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Thermal Spray Based Rapid Manufacturing, Part Refurbishing and Reengineering

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The ability to respond timely and cost effectively is bringing rapid manufacturing techniques into the mainstream production/repair arena. The Army can benefit from such technologies to avoid long lead times and high costs of procuring and inventorying replacement parts. But, a technology that offers versatility in terms of product size, cost and the ability to fabricate production components rapidly is yet to be available. This paper describes thermal spray technologies as applied to rapid manufacturing, part refurbishing and reengineering. A hybrid thermal spray system that can deposit a variety of materials with high throughput and density has been developed. Several generic materials that can meet the functional requirements of many parts and at the same time can be easily deposited by a thermal spray technique are discussed. An expert system software assisting the operator from CAD information, reverse engineering to part refurbishing is presented. Examples on the use of multiple schemes to remanufacture a part are also discussed. These schemes offer new avenues to fabricate replacement parts and/or salvage damaged parts and can benefit the Army considerably.

1 Introduction

The ability to rapidly procure replacement parts is severly limited by the cost and time asscociated with designing, building and setting up molds and dies for casting and forging operations as well as the availability of the feedstock. Especially, for military operations this is very critical because of the production volume and the nature of procurement and inventoring operation. Therefore, solid freeform fabrication (SFF) has been very attarctive to the military and several technologies such as laser aided net-shape manufacturing is under investigation. However, the turn around time for large components as well as the limited list of materials that can be successfully used in laser aided fabrication technique has fueled interest in alternative or complementary technologies. Thermal spray is one of the potential technologies that can offer cost effective solution especially when a damaged part is repairable.

Thermal spray technology has been around for long time and many variants of the process exist. However, the use of thermal-sprayed coatings to date has been primarily for the life extension of engineering components. Lately, thermal-spray technology has entered a new phase of development. Largely accepted by the gas-turbine industry, [1] the process is rapidly gaining recognition as a viable process in "front-end" design in other industries. Applications involving component repair as well as fabrication of net-shape components are rapidly emerging. [2,3] For example, Ford Motor Company has an ongoing multi-year program on the rapid fabrication of tools using arc spray technology. Infact, stamping dies made by the process (Fig. 1) have gone into production line. However, widespread implementation of the technology for such applications is lacking. This requires considerable enhancement of the reliability and reproducibility of the deposits, as well as establishment of a knowledge base on their intrinsic materials properties and behavior. There is a need to develop strong scientific correlation among the complex parameters, which calls for a concerted, integrated interdisciplinary approach. This paper presents a systems approach framework for the development and implementation of thermal spray in repair and rebuilding of components, especially in the military environment.

2 Thermal Spray Based Rapid Manufacturing

For thermal spray technology to gain the recognition as a rapid manufacturing alternative, first, the process development efforts should aim at delivering quality deposits at a high rate with a variety of materials. The deposit should be reliable and repeatable, aided by online controls and diagnostics. There should be an integrated material and part database so that the repair operation can be performed in an efficient manner. Like any other SFF techniques thermal spray produces near-net shapes and the final product needs additional machine work to grind, polish, tap, or cut-to-tolerance. The machining issues on these materials should also be simultaneously addressed. This paper addresses the process development and the implementation issues systematically in the following sections.

2.1 The Spray System

Among a plethora of approaches to deposit materials by thermal spraying, atmospheric plasma spraying (APS) and high velocity oxyfuel (HVOF) flame spraying are the most frequently utilized surface technologies. Nevertheless, as compared with arc-spray process, the APS and HVOF processes usually have much higher cost and application difficulties. Therefore, the process development efforts in this project aim at exploiting the benefits of both arc spray technique as well as the HVOF/APS technique. In this process, the tips of two/four consumable wires are fused by an electric arc and atomized by a high-velocity jet [4]. The HVOF part of the system (Fig. 2) is similar to the commercially available HVOFs and combusts propylene/hydrogen with oxygen. The HVOF component can also be replaced with a plasma jet.

