Application of Reverse Engineering in Manufacturing Industry

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ABSTRACT
This paper discusses the practice of reverse engineering that usually consists of two phases: (1) decoding the original design details with programmatic analysis, and (2) reproducing an "identical" counterpart. The most challenging technical tasks in both phases are directly related to manufacturing processes because the prior history or trails of many manufacturing processes are erased in the final product. Following a broad discussion on potential applications of reverse engineering and their potential benefits, this paper will focus on the technical challenges of applying reverse engineering in verifying and reinventing the part manufacturing process.

KEYWORDS
Reverse Engineering, Manufacturing, Materials, Processing, Imaging

INTRODUCTION

Reverse engineering is used to reinvent an existing part either due to lack of original design data or financially responding to market demands. Despite all its potential impacts, reverse engineering might be one of the most elusive engineering disciplines in modern technology. The Society of Manufacturing Engineers (SME) states that the practice of reverse engineering "*starting with a finished product or process and working backward in logical fashion to discover the underlying new technology*" [1] This statement highlights the two essences of reverse engineering practice: logical analysis and reinvention of new technology.

This paper will discuss the engineering challenges of applying reverse engineering in the manufacturing industry with possible solutions, and the potential benefits.

APPLICATIONS OF REVERSE ENGINEERING

To manufacture an ancient chariot today, reverse engineering might be the only option. However in many other occasions reverse engineering is also used for various reasons by manufacturers, inventors, and researchers. [2, 3, 4] For example, an engineer can first build a new truck model with clay that can be easily modified as needed, and then digitize this clay model for reverse engineering to turn the new design into a product much faster. The following is a list of some applications of reverse engineering that have been found to be very beneficial.

1. The original design data is not readily available, either due to part vintage, legal restriction, or trade secrecy.
2. The original manufacturer is out of business or does not produce the part any longer. This is a common dilemma in the aviation, automotive, and even home electronic product industries.
3. To repair a worn-out part without the original design data or any spare parts available, such as the engine cylinder head of an old piston engine used in crop-dusters.
4. To shorten the research and development cycle time for a new product based on an existing part. It is few and far between to introduce a brand new product from scratch into the market. More often than not, a new product is just a new model of an old one. The application of reverse engineering to the old base product using computer modeling with data input directly from 3D scanning, followed by digital prototyping with computer simulation can be very beneficial for new product design. Indeed, reverse engineering is not only used in the aftermarket to reinvent competitor's products, but also can be used by the original equipment manufacturer (OEM) for new product development.

5. To enhance customer communication with quick turn-around prototypes to meet customer's expectations. Another advantage of reverse engineering application in OEM manufacturing is that it allows engineers to quickly reiterate numerous versions of prototypes of a new product, one based on another, at relatively low costs to optimize the product and satisfy customer's requirements. For example, several iterations might be required to develop a new snow remover (even based on an existing old model) to meet customer's demands in vehicle mobility, stability and safety.
6. To analyze a competitor's part for business advantage. Reverse engineering contributes to a multi-billion-dollar spare parts aftermarket annually just in the aviation industry alone.
7. To study an existing part or machine for research or academic purposes. For example, to search for the optimal reinvention of an automotive truck to meet the ever rigorous emission standards, hundreds of parts and components that interact with one another might have to be studied for modification. Reverse engineering can significantly reduce the model building cycle, and drastically save prototyping costs by starting with an existing "obsolete non-compliant" model as a base to develop the new model.

VERIFICATION OF MANUFACTURING PARAMETERS

Heat Treatment

Modern analytical technologies such as quantitative metallography and residual stress measurement have made it relatively easier to reveal some prior history of a manufacturing process. Nonetheless verifying the complete manufacturing process of a part can still be a complex and somewhat "clueless" task, such as, the verification of the temperature, cycle, and time duration of a heat treatment process applied to an automotive part such as the brake disk.

