# Development of forging process for magnesium alloy continuous cast bars

## — Forging process utilizing grain refinement —

**Naobumi SAITO[1]*, Hajime IWASAKI[2], Michiru SAKAMOTO[3], Kazuo KANBARA[4] and Tunehisa SEKIGUCHI[4]**

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Reducing resource consumption and carbon dioxide emission are recognized as urgent issues. One way of addressing these issues is to reduce product weight. Magnesium alloys are considered promising candidates because of their lightness. To manufacture products using magnesium alloys, we require forging technology that afford higher size accuracy and strength. This paper introduces the results of joint research with a company for the development of a new forging process for magnesium alloys continuous cast bars. We describe the research background, goals of the project, fundamental technologies employed to address these goals, and the integrative/synthetic process.

*Keywords* **:** Magnesium alloy, continuous cast bars, forging, dynamic recrystallization, grain refinement, heat sink

## 1 Introduction

Against a background of social demand for energy and resource saving, the weight reduction and recycling promotion are issues in a wide range of industrial products from transportation machines to home appliances. Magnesium is the lightest material among the structural metallic materials and is readily recyclable. Therefore, its application to various industries including vehicles is expected. However, it is not widely used compared to the aluminum alloy at this point, one of the reasons being that the magnesium alloy parts are expensive. Table 1 shows the comparison of the magnesium alloy and aluminum alloy for the forged parts that are the subjects of this research. There are not many differences in the material properties between the aluminum and magnesium alloys. However, in terms of the cost of material, magnesium alloy is five to six times more expensive than the aluminum alloy. Also, magnesium alloy has poor plastic deformability, so that only hot forging can be done. In contrast to magnesium alloy, the aluminum alloy can be forged at lower temperatures (warm and cold forging). Therefore, the power consumption for processing is higher for forging magnesium alloy. Due to the above factors, the cost of magnesium alloy forged products is six to seven times more than the cost of aluminum alloy forged products. However, forging is a plastic forming process that allows the manufacture of high quality parts at high productivity. Therefore, the industry is seeking the establishment of the forging technology for magnesium alloy and the cost reduction of the magnesium alloy forged parts.

AIST aimed for the manufacture of magnesium forged parts with low cost and high reliability, jointly with the Sokeizai Center, in the "Project for the Development of Magnesium Forged Parts Technology" supported by the New Energy and Industrial Technology Development Organization (NEDO) for the fiscal years 2006 to 2010. After the completion of the Project, joint research was done with the Miyamotokogyo Co., Ltd. to continue development toward practical realization of the newly developed technology.

## 2 Background of the development of forging technology for magnesium alloy continuous cast bars[1]

In this chapter, we discuss the situation of magnesium alloy forging in 2006, and the goals set for the development of forging technology for magnesium alloy continuous cast bars in the NEDO Project.

### *2.1 Situation of the magnesium forging process*

In the NEDO Project, to clarify the issues in the development of magnesium alloy forging technology, we conducted prototype forging and evaluated the actual parts made by a commercial process using a general-use mechanical press, with the actual magnesium alloy extruded material as forging material. As a result, it was found that in the prototype forged parts, the grain size was coarse since they were forged at high temperature of about 400 ºC, and this prevented the improvement of the mechanical properties of forming that is expected for forged parts. That is, in 2006, there was

1. Materials Research Institute for Sustainable Development, AIST 2266-98 Anagahora, Shimo-shidami, Moriyama-ku, Nagoya 463- 8560, Japan * E-mail: naobumi-saito@aist.go.jp, 2. The High Process Research, Ltd. (Former, Materials Research Insitute for Sustainable Development, AIST) 3-17-13 Takada-dai, Kamigori-cho, Ako-gun 678-1226, Japan, 3. Measurement Solution Research Center, AIST 807-1 Shuku-machi, Tosu 841-0052, Japan, 4. Miyamoto Industry Co., Ltd 9133 Funyu, Shioya-machi, Shioya-gun 329-2441, Japan

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**Table 1. Comparison of the magnesium alloy forging material and aluminum alloy forging material**

| | | | Magnesium alloy (AM60) | Aluminum alloy (A6061) |
|---|---|---|---|---|
| Material | Specific gravity | | 1.74 (pure Mg) | 2.70 (pure Al) |
| | Material, structure | Material | Extruded material | Extruded material |
| | | Grain size | 20～50 µm | 20～50 µm |
| | Property | Strength | 260 MPa | 280 MPa |
| | | Elongation | 10 % | 12 % |
| | | Drawing ratio | 35 % | 45 % |
| Process | Weight reduction rate* | Thinning, downscaling | Weight reduction 30 % or more | Weight reduction 20 % or more |
| | Forging, forming | Forming method | Hot process only | Cold and hot processes |
| | Size accuracy | During hot process | ±1.5～2.0 mm | ±1.0～1.5 mm |
| Cost | Material | Comparison with current product (extruded material) | 500～600 | 100 |
| | Product | Finished forged product | 600～700 | 100 |

Here, the examples shown are for the AM60 (Mg-6 mass% Al -0.1 mass% Mn) magnesium alloy and the A6061 (Al-0.8 mass% Mg-0.7 mass% Si) aluminum alloy that are representative forging materials.