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14. ABSTRACT
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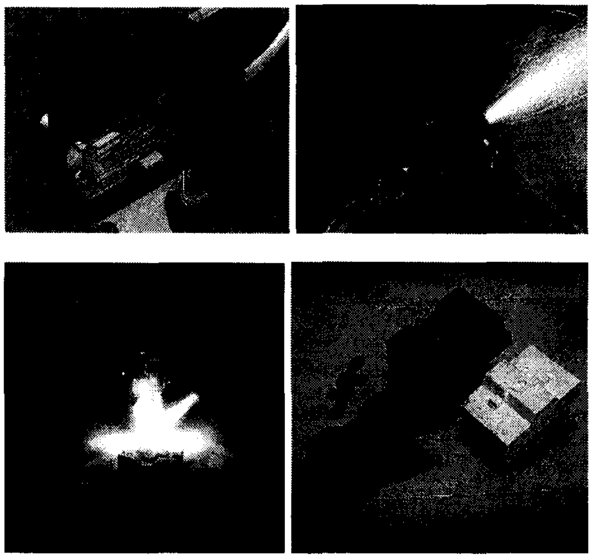

Fig. 1. (a) HVOF-ARC Hybrid Gun, (b) Hybrid gun in operation, (c) The integrated system, and (d) Rapid tool fabrication [Ref. 2].

This so called "hybrid" concept offers many advantages. The process offers all benefits of wire stock and productivity of electric arc spraying combined with noticeably improved coating density of HVOF/APS. It can operate as a simple HVOF/APS system or arc system. It can feed multitude of materials such as wire feed material through the arc systems and powder/wire through the HVOF component enabling the deposition of simple metallic alloys to composite materials. Sample deposited materials obtained from this process are presented later in this paper.

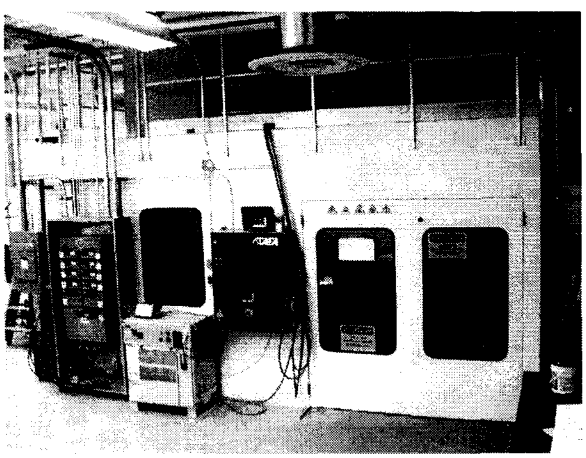

Fig. 2. Spray Booth

The integrated robotic system (ABB) contolled by a PLC, is designed to mount a HVOF-Arc, an APS-Arc, a Cold spray and an EDM system together. The notion behind this integration is to create a single platform that can deposit many different types of materials as well as complete the finishing operation. If a high volume single operation is desired, the system can also operate four-same type guns simultaneously as shown in Fig. 1c. The target manipulator can be a simple rotary table as shown in Fig. 1c or another 6-axis robot(Kowasaki) mounted on a movable platform. This system is housed in an operating chamber shown in Fig. 2. The cold spray and the EDM components are not implemented yet. There is a membrane based onsite nitrogen generator and a 470 CFM/150psi compressor.

2.2 Modeling, Diagnostics and Control

Thermal spraying is a highly complex process with a large number of interrelated variables. The multitude of interdependent process parameters results in a range of thermal histories for the molten particles, producing a wide distribution of particle velocities and temperatures within the spray plume. This, in turn, results in a variation in the intrinsic properties of incoming particles, such as temperature and viscosity, substrate impact behavior, fragmentation and consolidation behavior. The final characteristics of the complex multilayered deposit are determined by these interrelated phenomena. Traditionally, satisfactory deposit quality is achieved through a design of experiment (DoE) approach. Numerous engineering parameters, such as power level, gas type and flow rates, standoff distance, etc. have to be tried empirically and systematically through parameter matrix to determine the optimal parameters. However, despite the best DoE achieving a consistent coating quality on a production scale is virtually impossible. [5] Improved control of these parameters was the focus of many developments that have occurred during the past few years, and is the focus of many current developments. Our envisioned process control schemes as well as the weak links (shaded) are shown in Fig. 3.