One way to decode a heat treatment process by reverse engineering in manufacturing is to verify as many parameters as possible, and then select the best probable heat treatment process following the material specifications commonly used in the manufacturing industries. For example, refer to SAE International Aerospace Material Specification (AMS) 2759 series for heat treatment general guidance. When the part is further identified as a "precipitation-hardening corrosion-resistant and maraging steel part," then follow the specifications listed in AMS 2759/3. Follow AMS 2759/4 for an "austenitic corrosion-resistant steel part," or AMS 2759/5 for a "martensitic corrosion-resistant steel part" if the parts are identified as such.

To ensure the proper heat treatment process is used for the reproduction of a reverse engineered part, several post-heat treatment verification methods can be used. One of the most effective and convenient methods is to compare the microstructure between the original part and the reinvented part. If they show close similarity in grain size and morphology, chances are two reasonably similar heat treatment processes have been applied for these parts because the microstructure is heavily dependent on the heat treatment. However, the relationships between microstructure and heat treatment are too complicated to be comprehensively discussed here. More discussions and examples are presented at "*Material Identification and Process Verification*" in "*Reverse Engineering: Technology of Reinvention*." [2] Some simple tests on part properties such as hardness can be conducted as a basic evaluation to compare and assure the equivalence of these two parts. The engineer can further evaluate other material properties such as fatigue resistance, and some pertinent part functionality such as endurance, to assure the comparability between the original and reinvented parts.

Casting Process

Casting is one of the earliest manufacturing processes that has been used for thousands of years in human history. These processes, from early sand casting to modern-days precision investment casting, have been drastically improved with our better understanding of the science of thermodynamics and kinetics. Figure 1 illustrates a variety of parts manufactured by investment casting. However, the exact parameters of a casting process are as difficult to figure out by reverse engineering as those used in a heat treatment process, even the trails of solidification process, such as part microstructure and grain morphology can be distinctively identified in the finished product.

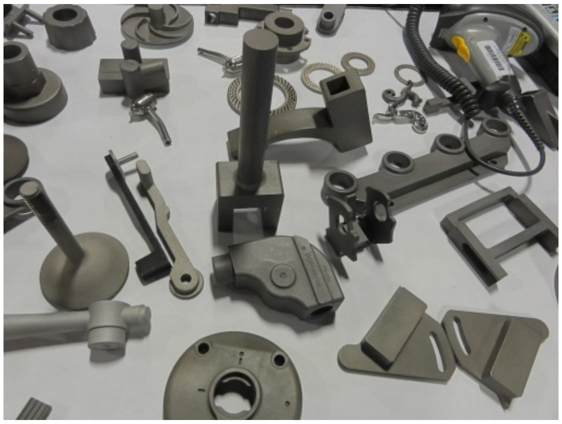


Figure 1. Various products manufactured by investment casting.

The kinetic and thermodynamic data pertinent to a casting process such as liquid density and viscosity are very material-specific. To accurately determine the values of these data, engineers have to identify the material type and its composition, that will be further discussed in the next section. Other parameters such as melt temperature and cast mold flow path are also critical to a casting process and are essential in reverse engineering to reinvent this process. The part microstructure can provide some hints of the melt temperature and the cast mold design by revealing the grain flow pattern, and grain morphology, such as grain size and its distribution. The primary dendrite arm spacing is a function of cooling rate that in turn depends on the casting process and can also provide a clue to reinvent the casting process.

