Rocket Engine Made by Additive Manufacturing

A method for manufacturing rocket engine components using additive manufacturing, one of the most advanced monozukuri technologies, has been developed

Additive manufacturing is rapidly advancing in technology and often heard on the news in recent years.
Using this technology capable of making metal components of any shape in a sense, IHI will innovate the method for manufacturing rocket engines, one of the most hard-to-realize industrial products.

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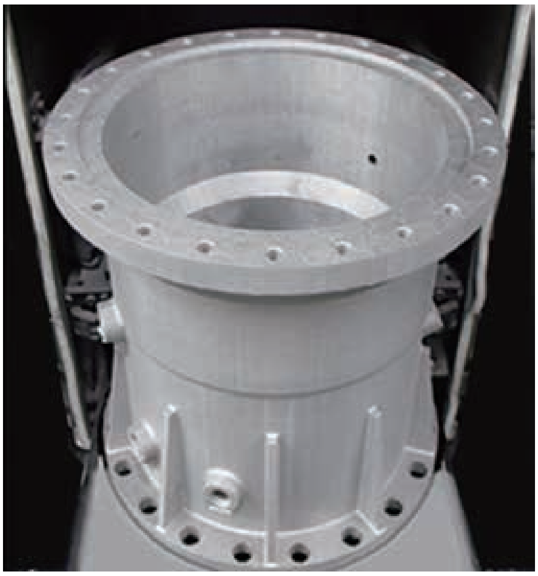


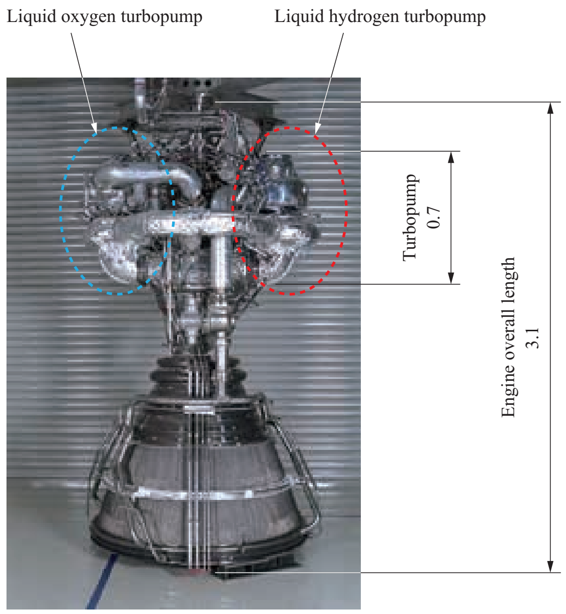

Rocket engine component manufactured by additive manufacturing

Liquid rocket engine and turbopump

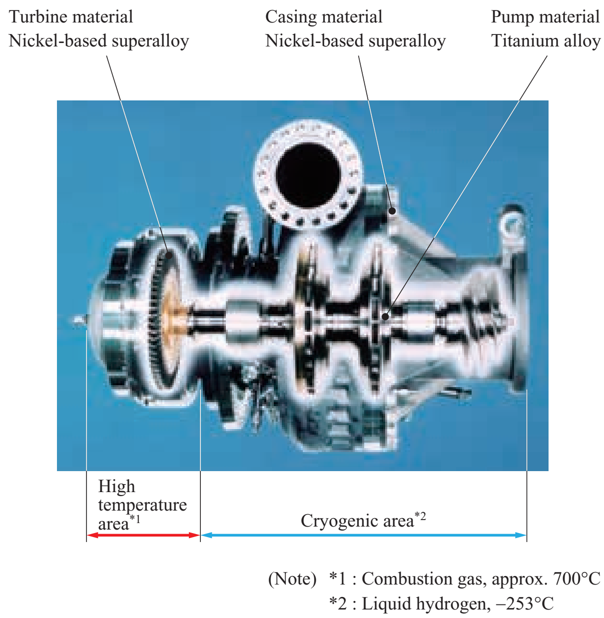
A liquid rocket engine usually incorporates a high-speed rotating pump called a turbopump, because this engine system has an advantage of reducing the structural mass of an entire rocket.

The function of a turbopump is to raise the pressure of a propellant inside a tank to feed it into an engine's combustion chamber by driving a turbine by some means such as using combustion gas, and the turbopump has some big features due to its peculiarity.

Taking the first stage engine LE-7A of the H-IIA Japanese rocket as an example, the turbopump is required to raise the discharge pressure of liquid hydrogen to approximately 28 MPa at a rate of as much as approximately 530 *l*/s, which corresponds to approximately 20 MW as a power output. On the other hand, the very severe requirements to save the weight, which is directly connected to the launch capability of the rocket makes the mass of a structure for obtaining



Rocket engine (LE-7A) (unit: m) ©JAXA



Cross-sectional view of turbopump and materials ©JAXA

such high flow rate, high pressure, and high power output to be limited to as low as 200 kg. For this reason, the energy density of the turbopump machinery is inevitably increased to an extreme.