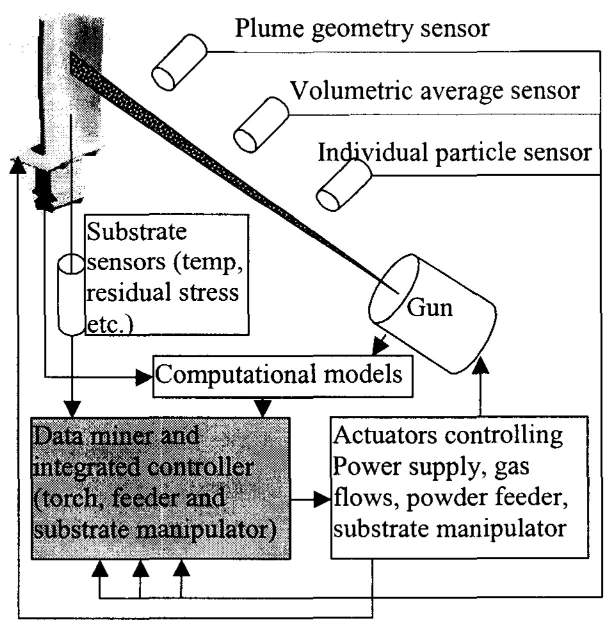

Fig. 3. Process control schemes and the weak link (shaded)

At present, we have implemented the individual particle sensor (DPV/CMS 2000) as well as the target temperature measurement sensors. Simultaneously, mathematical model to predict the process attributes are also underway. The expert system and the data mining software (discussed later) continuously build-up the knowledge-base, which is required for an effective manufacturing system. [6] Figs. 4 and 5 present the comparison of model predictions [7] and the measurements in the HVOF process. This is useful information for a robust process development.

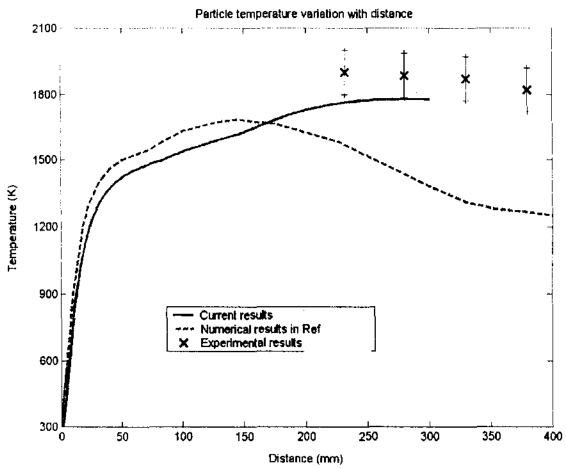

Fig. 4. Particle temperature prediction and measurement. [7]

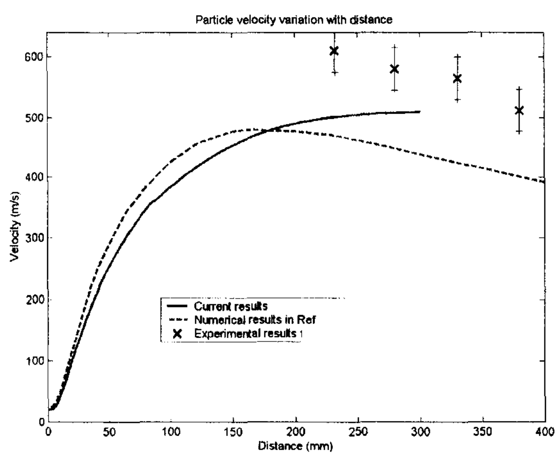

Fig. 5. Particle velocity prediction and measurement.