The thermodynamic equilibrium phase diagram and the kinetic continuing cooling curves (also known as time-temperature-transformation, TTT, curves) along with the phases identified and their respective percentage present in the cast part can offer additional insight of the cast process used for the original part. Figure 2 [5] illustrates a typical Fe-C equilibrium phase diagram that shows the temperature and composition (carbon content in iron) relationship and different phases when the subject Fe-C system reaches its steady-state thermodynamic equilibrium. Though it will take forever to reach the steady thermodynamic equilibrium status and the equilibrium phase diagram is primarily based on theory; it does provide the foundation to better understand the phase formation in a cast part derived from the TTT curve. Equilibrium phase diagrams are often available in a reference handbook. However, a TTT curve might have to be established specifically for a reverse engineering project. A sample continuous cooling curve of iron-carbon alloy is illustrated in Figure 3 [6]. This figure shows the effects of cooling rates on cast part microstructure. Curve A represents a fast cooling rate. The part shows a mixture primarily of austenite and martensite phases. Curve B has a moderate cooling rate and the microstructure of the cast part will show austenite, ferrite, bainite and some martensite. Curve C has a slower cooing rate. The microstructure of the cast only shows a mix of austenite and ferrite, along with a trace of pearlite, but no martensite. These relationships between microstructure and the cooling rate showcase an analytical technique very effective in reverse engineering to reinvent the casting process of the original part. Figures 4(a), (b), (c) and (d) show the distinctive microstructural features of martensite, bainite, pearlite and a mix of ferrite and pearlite. [7, 8, 9, 10]

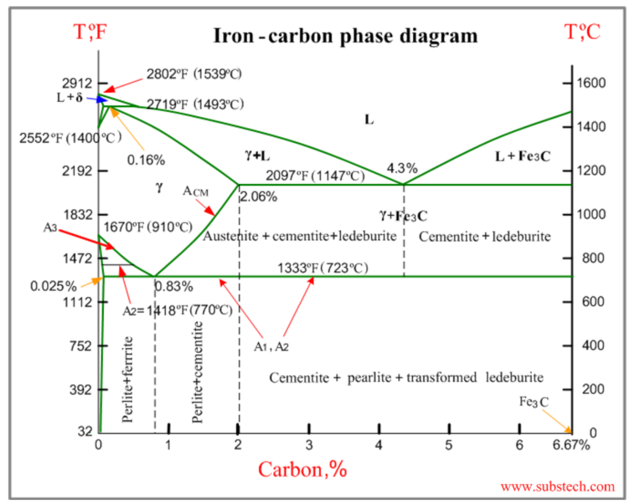


Figure 2. Fe-C equilibrium phase diagram. [5]

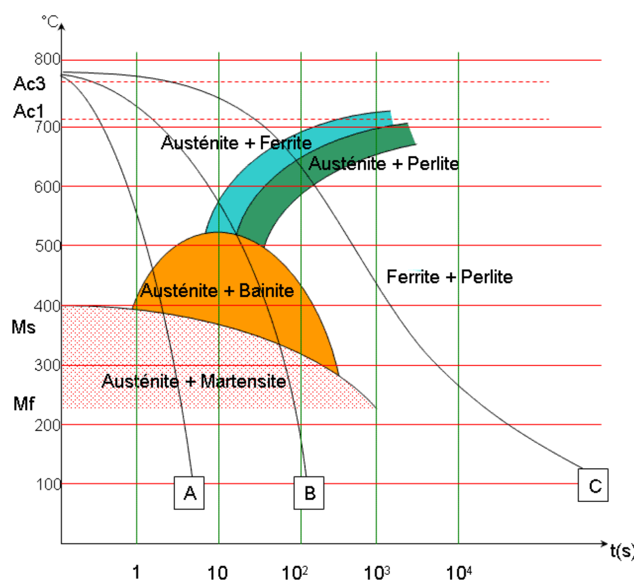
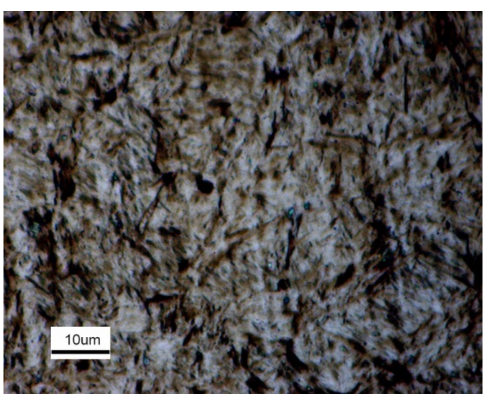