In addition, the turbopump contains the liquid hydrogen that is cryogenic fluid having a temperature of –253°C as a propellant, whereas the temperature of the combustion gas for driving the turbine is approximately 700°C, so the maximum temperature difference in the turbopump reaches as high as 950°C.

Meanwhile, a required lifetime is very short, and in the case of a turbopump for the expendable rocket, the operating time is approximately 400 seconds. Even a lifetime to be verified in a development test is only approximately 2 000 seconds.

The turbopump is a high-speed rotating machinery carrying the function of converting the enormous energy of the combustion gas into the pressure rise of the propellant in a very short time of 400 seconds under an extreme environment, and the term “limit design” literally applies to structural components used in the turbopump. This article focusses on the additive manufacturing based manufacturing of this turbopump which has been developed by IHI for Japanese rocket engine for many years.

Conventional manufacturing method

The cross-sectional view and materials of the turbopump used are illustrated in the upper right. As materials for the turbopump components so far developed by IHI, a nickel-based super alloy and a titanium alloy are mainly used because they are resistant to both high temperature and cryogenic condition in order to withstand severe environment.

Two manufacturing methods are mainly used, i.e., one is to machine a metal block called forging stock to a necessary shape, and the other is to cool and solidify molten metal in a specific shape mold, called casting.

However, in the case of the machining method, a desired shape cannot be formed if a component has an area not reached by a cutting tool. In the case of the casting method, it is also very difficult to obtain a metal component with a desired shape if a component has a complicated shape, especially the inside of a component.

For this reason, a final component shape is determined by trial and error on the assumption of “being able to make” considering to the strength requirements to be satisfied as a structural component. However, a designer cannot help but give up many desirable shapes due to limitations on the manufacturing method. Speaking of extremes, it is no exaggeration to say that a turbopump component has a shape finally obtained as a result of a series of compromises between design requirements and manufacturing limitations. What is expected to break through such a situation is the additive manufacturing.

Features of additive manufacturing

The additive manufacturing cannot be referred to as a single group, but include many types. For metal precision components, a type called powder bed fusion is often employed in terms of manufacturing accuracy. As illustrated in the image on the next page, the powder bed fusion is a technique, which sequentially includes the steps of forming a very thin layer of metal powder having a thickness of a few tens of micrometers, irradiating a relevant cross-sectional shape portion of the layer with laser light to instantaneously melt and resolidify it, and repeating the previous steps to stack the resulting single metal layer to the height of the component.

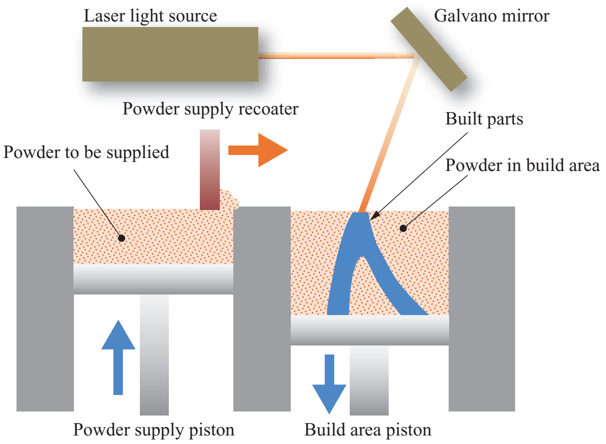


Image of additive manufacturing machine (powder-bed fusion type)

The manufacturing method of the additive manufacturing has mainly three non-conventional features shown as following;

① High freedom for manufacturing

Since the cross-sectional shape of any component can be defined when cutting the component along a certain surface, by forming a thin cross-sectional shape one by one layer, any complicated shape can be manufactured in principle. For example, any shapes such as a hollow structure can be manufactured, which have been impossible by a conventional method.

② Low manufacturing cost for low volume production

Since the additive manufacturing uses only a needed amount of material (metal powder) for making a component itself, no machining dust is wasted and no disposable mold is required. As a result, even when manufacturing only one component, the manufacturing cost is almost the same as that for mass production.

③ Short manufacturing period

Since no work (such as obtaining a metal block and making a mold) is not necessary to be prepared in advance, a period to manufacture a first component, for which the conventional manufacturing method usually requires one year or at least half a year, can be dramatically shortened to, for example, approximately one week.

Although only the above three features can make the additive manufacturing very attractive, this method additionally would have a feature of free control of metal structure, which allows the additive manufacturing to have infinite possibilities.

Regarding conventional metal materials, since that is formed by heating a metal material to soften and forge or by melting a metal material to pour it into a mold, and then cool the molten metal material to solidify it, it is difficult to make an ideal metallographic structure determined by a cooling rate and other factors, and one metal component has only the same metallographic structure. On the other hand, regarding the additive manufacturing, since metal powder is melted and solidified within a small region repeatedly layer by layer, the phenomenon where metal is solidified within a narrow area can be well controlled by manufacturing conditions. Further, by controlling different metal powders used, a dream metal component, which is made of different kind of metals, can also be made.