2.3 Expert System

Reverse engineering is an integral part of any rapid manufacturing system. In recent years the increased use of 3D scanning hardware has introduced a new type of data to the design and manufacturing field. In many design and manufacturing applications (e.g., part refurbishing or re-manufacturing) a scanned 3D model may be provided as an input to a shape matching system to search the database for related or identical models with the purpose of extracting useful information. The introduction of scanned 3D models restricts the use of traditional CAD-based 3D model search and comparison methods due to significant differences in model representations. [8] The CAD models provide structured and high-level representation of the part features, whereas the scanned 3D models usually come unstructured, in a polygonal mesh representation, which does not directly reveal the engineering features of the part. These differences require new algorithms for comparing shapes of scanned 3D models. In this project new approach and algorithms for scanned 3D shape matching and comparison are developed. Given the scanned 3D model as an input the approach developed in this project first uses general-purpose shape matching methods to identify small list of likely matches (i.e., candidate models) for more detailed shape comparison (Fig. 6). To perform detailed comparison of the shapes each candidate model is geometrically adjusted (i.e., rotated and translated) with the input using one of two new view point algorithms developed in this project. (Fig. 7) Once the candidate models are adjusted they are compared to the input to identify the similarities and differences between their shapes. To accomplish this task new shape comparison algorithm is developed.