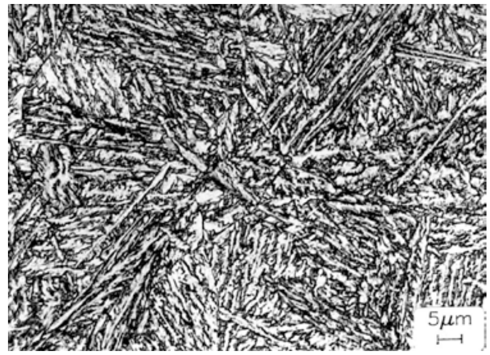
Figure 3. Continuous cooling curve. [6]

Reverse engineering a casting process can also be impeded by certain natural restraints. Engineering aluminum alloys such as 2024, 7075, and 6061 are widely used in many industries including aviation, automotive, and medical devices. The addition of lithium to a conventional 2024 aluminum alloy can improve its rigidity and tensile strength, while reducing its ductility and fracture toughness. Let's reverse engineer the casting process of a lithium-containing 2024 aluminum alloy. The composition of the final product will be different from the original ingot. The typical melting temperature of an aluminum alloy is approximately 660°C (1220°F), which is well above the melting temperature of lithium, around 180.5°C (356.9°F). As a result, the lithium content in the original ingot will be evaporated during the casting process at a temperature higher than 660°C (1220°F). The exact amount of lithium lost during this process depends on the melt temperature, casting process, and environment. The casting parameters can be well designed based on the expertise and experience of the original designer that needlessly to say are most probably not available to the engineers who are reverse engineering this process. How to reinvent these casting parameters can be a daunting task. This example highlights a unique feature of reverse engineering practice. What we see in the final cast is not necessarily what it was in the raw material. We have to rely on engineers' experience and specialized expertise to overcome this hurdle

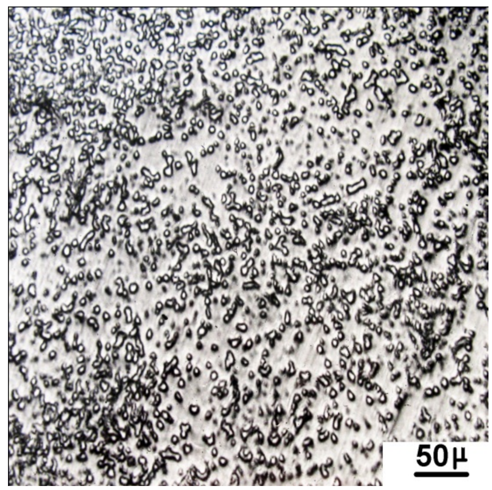
This leads to another technical challenge: how to identify the material chemical composition of a part with certainty, a 100 percent certainty if possible.



(a) Martensite



(b) Bainite



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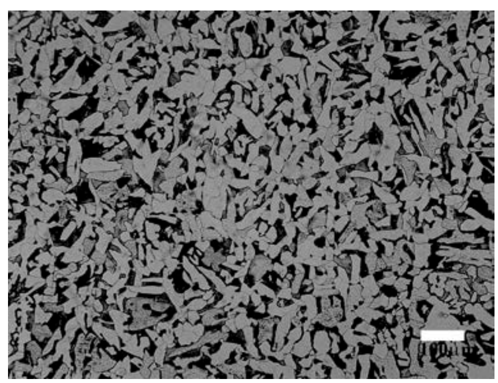
(d) Ferrite-pearlite mix

Figure 4. Microstructure of (a) martensite [7], (b) bainite [8], (c) pearlite [9], and (d) ferrite-pearlite mix [10].