*Here, weight reduction rate is the weight reduction achieved by replacing the small automobile parts such as the iron structural support material with aluminum or magnesium alloy materials.

insufficient improvement of the properties of the forged product itself, because importance was placed on the forming technique without defects or cracks for the magnesium alloy forging.

### *2.2 Goal setting for the forging technology development*

For the popularization of the magnesium alloy forged parts, direct forging from low-cost cast material is desired instead of extruded material. Also, the improvement of mechanical property by forging must be realized. Therefore, in the NEDO Project, the R&D topics for magnesium alloy forging were set as follows and the R&Ds were started: 1) the investigation of forgeability of low-cost materials (continuous cast bars), 2) the development of forging process for continuous cast bars, 3) the achievement of forging at temperatures lower than 400 °C (suppression of grain size coarsening in forged parts), and 4) the achievement of improved mechanical property of parts by forging (by controlling the grain roughness in forged parts).

Figure 1 shows the estimate of cost reduction expected by using magnesium alloy continuous cast bars as forging material. When the forged parts are manufactured using the magnesium alloy continuous cast bars, it is expected that the price of the forged parts will fall to about one-fourth of the current price because there is no extrusion process.

## 3 Increasing the formability of magnesium alloy continuous cast bars[1]

### *3.1 Investigation of the solution methods based on conventional knowledge*

The point of this R&D is to increase the formability of forging material and to increase the strength of forged parts. While the magnesium alloy forging is a process in which the materials are deformed at elevated temperature, it is known that the deformation of metallic materials is dominated by grain boundary sliding at elevated temperature.[2] Also, since the stress for grain boundary sliding decreases as the grain size becomes smaller, deformation occurs readily at elevated temperature as the grain size of the material becomes smaller.[2] On the other hand, the phenomenon where the yield stress of the metallic material at room temperature increases as the grain becomes smaller is known as the Hall-Petch relation.[3]-[5] From the above knowledge, we thought the reductions of grain size of the forging materials and forged parts were important in solving the issue.

It is known that when the metallic material is deformed at elevated temperature, new grains are generated due to dynamic recrystallization, and the initial grains disappear.[6] Also, it is reported that magnesium alloys readily undergo dynamic recrystallization, and grain refinement can be achieved relatively easily.[7] Therefore, we started the R&D by investigating the grain refinement behavior by dynamic recrystallization of the magnesium alloy continuous cast bars.

### *3.2 Investigation of the dynamic recrystallization behavior of magnesium alloy continuous cast bars*

In this chapter, we explain the result of investigating the grain refinement behavior by dynamic recrystallization of the magnesium alloy continuous cast bars, in the NEDO Project led by AIST to obtain the basic knowledge for the development of forging technology.

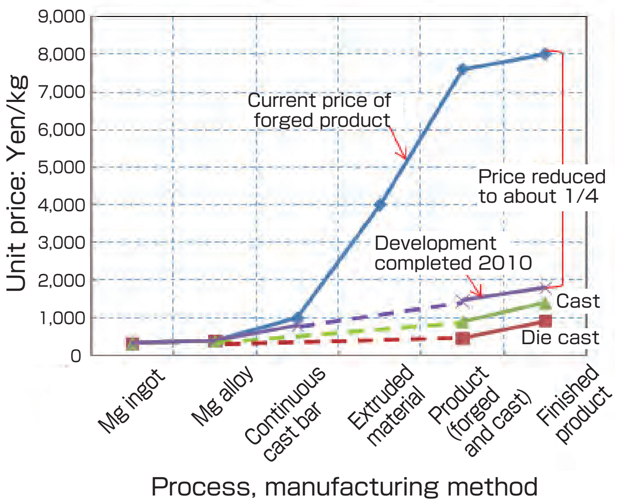



**Fig. 1 Cost estimate of the magnesium alloy parts**

### *3.2.1 High-temperature compression test of the AZ91 alloy continuous cast bar*

We conducted a high-temperature compression test at AIST, using the homogenized (heated at 410 ºC for 24 h) AZ91 (Mg-9 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar (made by Sankyo Tateyama, Inc.). As a representative example, the test samples of 10 mm diameter and 12 mm height were compressed to 80 % at three different temperatures (250 ºC, 300 ºC, and 330 ºC) and strain rates (0.01 $s^{-1}$, 0.1 $s^{-1}$, and 1 $s^{-1}$). The obtained microstructures (grain size) are shown in Fig. 2. From this result, it was found that the grain size could be relatively easily refined to 10 μm or less when the AZ91 magnesium alloy continuous cast bar was compressed and deformed at 300 ºC or less.

### *3.2.2 Upset compression test of the AZ91 magnesium alloy continuous cast bar*

Next, we conducted the upset compression test for the scale-up AZ91 alloy sample pieces (40 mm diameter, 48 mm height), using the servo press owned by Miyamotokogyo Co., Ltd. to investigate the effect of reduction ratio and compression speed on the grain refinement behavior. Figure 3 shows the variation in grain size as a function of the reduction ratio when deformation was done at 200 mm/s. The grain became finer at high reduction ratio, but cracks occurred on the side of the sample at reduction ratio of 60 %. Figure 4 shows the variation in grain size as a function of the processing temperature when the deformation was carried out at reduction ratio of 40 %. Although the grains became finer as the temperature decreased, there was no dependency on deformation speed of the grain diameter at 300 ºC. From the above results, it was found that the grain diameter of AZ91 magnesium alloy continuous cast bar could be refined to about 10 μm without cracking, if the deformation of 30~40 % was done at 300 ºC.