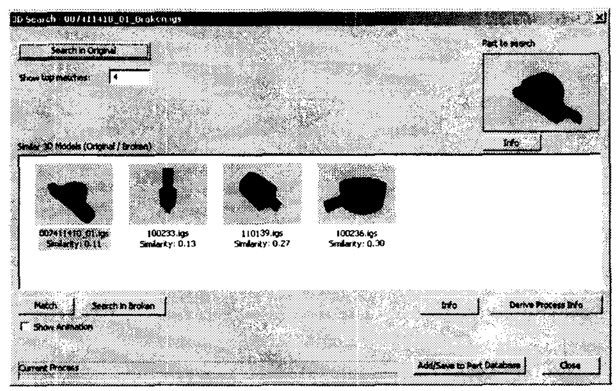

Fig. 6. Part databse

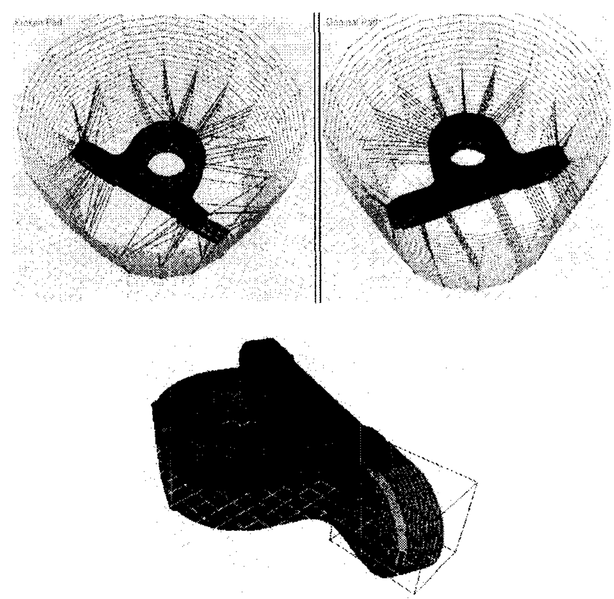

Fig. 7. Part matching

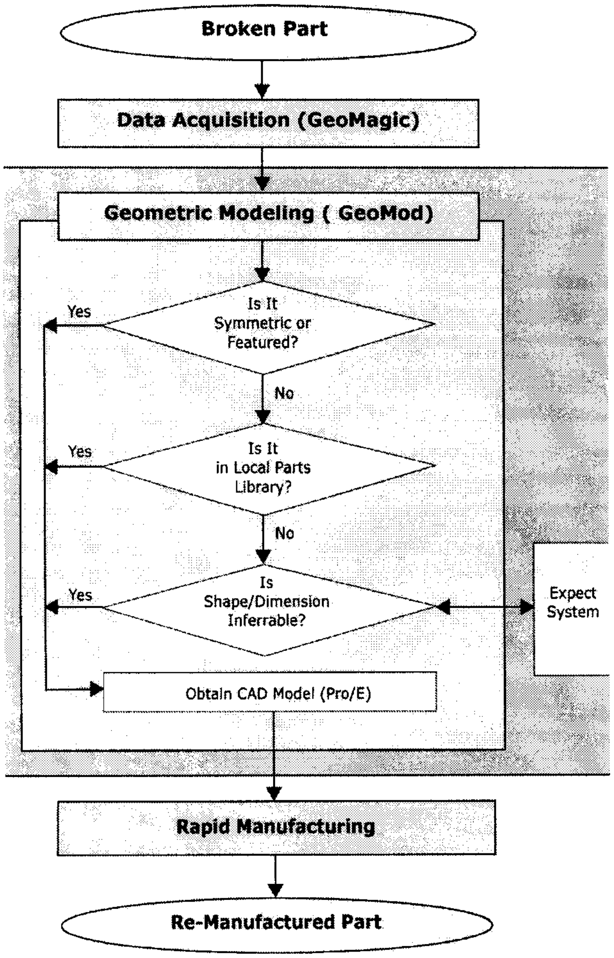

Fig. 8. Schematic repair operation.

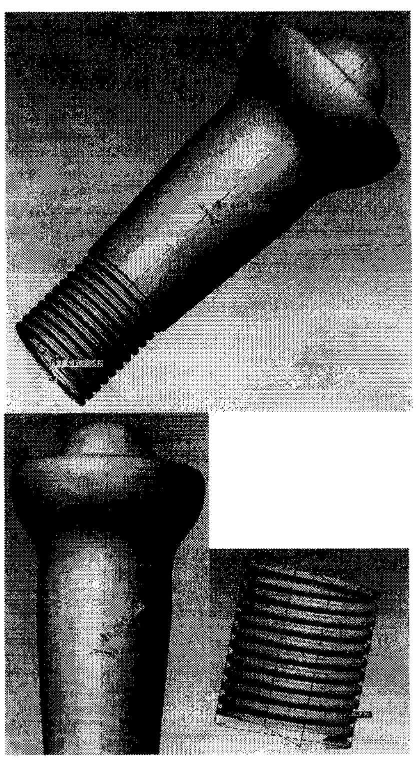

Fig. 9. Profile generation for a complex part

Fig. 8 presents the schematic view of the entire repair operation. Fig. 9 presents the profile generation operation for a complex geometry by this software. This information is very critical for bringing the component to the specification by machining. Besides, the expert system also develops a process layout based on the part information and knowledgebase which it continuously updates with each manufacturing event.

2.4 Case Studies

This section presents some examples of repair operations starting from a simple coating replacement to repair complex components. Many look at SFF technology as a curiosity that won't interest them until it provides materials identical to those they currently use with traditional fabrication techniques. They see it only as an alternative way to do the same things they have been doing. But our approach is to explore the functional uses of the current technology, i.e., to explore what is possible with new design freedoms. Fig. 10 presents a fuel filter water separator control mounting plate. It entailed removing the current cadmium plating and replace with zinc. The part was simply grit blasted to clean up. Sprayed with alternative zinc coating. The mounting holes were than re-tapped as required by the specifications.