Material Identification

To reinvent a part by reverse engineering, we have to identify the material the part is made of before it can be reproduced. However, we can never identify the material chemical composition with 100 percent certainty because of the Second Law of

Thermodynamics. It states that any system, the material in this case, will have the tendency to reach the status of maximum randomness. In other words, whenever any impurity appears in the proximity of this material, the material will have the tendency to mix the impurity into its composition in accordance with the Second Law of Thermodynamics to reach its equilibrium status. During any manufacturing process, no matter casting, forging or extrusion, the material will have many unexpected impurities present in the surrounding environment or introduced from the instruments and facilities. The impurity contents in the final product will never be the "same" as the original raw material.

The challenge of precisely defining the chemical composition of a material is also reflected in the material specifications. For example, SAE AMS 4120 lists the nominal chemical composition of a typical 2024 aluminum alloy as Al-4.4Cu-1.5Mg-0.60Mn by weight percentage; while allowing a range of composition variations from a minimum of 3.8% to a maximum of 4.9% for copper, 1.2% to 1.8% for magnesium, and 0.3% to 0.9% for manganese. It also allows a maximum content of iron, silicon, zinc, titanium, chromium up to 0.50%, 0.50%, 0.25%, 0.15%, and 0.10%, respectively. These alloying elements are added into the base alloy by design to improve specific properties of the engineering alloy 2024 that is widely used in many manufacturing industries for aircraft frames and other light-weight load-bearing machine structures. To be consistent with the pertinent laws of nature and acknowledge the inaccuracy of analyses, the AMS 4120 specification allows for other elements provided each of them is less than 0.05% and the total amount is less than 0.15%. Unfortunately some undesirable impurities such as calcium or sodium might present in 2024 aluminum alloy as well.

The challenges of identifying a 2024 aluminum alloy using reverse engineering are multifold. First, the engineer has to determine the weight percentage of the primary constituents such as copper, magnesium and manganese. This task is accomplishable in light of the "reasonable" range of composition variations. The task becomes more challenging to quantitatively verify the elements with relatively small percentage such as titanium and chromium, etc. It is worth noting that a tiny variation of some alloying elements sometimes can have a significant impact on the alloy properties that could lead to its rejection. The most difficult challenge is to determine what and how much of the impurity contents are present to show the equivalence between a reinvented part by reverse engineering and the OEM part, that are functions of ingot source, material handling and manufacturing process.

The best practice of reverse engineering an engineering alloy is to collect as much analytical data as possible, and then verify the conclusion with supporting test data such as microstructure, tensile, or fatigue properties.

Geometric Shape and Form

The re-creation of external geometric shape and internal details is essential to reverse engineer any mechanical part. Compared to material process verification and material composition identification, the part's dimensional conformity is relatively easier to accomplish because of the advancement of modern metrology in recent decades.

Three techniques are usually applied to collect the geometrical and dimensional information of a part in reverse engineering: direct-contact probing, non-contact scanning, or 3D imaging. A Coordinate Measuring Machine (CMM) is a device used for dimensional data acquisition with direct-contact probe or non-contact scanning. These CMMs can be operated either manually or by direct computer control; and are equipped with various styli. The data collected by direct contact are more accurate, while non-contact scanning can speed up the process and obtain a lot of data in a short period of time. Figure 5 shows a CMM collecting part dimensional data with a direct contact stylus.

