

CONCLUSION

This study shows that part repair can be done in a hybrid manufacturing systems. The accuracy and reliability can be achieved with the integration of the hardware and repair software. The bond strength of the repaired part done in hybrid manufacturing systems is higher than that of the welding process. Thus, the hybrid manufacturing systems has the potential to repair damaged parts.

By integrating the repair software, parts with different types of damages can be fixed. Ball-end-hole option is suitable for parts with pits and small cracks. Longer cracks can be repaired with the Ball-end-slot option. Removing the damage using a cutting plane is appropriate with parts with corroded surfaces and worn-out surfaces as well as broken parts.

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