Application to rocket engines

As described above, since rocket engine components are used in extremely severe environment, limit design is performed but, on the other hand, a final shape is determined as a result of a series of compromises because of the limitations on the conventional manufacturing method.

Using the additive manufacturing to eliminate the limitations means that a complicated shape, which is abandoned by a conventional method, can be designed. In other words, the ultimate design becomes possible for reducing weight to the limit simultaneously with withstanding extreme environment.

In addition, the advantage of being able to dramatically shorten a manufacturing period as well as to reduce manufacturing cost can be great advantage. Although the development of one type of engine needs at least five years currently, the shortening of an engine development period less than one year comes into view if a component can be made by the additive manufacturing in a week.

Make actual rocket component by additive manufacturing

The additive manufacturing has possibility to bring about innovative progress in component design and development period. However, unfortunately, anyone can not always manufacture a desired metal component, which should satisfy extremely severe requirements such as those for rocket engines, even if an additive manufacturing machine is just purchased and operated. So, in order to handle the additive manufacturing machine well for rocket engine component, there are many items to be technically understood.

For example, in the case of the additive manufacturing, as the size of a component increases, more residual stress with heat accumulation resulting from laser irradiation easily cause deformation, so in order to make a highly accurate component, it is necessary to suppress such deformation behavior. For this reason, many additive manufacturing metal components currently manufactured in the world are limited to small components having a size of 100 mm or less.

On the other hand, turbopump components have sizes of 500 mm or more, so manufacturing such large components with satisfying severe requirements for size and strength is a big challenge for the additive manufacturing. Therefore, IHI has repeatedly made various prototypes, and accumulated many pieces of knowledge on how to satisfy requirements. Illustrated on the right are images of an evaluation example obtained as a result of detailed evaluation of components manufactured by the additive manufacturing. Consequently, IHI has confirmed that even a large-sized component is possible to manufacture, like a component having a size up to 500 mm. The results of prototype evaluation so far have revealed that both manufacturing cost and prototyping period can be potentially considerably reduced as compared with conventional process, and the advantages of the additive manufacturing can be utilized to the maximum extent.

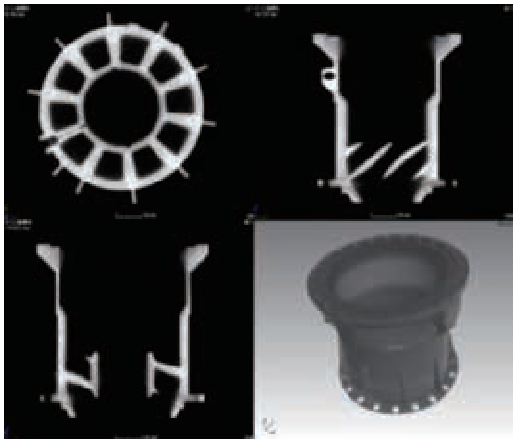
In terms of ensuring the quality of a manufactured component, IHI is proceeding the additive manufacturing process development. For example, IHI evaluates the effect of metal powder as a raw material on the component quality, and various post-processes including a surface finishing process necessary after building a component. Additionally, IHI confirms the final component quality including dimensional accuracy and internal defects.

In addition, as described that there are possibilities of being able to freely make metallographic structure by controlling the metal solidification phenomenon, it is important to understand the phenomenon in terms of controlling the quality of manufactured components. IHI is also actively working on research and development for understanding and controlling the phenomenon of melting and resolidification of metal occurring in a very minute region during the additive manufacturing process (although the phenomenon requires fine and minute knowledge in terms of engineering).

Potentiality of additive manufacturing

The additive manufacturing, having many advantages not obtained by the conventional manufacturing method, are the very innovative technology capable of fundamentally changing the concept of conventional metal component manufacturing. IHI is gathering the group's ability of monozukuri, and while repeatedly making discussions with professionals in various fields together, working on understanding physical phenomena by acquiring a lot of data, from strength evaluation for evaluating how much load is required to break a metal component made by the additive manufacturing to the evaluation of fine metallographic structure of a micron level. The additive manufacturing world is currently at a stage where actual components of a size classified into "ultra large" can be successfully manufactured.

Although there are infinite possibilities of the additive manufacturing, they are still immature technologies of only less than 40 years since first appearance in the world. Accordingly, different from other manufacturing methods such as forging and casting of more than 1 000 years old, it is no exaggeration to say that there is almost no accumulation of knowledge on what kind of manufacturing trouble occurs. However, since rocket engines are products that must not be allowed to fail, we are proceeding with development work toward application to actual components while paying utmost attention.



X-ray evaluation example of prototype

Next step

IHI is planning to repeatedly perform prototyping and evaluation to accumulate further detailed knowledge, as well as, apply it to a flight product after verifying actual components of a turbopump by the additive manufacturing by engine combustion tests.

In addition, based on the knowledge to be accumulated in that plan, IHI will actively apply the additive manufacturing technology to products other than rocket engine components.

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