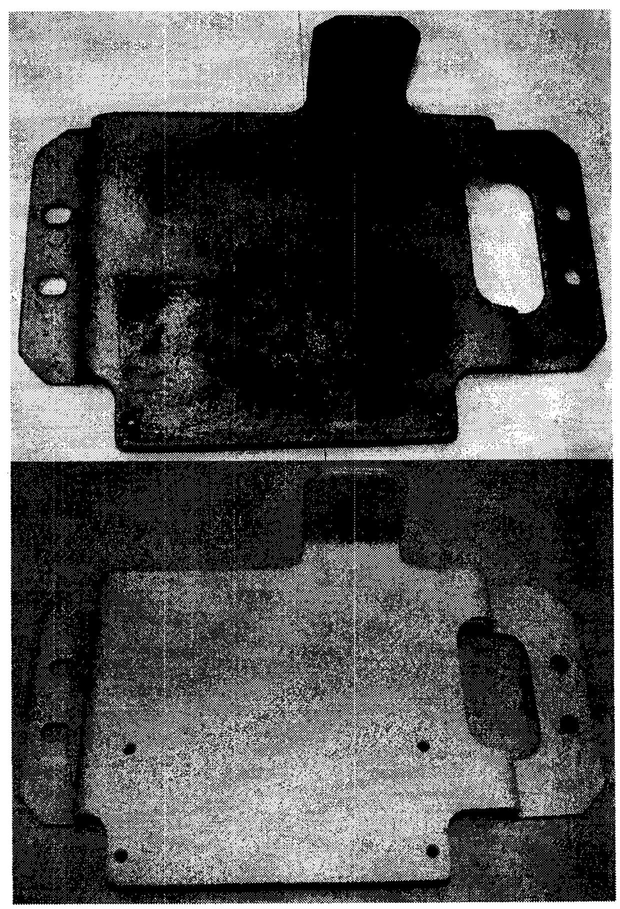

Fig. 10. Simple Cd replacement example

Fig. 11, presents a bearing retainer spacer. This part required both worn down ends to be repaired. This part required masking to avoid over spray on other surfaces and was grit blasted. One end was sprayed with the original silicon bronze and grinded to finish. The second surface is sprayed with molybdenum replacement which has excellent friction properties and can be easily sprayed. The surface finish was excellent and needed no machining. This demonstrates that it may be possible to spray a material with the same or superior properties with no secondary machining, resulting reduced processing steps and cost savings. The microstructure is presented in Fig. 12. It is observed that the coating was dense and oxide free.

