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# Development of the Pre-placed powder based Rapid Tooling System

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***Abstract***: Rapid prototyping (RP) is a technology that uses layer additive concept to build 3D parts. Rapid tooling (RT) technology is a natural extension of RP. RT can be used to produce temporary molds as well as per manent molds in mass production. RT provides more benefits from the design stage to mass production.

This research has developed a pre-placed metallic powder based rapid tooling system. The hardware architecture (a 2.5KW Nd-YAG laser system, a pre-placed powder mechanism, a linear planar motor based working table, and a shielding gas supply system) have been introduced respectively. After finding out the suitable processin g parameters, some metallic RT parts were manufactured with the proposed RT system. The experimental results demonstrate that the developed RT system could fabricate metallic prototype or functional parts.

***Keywords***: Rapid prototyping, Rapid tooling, pre-placed metallic powder, Nd-YAG laser, functional parts.

## I. INTRODUCTION

Rapid Prototyping technologies had provided a method of making models or visual prototypes quickly, but there was demand from industry for quicker ways of making technical prototypes, manufactured in the correct material using the appropriate production method. Rapid Prototyping technologies have introduced a new generation of Rapid Tooling processes. Rapid Tooling technologies offered a potential solution to this problem, by supplying the master pattern from which rapid tools could be generated and also by the opportunity to manufacture both prototype and production tools directly. Producing tooling directly from CAD models is regarded as an important process of reducing the cost and time to market for new products.

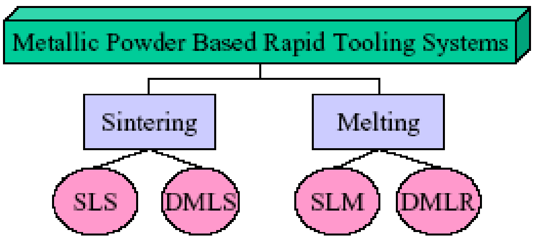


Fig. 1 Classification of metallic powder based rapid tooling technologies

At present, there are more than 20 different metallic powder based rapid tooling processes that have been invented by commercial corporations or academic organizations. In Fig. 1, some main pre-placed metallic powder based processes are introduced.

Sintering is the basic method used in building desired part from the proprietary powdered metals layer by layer. In rapid tooling technologies, it usually utilizes $CO_2$ or Nd-YAG laser as a heat source to sinter the powders. When the laser beam is scanned over the powder bed, the lower melting point component is liquefied by the laser induced energy, while the other components remain solid. The liquid lower melting point component wets the high melting part of the powder which makes a strong bonding after cooling.

Direct Rapid Tooling systems which can produce metallic parts directly from powders have come to the market very soon. Selective Laser Sintering (SLS) [1] was first invented at the University of Texas at Austin and the process was commercialized by two companies, DTM Corporation and EOS GmbH. This process utilizes $CO_2$ laser beam either in continuous or pulse mode as a heat source to scan and join powders in predetermined sizes and shapes of layers. First, this process uses a flat sheet of powder heated to close to its melting point. The $CO_2$ laser beam scans over the powders and heats them so that they melt on the outside and stick together (sinter). Then the base plate moves down slightly one layer thickness and the next layer of powder is spread across the surface by a roller. The marked character of SLS process is that the object is supported as it is made by the tightly packed un-sintered powder so it does not need extra supporting mechanism.

Direct Metal Laser Sintering (DMLS) [2-3] is also a laser-based rapid tooling and manufacturing process developed in cooperation by Rapid Product Innovations (formerly Electrolux Rapid Development, Rusko, Finland) and EOS GmbH. The basic principle is similar to SLS process and it fabricates true net-shape metal parts directly in a single process. This is done by using higher power laser to sinter special *non-shrinking* steel or bronze-based metal powders layer by layer. The idea of the DMLS process is based on a patented, non-shrinking bronze powder mix and the next major step was to use steel-based powder material. However, the metallic parts made by the SLS or DMLS processes do not have enough strength and density to be used as dies and tools for metal forming.