## 4 Prototype forging of the magnesium alloy continuous cast bar and investigation for achieving high strength in forged parts[1]

In this chapter, we explain the outline of the forging technology for magnesium alloy continuous cast bars developed by AIST based on the research results obtained in the NEDO Project as explained in the previous chapter, and the prototype forging at AIST using the developed technology.

From the experimental results of the dynamic recrystallization behavior of the magnesium alloy continuous cast bars, AIST proposed a forging process shown in Fig. 5. In this process, the compression process of 30~40 % was applied at 300 ºC to the magnesium alloy continuous cast bar to refine the grain size to about 10 μm in the first half of the process. The forging material, hence, is expected to change into a material with good formability due to grain refinement. In the latter half of the process, the forging process was continued until the final form was achieved.

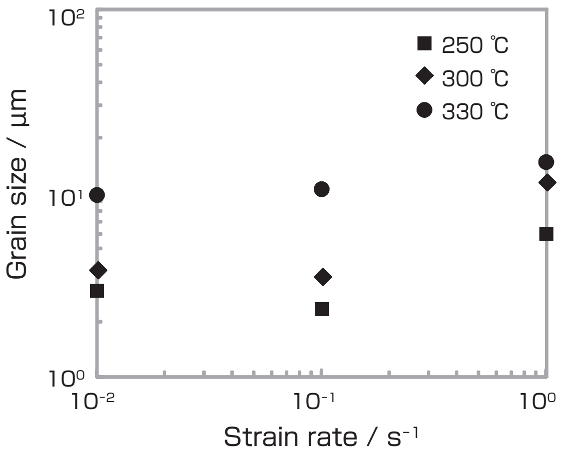



**Fig. 2 Grain size of AZ91 (Mg-9 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar after high-temperature compression (reduction ratio : 80 %)**

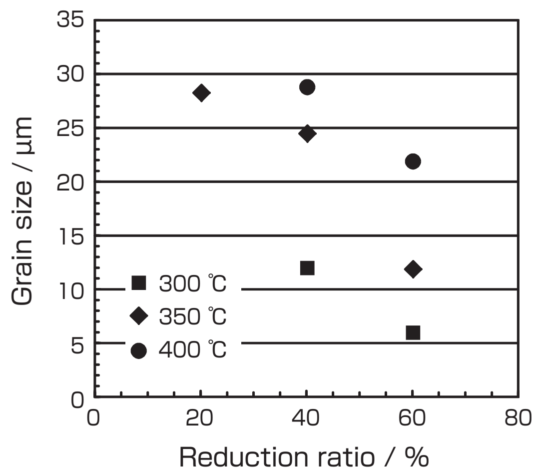



**Fig. 3 Variation in grain size as a function of the reduction ratio for AZ91 (Mg-9 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar (deformation speed: 200 mm/s)**

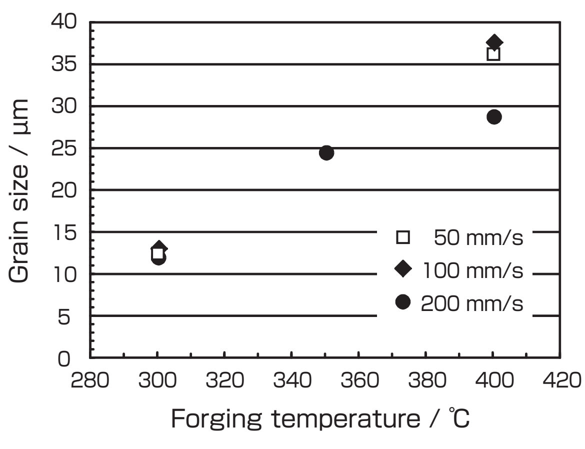



**Fig. 4 Variation in grain size as a function of the processing temperature for AZ91 (Mg-9 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar (reduction ratio : 40 %)**

As mentioned in the previous chapter, the dynamically recrystallized microstructure of magnesium alloy is dependent on the processing temperature and strain rate.[8] Therefore, to achieve the process set as the goal, the servo press was useful since the processing speed and sliding position could be controlled arbitrarily. The prototype forging was conducted using the servo press at AIST, and the adequacy of the aforementioned forging process was investigated.