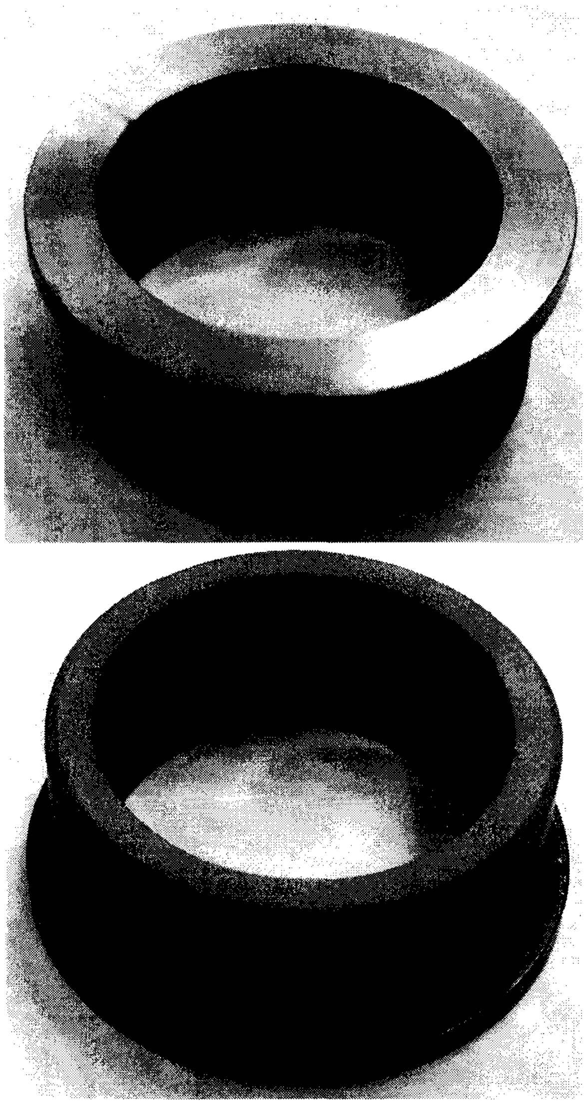

Fig. 11. (a) Silicon bronze and (b) Molybdenum

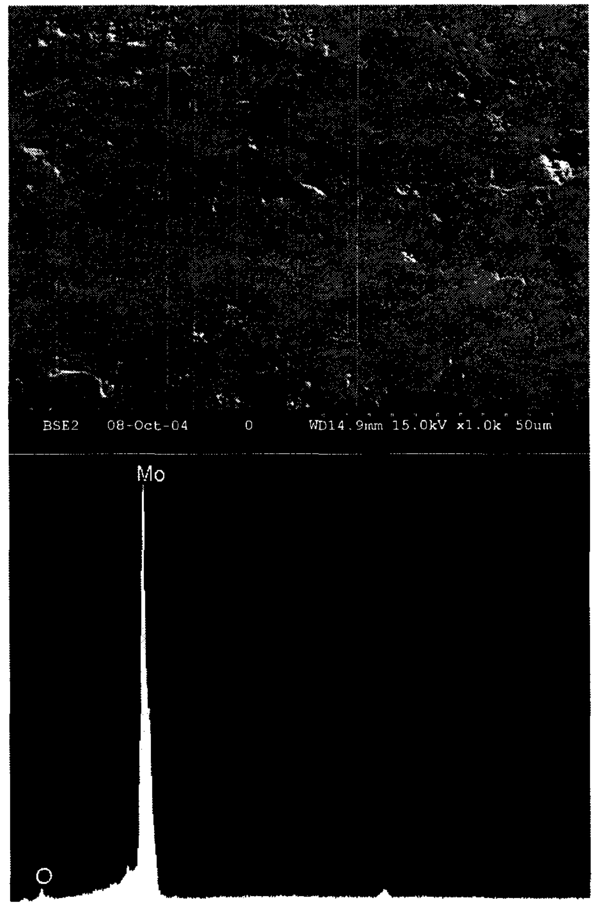

Fig. 12. Molybdenum coating

Fig. 13 is a quick disconnect splined adapter assembly. The original surface was flame or induction hardened to Rockwell C 45 minimum to a depth of .025 - .100 inches. This worn down part also required masking and had to be grit blasted. This surface was sprayed with a tungsten-chrome-nickel carbide and ground with a diamond wheel. The microstructure and chemical composition is shown in Fig. 14. The average hardness of the deposit was 1100 vickers.

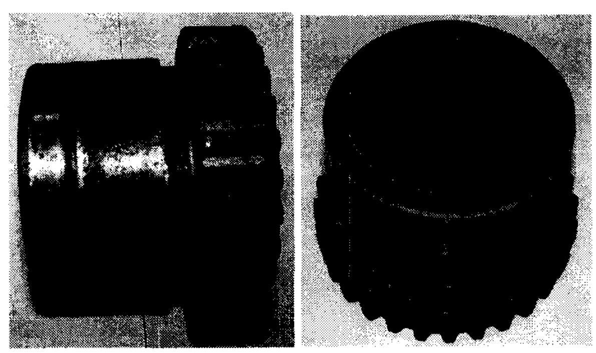

Fig. 13. Repair of wornout component

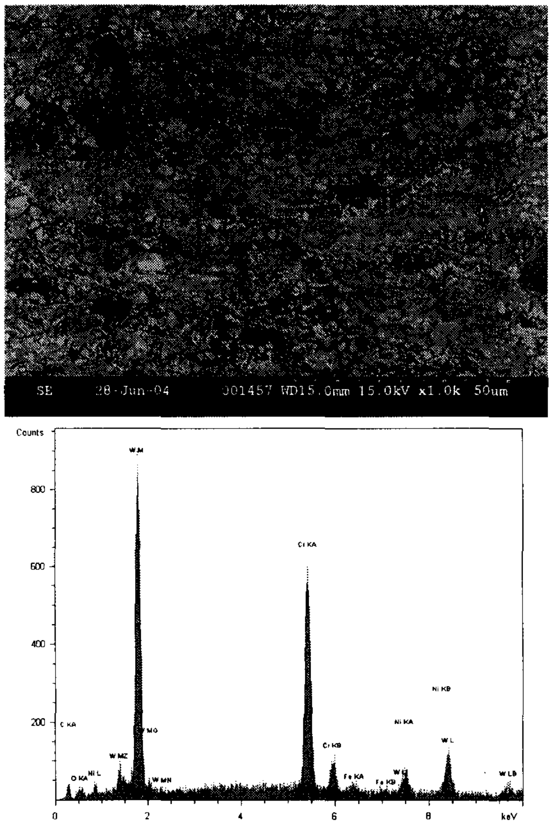

Fig. 14. Microstructure of the carbide deposit

The fourth example (Fig. 15) demonstrates the feasibility of rebuilding a complex spline. The original component is a forged and welded product. Here the material can be same as the original product or can be an alternative material for life enhancement such as amorphous steel.[9]