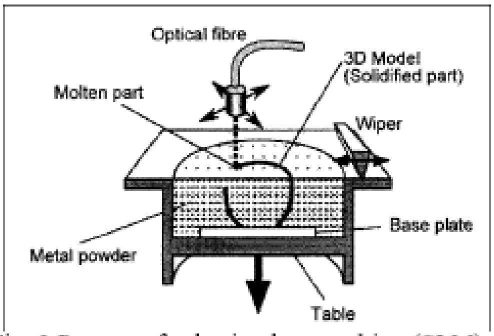


Fig. 2 Process of selective laser melting (SLM)

In order to make strong metallic parts directly from metallic powders, F. Abe et al. [4] proposed a new forming method, Selective Laser Melting (SLM), in which the metallic powders are completely melted without retaining much porosity. The concept of the proposed selective laser melting process is shown in Fig. 2. In this process, metallic powders are successively melted by laser energy, differently from SLS in which only a part of the powders are melted. Since volume change during melting and rapid solidification during cooling, the undesired thermal stress occurred in the RT parts. The deflection and cracking are caused in the product by rapid heating and quenching. To solve the problems, the dual laser scanning system improves the ductility of the formed material when the part melted and solidified by YAG laser is reheated by $CO_2$ laser with an appropriate time delay [5].

Direct Metal Laser Re-melting (DMLR) [6-8] is a rapid prototyping process based on selective laser sintering. Unlike SLS process, DMLR process uses a higher power (90W) Nd-YAG laser to fully melt the metal powder bed. Nd-YAG laser is advantageous because shorter wavelength radiation (1.064 $\mu$ m) couples more efficiently with metals, compared to $CO_2$ laser radiation (10.64 $\mu$ m). DMLR was developed to address some of the shortcomings of the SLS process. It avoids the use of binders to bond the metal powders together and the furnace sintering of the final components. It also overcomes the maximum density limit of 63 percent (in SLS process) and the need for a further infiltration process to reach full density.

## II. Hardware of the Pre-placed powder based Rapid Tooling system

The hardware architecture of the pre-placed powder based RT system is shown in Fig. 3. The 500W CW (Continuous wave) Nd-YAG laser, which is transferred through the optical fiber, is focused to melt the metallic powder on the pre-placed powder mechanism. The pre-placed powder mechanism is placed on the linear planar motor based XY table, and the laser head is mounted on the Z axis elevator. After fabricating one layer, the RT forming trough of the powder mechanism will descend one layer thickness and the powder feeding trough will ascend one layer thickness at the same time. Then the flat scraper will move from left to right, so that the powder placed on the top of RT forming trough is flat. The next layer of powder is laid and the scanning by Nd-YAG laser is repeated. Layer after layer, the metallic powders are added and melted until the whole RT part is completed.

