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Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis

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ABSTRACT

Laser direct deposition provides an attractive and cost effective means for repairing or remanufacturing high value engineering components. This study demonstrates the successful repair of defective voids in turbine airfoils based on a new semi-automated geometric reconstruction algorithm and a laser direct deposition process. A Boolean difference between the original defective model and the final reconstructed model yields a parameterized geometric representation of the repair volume. The experimental results of this method demonstrate the effectiveness of laser direct deposition in remanufacturing and its potential to adapt to a wide range of part defects. A Life Cycle Assessment (LCA) on the energy and environmental impacts by remanufacturing is also presented.

1. Introduction

Sutherland et al. (2003) presented that rising concerns over escalating emissions, resource depletion, and other environmental issues have led to an increased emphasis on the design and manufacturing of environmentally benign products. Consequently, Ramani et al. (2010) describes that remanufacturing has emerged as a promising practice to reduce the environmental impact of products by extending their lifespan and thus precluding the need for consistent replacements that are costly in terms of both energy consumption and financial expenditure. Its value can be understood by analyzing the results of a recent study conducted by the Department of Defense, which evaluated used components worth over $100M in the Corpus Christi Army Depot to be amenable to repair and a new life through laser-based remanufacturing according to Hedges and Calder (2006).

Aerospace and automotive components are susceptible to wear and damage over time. Many of these components reach their "end of life" stage prematurely due to limitations prevalent in overhauling techniques. This problem arises due to the fact that most of such components use high strength alloys, which help achieve good thermo-mechanical properties but also present challenges in manufacturing. Such materials require special tooling and consume a significant amount of energy during manufacturing processes. This cost is further exacerbated by the high financial expenditure associated with purchasing the necessary raw materials and conducting requisite manufacturing processes. Consequently, a cost effective and efficient repair process is necessary to remanufacture such damaged components.

Teams of researchers, Grant and Tabakoff (1975) and Antony and Goward (1988), indicated that damage in high valued metallic components is often found in the form of cavities or voids in the material. As the material degrades or the critical dimensions of the component no longer match the specified dimensions required for efficiency, the performance of the component also diminishes. After remanufacturing, these components can regain all of their efficiency, or regain even more, by incorporating more advanced materials or by adapting to the improved design.

In the past there have not been any good methods to remanufacture these kinds of voids or cracked parts in a cost effective manner as described by Zhang et al. (2002) and Bonacorso et al. (2006). Traditionally welding has been the primary method used to restore shape and functionality of damaged aerospace and automotive components. The welding process is often very manual and tedious. Gas Tungsten arc welding (GTAW) is one example of the welding repair processes. Eiamsa-ard et al. (2005) showed that the bonding between the filler material and the damaged part provided by GTAW is poor and unreliable for high performance mechanical parts. Other problems related to GTAW are its incompatibility with a wide range of advanced materials and the high operating temperatures (up to 5500 °C) that can be detrimental to the parts being repaired. Furthermore, manual welding repair

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typically requires manual grinding after the welding is completed, causing the process to become even slower, less automated, and consequently less accurate. Recently, Roy and Francoeur (2002) introduced the refined process using micro arcs to weld filler material onto the substrate. However, Francoeur (2002) indicates that this method is still contingent upon the skill of the welder, and falls short of an efficient automated process.

Smith and Keoleian (2004) and Östlin et al. (2009) showed that the advent of accurate material additive processes has made such repair not only economically viable, allowing the restoration of the shape back to its correct dimensions, but also facilitates design enhancements at the time of remanufacturing. By utilizing the knowledge attained from observing the product's past performance, its weakness can be strengthened and design improvements can be incorporated into its current framework. Furthermore, Michaud and Llerena (2006) presented that remanufacturing also cuts down the cost for waste disposal, since it builds upon the non-damaged portion, which is close to its final form, and thus requires only a fraction of material processing. Consequently, remanufacturing by accurate additive processes will enable industries to save energy and material, and contribute towards sustainable design and manufacturing.

The advancements made in additive manufacturing technologies have provided a strong prospect for the automation of the aforementioned repair process with a significant increase in the accuracy of the final repair. One of such promising material additive processes is laser direct deposition (LDD) or laser engineered net shaping (LENS®). LDD has been commonly used in rapid prototyping of fully dense parts by Dutta et al. (2011). Such deposition systems are combined with computer numeric control (CNC) and computer aided design (CAD) systems that provide a flexibility, which lends itself to many different remanufacturing applications.