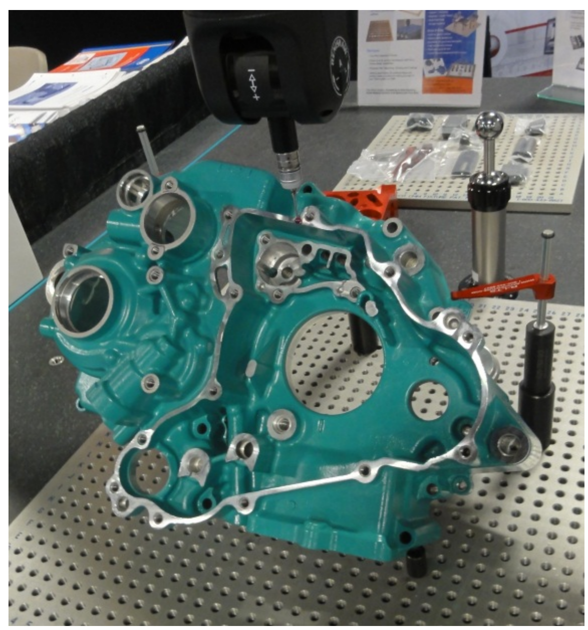

Figure 5. A CMM collecting part dimensional data with a direct contact stylus.

Both laser technology and optical measuring technology are used for part scanning and imaging with a wide spectrum of accuracy, and functional capability. Depending on the device, only incomplete data might be collected with **limited** scanning passes, as illustrated in Figure 6. It is critical to use a proper scanning device with appropriate imaging capability to assure sufficient data collection for later solid modeling and simulation.

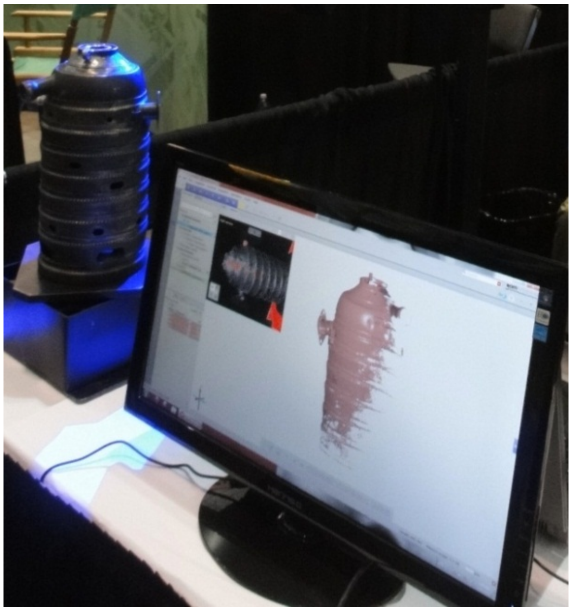

Figure 6. Scanning image.

A 3D imager is a non-contact measurement device that applies structured light projections with the principles of interferometry to collect part surface information for reconstruction. Two interferometric imagers are shown in Figure 7(a) and (b), respectively. Projected fringe patterns form a laser projector are captured by a camera as illustrated in Figure 7(a). Two cameras, one on each side, are installed in the imager shown in Figure 7(b), where optical fringe patterns are projected from the middle between these two cameras. The coordinates of the discrete pixel from the images caught in the camera(s) are calculated to generate a continuous polygon mesh of the subject's topographical surface. These data can be used for image reconstruction, or further processed and transformed to an STereoLithography (STL, also known as Standard Tessellation Language) data set, then subsequently used for solid molding or rapid prototyping production.

(a) 3D imaging with projected laser fringes

(b) 3D optical imager with two cameras

Figure 7. Interferometric imaging, (a) 3D imaging with projected laser fringes, and (b) 3D imager with two cameras.

Conclusion

The two primary objectives of applying reverse engineering in manufacturing are to reinvent a part for market competition or for part restoration. Technically both these objectives heavily rely on the success of three key elements: material composition identification, part dimension determination, and manufacturing process verification. Material composition identification with 100% certainty is beyond our reach; however, most of the time engineers can determine the material composition with reasonable acceptance from a manufacturing perspective. Part dimensional data can usually be precisely regenerated with advanced modern metrology. The most challenging task is to verify the detailed manufacturing parameters. Until more precise instruments become available to better decode the prior manufacturing process, the best practice is to demonstrate that the reinvented part has equivalent part functionality and performance. The conformity of part functionality and performance can be appropriately evaluated with proper tests and analyses.

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