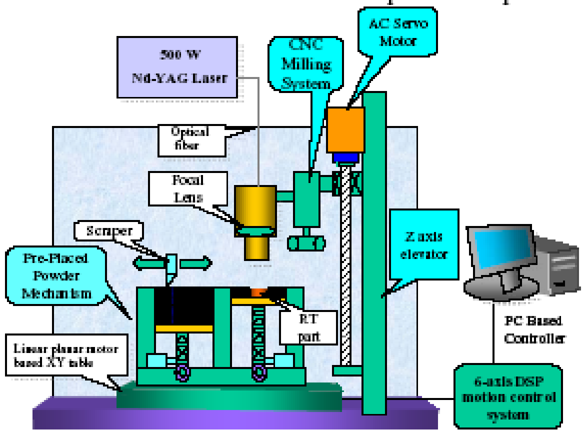


Fig. 3 The pre-placed powder based RT system

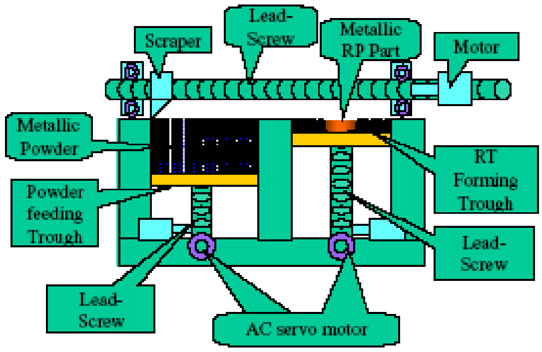


Fig.4 Pre-placed powder mechanism

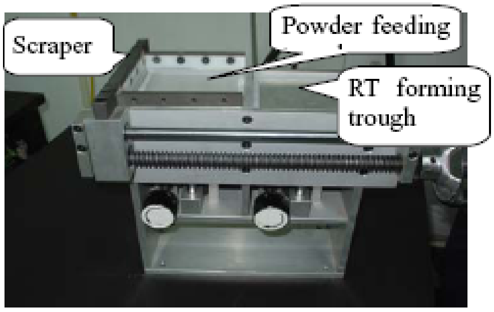


Fig.5 Photo of the pre-placed powder mechanism

The architecture of the pre-placed powder mechanism is shown as Fig.4. The architecture includes three parts: powder feeding trough, RT forming trough and scraper. The powder feeding trough and RT forming trough are driven by two AC servo motors and the flat scraper is driven by a DC motor. The powder feeding trough stores the metallic powder for manufacturing the RT part. Initially, the powder bed of the powder feeding trough will raise one layer thickness and the RT forming trough will descend one layer thickness simultaneously. Then, the scraper will wipe from left to right so that the metallic powder is placed smoothly on the top of RT forming trough. Fig.5 is the photo of the pre-placed powder mechanism.

## III. Critical Parameters influencing the quality of the Pre-placed powder based RT parts

This section discusses the processing parameters of the proposed system. The processing parameters in this research include laser power, laser spot size, pre-placed layer thickness, traverse speed of X-Y table and offset distance of tool paths as shown in Fig. 6.

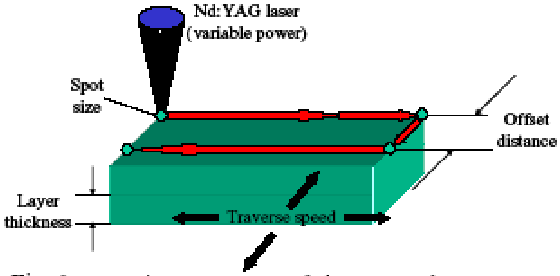


Fig. 6 Processing parameters of the proposed RT system

The surface quality is an important forming characterization for Rapid Tooling manufacturing process. From experiments, it can be found that the oxidation is the main factor to affect the surface quality of the RT parts. These oxides make great harm not only to the properties of the components but also the surface quality. Since the absorption of metal and oxides were different, the melt pool was unstable with different absorption, i.e. the shape and dimension of the melt pool will vary from time to time. The shielding gas (Ar or $N_2$) was used to prevent melted clad from oxidation, but it is difficult to completely avoid the oxidation in the air. Maybe these experiments could be taken in the atmosphere of inactive gas, such as argon or helium, to eliminate the oxidation.

To get better surface quality, we will make some experiments to determine the suitable processing parameters. As shown in Table 1, the process parameters in the proposed pre-placed powder based RT system are laser power (P) , scanning velocity (V), layer thickness of pre-placed powder (t), diameter of laser spot (d) and tool path offset distance. Other parameters like metallic powder (Colmonoy 69SC), substrate (S45C) and the shielding gas (Ar) are kept constant in this study.

Table 1 The process parameters in the pre-placed powder based RT system

| Laser power (W) | Scanning velocity (mm/min) | layer thickness of pre-placed powder (mm) | Diameter of laser spot (mm) | Tool path offset distance (mm) |
|---|---|---|---|---|
| 600 | 300 | 0.25 | 1 | 0.25 |
| 900 | 750 | 0.50 | 2 | 0.5 |
| | | | | 0.75 |

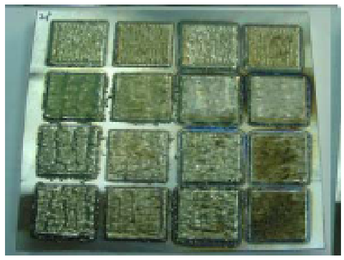

Fig. 7 The experimental results with single layered square shape for determining the surface roughness

The surface roughness is an important issue in the surface quality. The surface roughness is measured using a surface roughness measurement tester. According to the processing parameters in Table 1, the proposed pre-placed powder based RT system made many single layer RT parts with square shape for determining the surface roughness. We totally make 48 single layer RT parts with square shape. Fig. 7 is part of the experimental results. The processing parameters listed in Table 2 can make good quality RT part with better surface roughness and faster manufacturing speed. Although the surface roughness of the tested parts fabricated with the processing parameters listed in Table 2 is not the best, the scanning velocity of the tested parts is high enough to reduce the fabrication time.