Figure 6 shows the forging process using the servo press conducted at AIST. The preheated forging materials (blanks) were placed in the heated mold, and compression was applied from above by a punch process. Since the diameter of the blanks is smaller than the diameter of the mold, the blanks spread sideways at first, and the diameters of the blanks and mold match at a certain point. The so-called upset

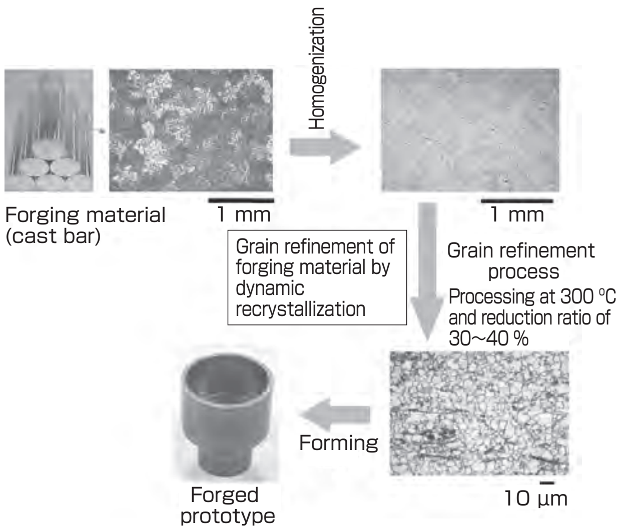



**Fig. 5 Outline of the forging process for magnesium alloy continuous cast bar**

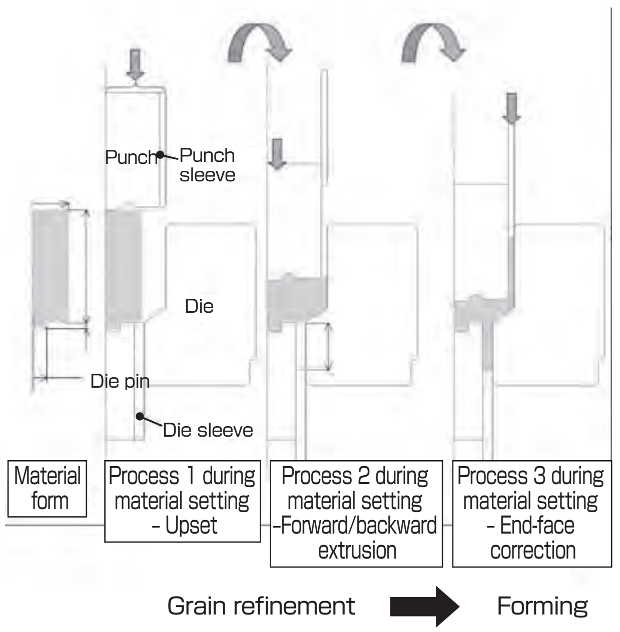



**Fig. 6 Forging process using the servo press**

compression process (reduction ratio of about 40 %) to this point is the process of grain refinement. When the material is pressed further with the punch, it is pushed out both forward and backward, and formed into its final form. This process is done in one step, but the first half is the grain refinement process, while the latter is the forming process.

Figure 7 is the photograph of the exterior appearance of the forged product (material is AZ91 magnesium alloy) created as the first prototype in this process. In the photograph, 1 is the part by backward extrusion, 2 is the part by upset forging, and 3 is the part by forward extrusion. AIST conducted about 150 prototype forging with varied temperatures, processing speed, and cooling speed of the forged product, and the results of the microstructural observation and the tensile test were organized into a database. The forged prototype shown in Fig. 7 was forged at 300 °C and forging speed of 10 mm/s, and there were no defects observed. It was confirmed that forward/backward tube extrusion forging with area reduction rate of 81 % was possible at 300 °C using the new forging process for magnesium alloy continuous cast bars proposed by AIST. This result was evaluated highly by the evaluation committee members in the follow-up evaluation of the Project. When the microstructure of the prototype formed parts was observed, the grain size was refined to 10 μm or less in the forwardly extruded, the upset forged, and backwardly extruded parts. As for the mechanical properties of the upset forged section, tensile strength at room temperature was 359 MPa and breaking elongation was 19 %. This tensile property was higher than that of the original material (226 MPa, 15 %), and the increased mechanical property by forming as expected for forged parts was realized. In conclusion, we achieved the goals that were initially set.

## 5 Investigation of the realization of the forging process for magnesium alloy continuous cast bars

### *5.1 Goals set in the realization research*

We succeeded in forging the magnesium alloy continuous cast bar at 300 °C that was about 100 °C lower than the conventional method at the prototype level, using the

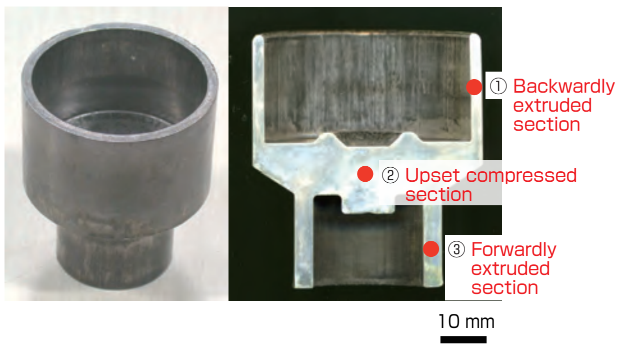



**Fig. 7 Example of the forged prototype (Material: AZ91 magnesium alloy continuous cast bar)**

**Table 2. Decrease of the processing cost expected by lowered forging temperature**

| | Conventional process | New process (low-temperature forging) |
|---|---|---|
| Material | 100 | 100 |
| Consumed power | 100 | 70 |
| Post treatment※1 | 100 | 50 |
| Post processing※2 | 100 | 98 |
| Total cost | 100 | 70 |