Since a part begins to wear after a number of cycles of operation, the original CAD model may not reflect the geometry of the worn part. In addition there are occasions when the Original Equipment Manufacturers (OEM) does not choose to remanufacture their own products as described by Gutowski et al. (2011). In these scenarios third-party remanufacturing firms are left to break down and reverse engineer the products without the aid of the original CAD model. When an accurate 3-dimensional (3D) model is not available, a reverse engineering process is required in order to reconstruct a geometric representation. Here, a 3D digitized mesh of the defective part and a surface reconstruction algorithm are applied to define part geometry. Moreover, the surfaces reconstructed are closely associated with a parametric representation, which enables manipulation of the surface geometry. Consequently, the geometric models of the defective part are amenable to a "virtual repair" process, which further enhances the quality of the actual repair.

Presently, LDD remanufacturing methods for high value metal components are inadequate. There has been a lot of focus on seamlessly moving from the digital data to a tool path used by the laser direct deposition machine, but few have discussed ways to increase the performance of the product while still accurately reconstructing the missing geometry. Gao et al. (2008) and Yilmaz et al. (2005) have focused on automating the repair of a specific type of component such as turbine blades. Bremer (2005) and Gao et al. (2010) addressed a more general repair solution for any geometry type. Yilmaz et al. (2010) automated the process of digitizing and meshing, and reconstructed the geometry from a digitized polygonal model using non-uniform rational b-splines (NURBS).

In this study laser direct deposition is employed to restore a damaged turbine blade. A previously developed algorithm by Piya et al. (2011) is used to reconstruct a model of a defective region of the turbine blade airfoil. This algorithm uses the Sectional Gauss Map concept to extract Prominent Cross Sections (PCS) from a mesh object. The PCS extracted from a defective airfoil mesh is thus utilized to facilitate semi-automated reverse engineering and geometric reconstruction of a component with complex geometry. The accuracy of these results is compared to a reference model generated entirely in a CAD system. Strength tests were carried out to validate the strength of the repair. Finally, a Life Cycle Assessment (LCA) is performed on the LDD process, and the environmental impact results are compared between the LDD-based remanufacturing of a turbine blade and complete blade replacement.

2. Prominent Cross Section (PCS)

To facilitate accurate tool path generation for the LDD process, a geometric model of the repair volume must be available. This section describes the algorithmic theory behind the PCS and its use in extracting a parameterized CAD model of the repair volume.

Sellamani et al. (2010) introduced a PCS at a point on the surface of a solid object, which is defined as the cross-section of the local sweep segment passing through that point. Fig. 1 illustrates two PCS (C1 and C2) corresponding to two seed points (P1 and P2) in a hyperboloid CAD model. Here, both PCS are part of the same sweep segment and lie normal to the sweep direction. A PCS at a point is obtained through a series of iterative steps, each entailing the following steps:

1. Slicing the CAD model by a cutting plane that passes through the given seed point. The orientation of the cutting plane in the first iteration lies along the maximum curvature direction and the surface normal at the seed point.
2. Extracting normal vectors of all mesh facets that intersect with the cutting plane.
3. Generating a Sectional Gauss Map by plotting the normal vectors into a unit sphere. The points of intersection between these vectors and the unit sphere are referred to as the Sectional Gauss Map data.
4. Obtaining a new and refined cutting plane orientation through the least squares method applied on the Sectional Gauss Map data. This orientation will be applied to the cutting plane of the ensuing iteration.

This iterative process is repeated until the angular difference between cutting planes of two consecutive iterations (error value) falls below a user-defined threshold. The curve of intersection between the final cutting plane and the CAD model yields the PCS at that particular seed point. Furthermore, to enhance the robustness of the method, the same iterative process is carried out at the given

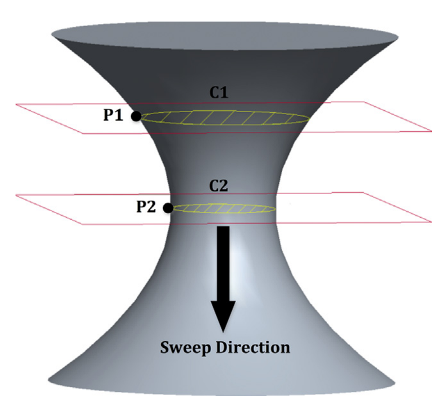

Fig. 1. Prominent Cross Sections on a hyperboloid.