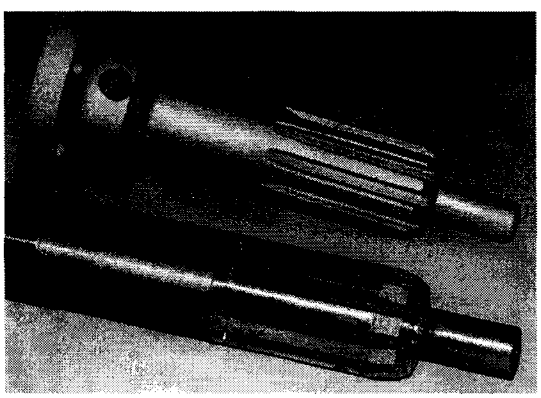

Fig. 15. Repaired spline.

3 Summary

It has been demonstrated that thermal spray can be a very powerfull technology for refurbishing operation for a variety of components. A multitude material can be deposited and often life extension can be enhanced. Operational cost reduction can be achieved through, waste cost elimination, raw material inventory cost reduction, skilled worker cost reduction, scrap cost reduction, tooling cost elimination, and set-up cost reduction. Repair cost is only one half of the financial equation for this technology, the other half is value - which is really just dislocated cost.[10] Being able to repair on demand parts and tools that will be needed at a moment's notice means the inventory necessary to satisfy immediate availability of seldom-used parts and tools is eliminated, and also means the obsolesence of inventory that is superceded by change orders or end-of-life is eliminated. Inventory costs go well beyond the carrying cost of producing a good and putting it on the shelf, it also includes the inventory system of people, storage space, and computer systems necessary to find that part and make it available on demand. And when these systems don't work perfectly, inventory is stored that is never found when needed, for which there have been plenty of real life well-known military examples that undoubtedly have their commercial equivalent in less visible corporate environments. And of course, all this can be achieved through continued research and development of the technology.

4 Literature

[1] N. P. PADTURE, M. GELL, and E. H. JORDAN: *Science*, 2002, **296**, 280-284.

[2] P. S. Mohanty, R. Allor, P. Lechowicz, R. Parker, and J. Craig, , Thermal Spray 2003, ASM, pp. 1183-1190.

[3] Gansert, R.V., R.Benary, C.C.Berndt, and H.Herman, "1994 Thermal Spray Industrial Applications", Ed. C.C.Berndt and S.Sampath, Pub. ASM International, Cleveland, OH-US, 1994, pp. 445/50.

[4] Vladimir, E. et. al., US Patent No. 5932293 (1999)

[5] . SAMPATH, X. JIANG, A. KULKARNI, J. MATEJICEK, D. L. GILMORE and R. A. NEISER: *Mater. Sci. Eng. A*, 2003, 348, (1-2), 54-66

[6] S. Hovik, Internation journal of Manufacturing technology.

[7] Model in Sherry' paper

[8] Sekou Singare, Li Dichen, Lu Bingheng, Liu Yanpu, Gong Zhenyu and Liu Yaxiong, *Medical Engineering & Physics, Volume 26, Issue 8, October 2004, Pages 671-676* "Design and fabrication of custom mandible titanium tray based on rapid prototyping"

[9] D.J. Branagan, et. al., Materials Transactions. 32A (2001) 2615

[10] Rick Dove: Delivering on the promise of those 'impossible' aims , Metal Powder Report, Volume *59, Issue 1, January 2004, Pages 28-32*

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