※1 : Mainly cleansing of forged products such as removal of lubricants
※2 : Post processing such as cutting and alumite treatment

process developed in the NEDO Project. As the next step after the completion of the Project, AIST held thorough discussions on the results of the aforementioned NEDO Project with Miyamotokogyo, from the perspective of applying them to actual practice. As a result, we were able to share the recognition that it was important to set the goal of developing forging technology to obtain high-strength, high-accuracy formed products at temperatures less than 200 ºC, and that the grain refinement was necessary to accomplish this. Setting these two as common goals, AIST and Miyamotokogyo conducted joint research. In the course of discussion, Miyamotokogyo proposed the following points for the processing cost, environmental measures, and workplace environment, as merits of low-temperature forging.

1) Processing cost: in hot forging where the temperatures are 300 ºC or more, special furnace to heat the forging material is necessary. In contrast, when forging at temperatures of 200 ºC or less, heating can be done sufficiently by an infrared heater or a hot plate. Also, since the product accuracy increases at low temperature, it is expected to reduce the number of steps and reduce the cost of cutting. Moreover, the amount of power needed to maintain the heat of the material and mold can be reduced, and the lifespan of the mold can be increased. Considering the above points, the expected decrease in processing cost by low-temperature forging is shown in Table 2. It is thought that the cost reduction in power consumption and after-treatment will be large, and it is estimated that the total processing cost will be 20~30 % less than the conventional processing method.

2) Environmental measures: In forging at temperatures of 200 ºC or less, water-soluble lubricant that can be more readily removed compared to graphite solid lubricants can be used. While the graphite lubricants have low cost with high lubrication property, there is the danger of fire since the flash point of the base oil used to disperse the graphite is 170~200 ºC. Also, the possibility that the contamination of the work environment by graphite may cause health damage to human beings has been indicated. Therefore, the workplace contamination in the lubrication process is expected to decrease by using the water-soluble lubricants.

3) Work environment: In the case of hot forging, the workers must wear special equipment to protect against burns, and the companies must pay extra allowance to workers for exposure to heat. In contrast, the materials can be handled without using special equipment if the forging temperature is 200 ºC or less. That is, the work environment is expected to improve compared to hot forging.

### *5.2 Consideration of the solutions based on knowledge obtained in the research so far*

In the "Project for the Development of Technology for Magnesium Forged Parts," it was not possible to decrease the temperature only of the forming process as forging was done in one step using a single mold. Therefore, this time, we tried the two-step forging where the grain refinement and forming processes were separated. The outline of the considered forging process is shown in Fig. 8. In this forging process, the processes of grain refinement and forming are separated into two steps. That is, the material is processed by upset compression at a certain temperature and at a certain compression rate, and the grain size is refined to about 10 μm by dynamic recrystallization. The samples are removed and the forging is done at 200 ºC or less. AIST has high potential for the microstructural control and analysis technologies for metallic materials, while Miyamotokogyo is a manufacturer with high potential for the forging process and peripheral technologies (mold, lubrication, etc.). Therefore, the individual potential was utilized to consider and investigate the processes in the following steps.

#### *5.2.1 Analysis of the grain refinement behavior in the forging material*

To check the occurrence of grain refinement by dynamic recrystallization, the upset compression test was conducted at AIST for the forging material using a servo press.

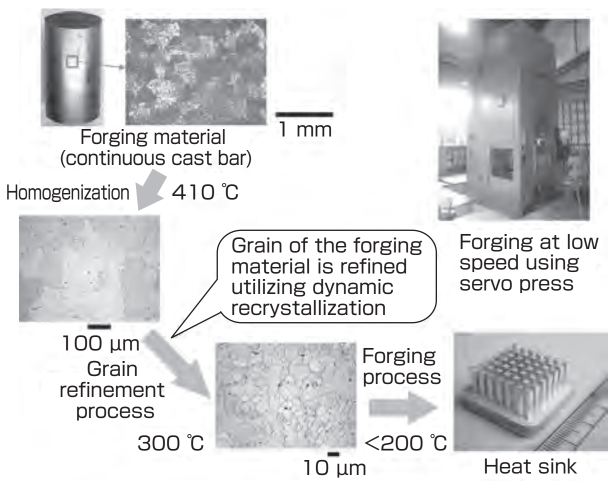



**Fig. 8 Outline of the developed low-temperature forging process**

The non-combustible magnesium alloys, where Ca was added to the AZ91 magnesium alloy to increase the flash point temperature to 200~300 ºC, were used as the forging material.[9] The amounts of Ca added were 0.2 mass%, 0.4 mass%, 0.6 mass%, and 1.0 mass%. The samples underwent 24-hour heat treatment (homogenization) at 410 ºC before the test. The sample size was 25 mm in diameter and 30 mm in height. Figure 9 shows an example of the measurement results of grain size for the material compressed at 350 ºC and 1 mm/s. While the grain size of the original material was 100~200 μm, the grain size after upset compression at 350 ºC to 60 % was 10 μm for all alloys. The grains were refined to one-tenth or less. In case of 1.0 mass% Ca added alloy, the grain size was stabilized at about 8 μm when the reduction ratio was 60 % or more.