Table 2 Processing parameters for fabricating good quality RT part with better surface roughness and faster manufacturing speed.

| No. | Laser power (W) | Scanning velocity (mm/min) | Layer thickness (mm) | Diameter of laser spot (mm) | Tool path offset distance (mm) | Surface roughness (Rq) |
|---|---|---|---|---|---|---|
| 4 | 900 | 750 | 0.25 | 1 | 0.25 | 4 |

## IV. Experimental results of the Pre-placed powder based RT System

After finding out the suitable processing parameters, we will make some RT parts with the pre-placed powder based RT system. First, the RT software reads the STL file and proceeds the slicing process. After finishing the slicing process, the RT software continues to generate the tool path and then save as a tool path text file. The tool path text file is then transferred to the PC based motion controller which can control the X-Y table to move with the tool path. After generating the tool path, we can fabricate some RT parts on the proposed pre-placed powder based RT machine. The experimental results are shown as follows.

### 1. 2.5D RT parts

In this section, a complicated 2.5D RT part will be fabricated by the proposed pre-placed powder based RT system.

Fig. 8 (a) is the CAD model of the GEAR. Fig. 8 (b) is the tool path of the GEAR. The metallic GEAR part is fabricated as shown in Fig.8 (c). After grinding the top surface of the RT parts, the finished GEAR part is shown in Fig. 8 (d).

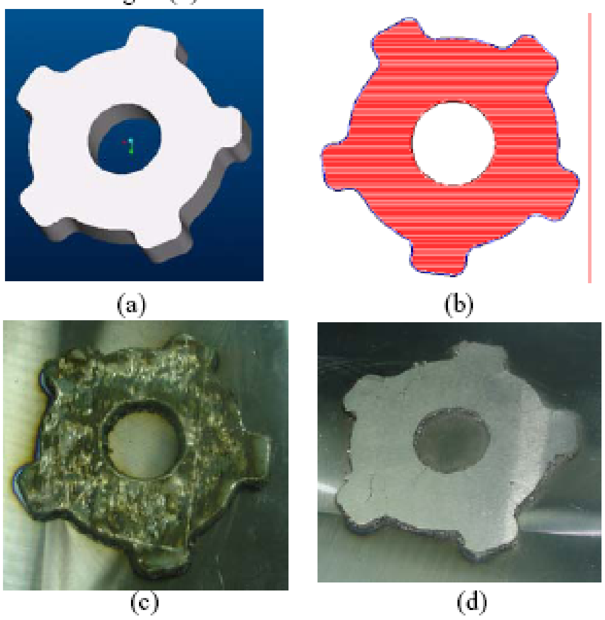


Fig. 8 (a) The CAD model of the GEAR; (b) Tool path of the GEAR; (c) The fabricated GEAR part; (d) The finished GEAR part after grinding.

**2. Metallic 3D RT part**

The metallic 3D RT parts can be fabricated by the proposed pre-placed powder based RT system. As shown in Fig. 9, the "Half ball" model was used again in this pre-placed powder based RT system. The metallic "Half ball" is fabricated as shown in Fig. 9. Another fabricated RT part by the proposed pre-placed powder based RT system was shown in Fig. 10. These parts may still need some post-processing, such as milling or grinding, to get smooth outer surface.

Fig. 9. The fabricated metallic Half ball part by the proposed pre-placed powder based RT system.

Fig. 10. Another fabricated RT part by the proposed pre-placed powder based RT system.

## V. CONCLUSION

This research has developed a pre-placed metallic powder based rapid tooling system. The hardware architecture (a 2.5KW Nd-YAG laser system, a pre-placed powder mechanism, a linear planar motor based working table, and a shielding gas supply system) have been introduced respectively.

Some experiments were carried out for tuning the process parameters on the proposed RT system. After finding out the suitable processing parameters, some metallic RT parts were manufactured with the pre-placed powder based RT system. The experimental results demonstrate that the developed RT system could fabricate metallic prototype or functional parts.

This research shows the potential to fabricate functional parts or molds directly and quickly from the pre-placed metallic powder based rapid tooling system. The further research is to do more experiments to improve the RT system and build molds with better quality.

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