### 5.2.2 Evaluation of the compression deformation property of the grain-refined material

To investigate the forgeability at 200 ºC or less, a high-temperature compression test of the grain-refined materials was conducted, and the compression deformation behavior was investigated at AIST.

Figure 10 shows the results of the compression test conducted for the magnesium alloy sample of 0.2 mass% Ca added AZ91 at temperatures of 200 ºC, 175 ºC, and 150 ºC and initial strain rate of $4.2 \times 10^{-3}s^{-1}$, in which the samples were compressed to 60 % at 350 ºC and 1 mm/s. The size of sample pieces was 8 mm in diameter and 12 mm in height. The reduction ratio where breakage occurred were about 16 % at 150 ºC, about 20 % at 175 ºC, and about 30 % at 200 ºC. The result that 16 % deformation was possible at 150 ºC indicates that forging at 200 ºC or less may be possible if the grain size of the material is refined to about 10 μm.

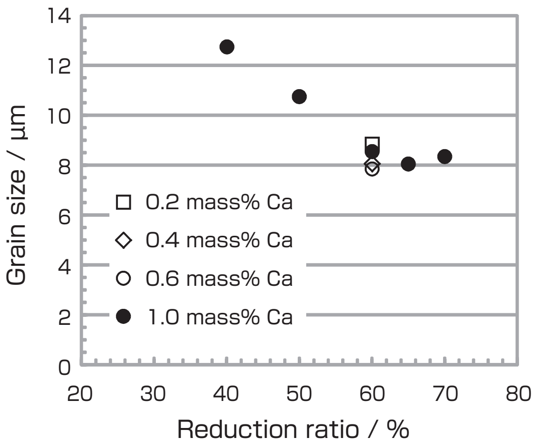



**Fig. 9 Grain size after high-temperature compression of AZX91 + 0.2 mass% Ca, 0.4 mass% Ca, 0.6 mass% Ca, 1.0 mass% Ca alloy continuous cast bars (temperature: 350 ºC, processing speed:1 mm/s)**

### 5.2.3 Consideration of the possibility of low-temperature forging

Based on the data obtained in the previous section, AIST and Miyamotokogyo discussed the possibility of low-temperature forging. As a result, it was judged that forging at 200 ºC or less might be possible by refining the grain of the material to about 10 μm. It was decided that prototype forging would be conducted. For the prototype forged part, the square pin heat sink was selected since Miyamotokogyo had the experience of forging it from aluminum alloys. The basic structure of the square pin heat sink was of 30 mm angle × 3.5 mm thickness, and the square pin part was of 2 mm angle × 8 mm height. There were 49 pins.

### 5.2.4 Grain refinement of the forging material

Next, upset compression was done using the servo press at Miyamotokogyo for grain refinement of the forging material. The microstructural observation was done for the material that underwent upset compression, and the grain refinement behavior was studied at AIST.

The two types of magnesium alloys used for forging were commercially available AZ31 (Mg-3 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar (155 mm diameter) and AZ61 (Mg-6 mass% Al-1 mass% Zn) magnesium alloy continuous cast bar (55 mm diameter). Both were homogenized for 24 hours at 410 ºC. In the grain refinement process, the blank materials with average grain size of 100 μm or more were upset to a specified compression rate at temperature of 300 ºC. From the perspectives of promoting the dynamic recrystallization and preventing the cracks in the blanks in the initial process, upsetting was done at relatively slow speed of average 5~10 mm/s. Although there were some regions where the grain diameter was about 10~20 μm in the AZ31 magnesium alloy continuous cast bar, refinement progressed to grain size of 5 μm or less by dynamic recrystallization. On the other hand, while dynamic recrystallization occurred in the AZ61 magnesium alloy continuous cast bar, the average grain size was 10 μm. Thus the grain refinement of the forging material by the upset compression process was confirmed.

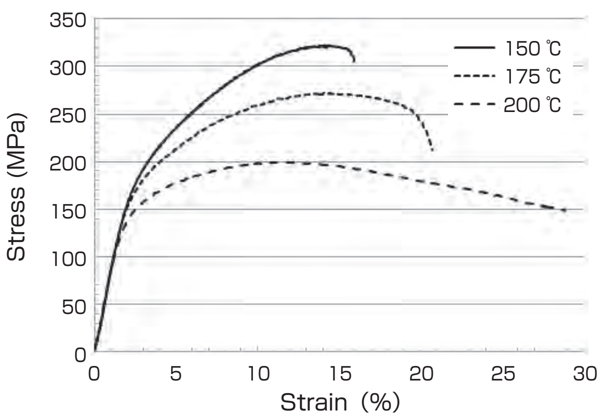



**Fig. 10 Result of the compression test of AZX91 + 0.2 mass% Ca alloy that underwent grain refinement**

**Table 3. Comparison of the development goal of this research and conventional technology**

| | | | Magnesium alloy (AM60) | Magnesium alloy (Development goal value) | Aluminum alloy (A6061) |
|---|---|---|---|---|---|
| Material | Material, structure | Material | Extruded material | Continuous cast bar | Extruded material |
| | | Grain size | 20 ~ 50 μm | 10 μm (after grain refinement) | 20 ~ 50 μm |
| | Property | Strength | 260 MPa | 340 MPa | 280 MPa |
| | | Elongation | 10 % | 15 % | 12 % |
| | | Drawing rate | 35 % | 60 % | 45 % |
| Process | Weight reduction rate | Thinning, downscaling | Weight reduction 30 % or more | Weight reduction 30 % or more | Weight reduction 20 % or more |
| | Forging, forming | Forming method | Hot process only | Warm process possible | Cold and hot process |
| | Size accuracy | | ±1.5 ~ 2.0 mm (during hot process) | ±0.3 mm (during warm process) | ±1.0 ~ 1.5 mm (during hot process) |
| Cost | Material | Comparison with current product | 500 ~ 600 | 120 ~ 140 | 100 |
| | Product | Finished forged product | 600 ~ 700 | 150 | 100 |

＊Development goal values of the research were added to Table 1.

### *5.2.5 Prototype forging as a forming process of grain-refined material*

Since grain refinement was confirmed for the forging material, we conducted prototype forging using the servo press at Miyamotokogyo. The manufactured prototype was subject to exterior evaluation at Miyamotokogyo and microstructure evaluation at AIST.

Figure 11 shows a photograph of the heat sink manufactured by the developed forging method using the AZ31 magnesium alloy continuous cast bar to which grain refinement treatment was done. The materials that underwent grain refinement treatment were used as blanks, and forging was done at temperatures 100 ºC, 150 ºC, and 200 ºC. The average extrusion ratio was 4.6, average extrusion strain was 1.5, and reduction of area was 0.78. To prevent cracking of the material, forging was done at relatively slow speed of average 5~10 mm/s. There were no cracks at all forging temperatures, and a robust heat sink with 49 pins of even height was forged. Similar heat sinks were manufactured by the new forging method, using the AZ61 magnesium alloy continuous cast bars. Heat sink is a part for which mechanical strength is not required. However, from microstructural observation, it was confirmed that the grain diameter of the square pin section was refined to 10 μm or less. Therefore, it is thought that it would have sufficient mechanical strength.

### *5.2.6 Investigation of the adequacy of our forging process and the magnesium alloy forged prototype*

After the completion of the prototype forging, the adequacy of the forging process was verified at Miyamotokogyo and AIST.

In the prototype forging, it was confirmed that the forging of magnesium alloy with relatively complex form was possible at 200 ºC or less, by controlling the grain size to about 10 μm or less. With the AZ61 alloy that has inferior forgeability compared to the AZ31 alloy, forging was possible without any problem if the grain was refined by dynamic recrystallization. From the above results, it is thought that this forging process can be put into practical use.

Also, when the research results are compared with those of

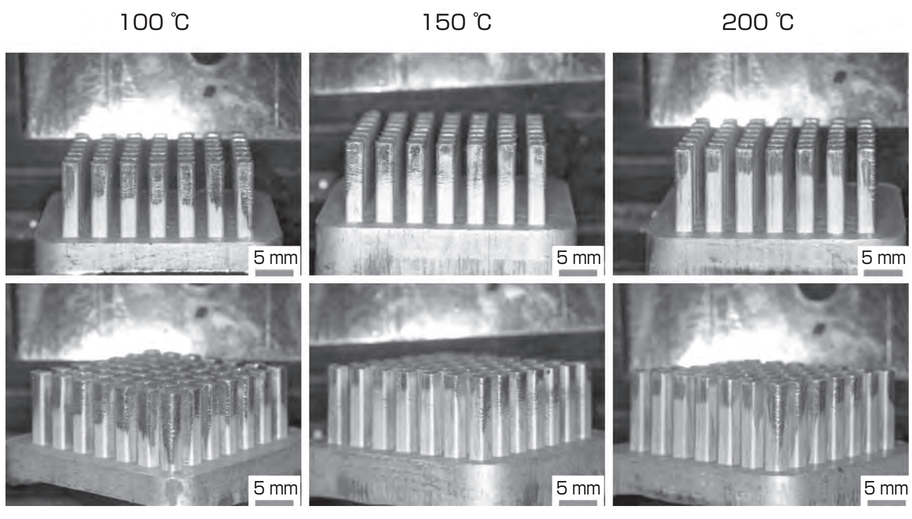



**Fig. 11 Appearance of the prototype heat sink (material is AZ31 alloy)**

aluminum alloy forged parts as shown in Table 3, although it is about 1.5 times the aluminum alloy in product price ratio, the price is expected to decrease to about one-fourth of the current magnesium alloy forged parts. Although further product cost reduction will be the issue in the future, practical use of magnesium alloy forged parts is now on the horizon for uses where demand for weight reduction is large.

## 6 Integration of the elemental technologies in this R&D

The development of low-temperature forging technology of the magnesium alloy continuous cast bar was possible by integrating the capabilities of AIST and Miyamotokogyo. Based on the contents and discussions presented up to chapter 5, Fig. 12 summarizes how the hypotheses and elemental technologies that were set in the NEDO Project and joint research to solve the problems were integrated, how the two institutions divided or joined the tasks, and how they were able to achieve the development of the final magnesium alloy forging process and the forged product.

AIST has potential for the microstructural control, analysis, and evaluation technologies of the metallic materials. The point of the low-temperature forging technology of the magnesium alloy continuous cast bar is the refinement ofl grain size of the material before forging the material into its final form. Therefore, AIST engaged in the analysis of grain refinement behavior by dynamic recrystallization of the forging material, and the analysis of deformation behavior of the grain-refined material at low temperature. Then, based on the results, the possibility of low-temperature forging was considered together with Miyamotokogyo.

Miyamotokogyo is an aluminum forging manufacturer with experience in parts used in home appliances, precision machines, personal computers, automobiles, as well as leisure products, and has high potential in forging processes and peripheral technologies (mold, lubrication, etc.). In this R&D, it conducted prototype forging of the actual parts using the developed process by utilizing the basic data provided by AIST. It also engaged in the exterior evaluation of the forged prototypes.

AIST was the main player in the first half of this joint research, while Miyamotokogyo played the main role in the latter half. AIST was in charge of the microstructure analysis of the forged prototypes conducted in the latter half. The R&D was conducted under close collaboration.

## 7 Evaluation of the results and future prospects

### *7.1 Evaluation of the results*

The result of the joint research for the low-temperature forging of magnesium alloy continuous cast bar was publicized in the AIST press release "Achievement of forging of magnesium alloy at low temperature of 200 ºC or less" on May 15, 2013.[10] Immediately after the press release, we had interview requests from newspapers, and several newspapers carried articles on this research. There were also requests for commentary articles from several magazines, and this contributed to the spread of the results.[11]-[13] Moreover, there were coverages by magazines and articles were written.[14] There were many responses to this research result and it was

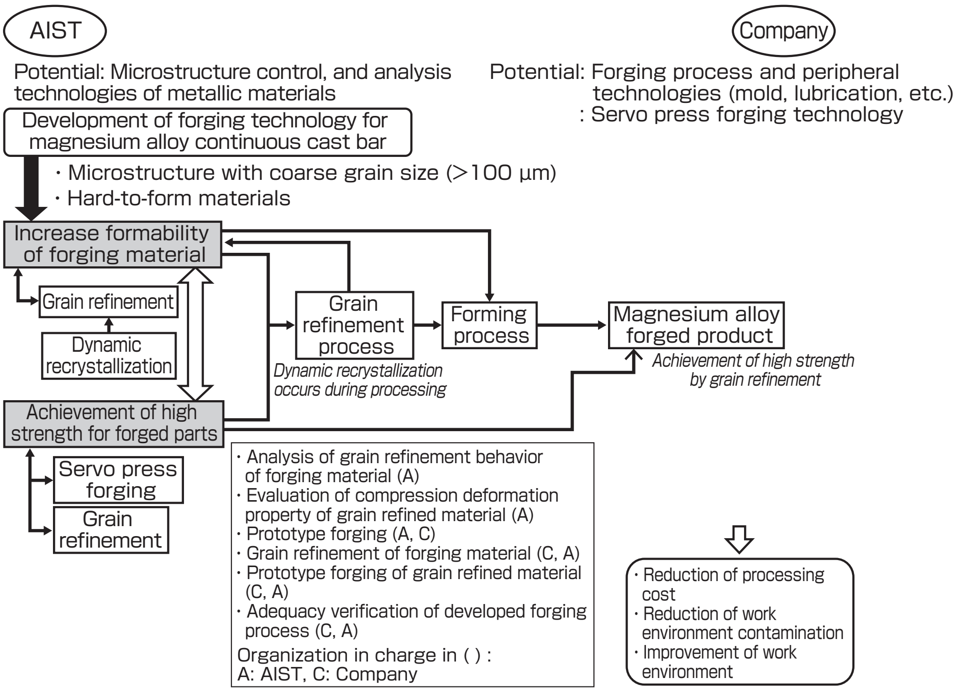



**Fig. 12 Integration of elemental technologies in this R&D**

highly evaluated.

### *7.2 Future prospects*

Miyamotokogyo is working on decreasing the forging temperature of magnesium alloy and is aiming to achieve cold forging at a region of 100 ºC or less. If this is realized, heat maintenance during forging becomes unnecessary, and this is expected to dramatically increase the productivity. Also, lubricants for cold forging can be used, forging accuracy will be increased, and further cost decrease can be expected.

If mass production of magnesium alloy becomes possible in the cold forging region, replacement in the fields where aluminum is currently used or in some fields that use iron may become possible. Application to optics, industrial machines, batteries, power source peripherals, automobiles, motorcycles, and other diverse fields will come into the horizon.

Currently, Miyamotokogyo is seeking new business using the results of this joint research. It has already progressed to mass production of digital camera parts made of low-temperature forged magnesium. Also, it is putting its sales efforts into cable connectors for bullet trains, centrifuge holders, and automobile parts.

## 8 Conclusion

The development of the forging technology for magnesium alloy continuous cast bars was started as a NEDO project, and continued as joint research with Miyamotokogyo. The point of this R&D was to actively incorporate dynamic recrystallization, which is a phenomenon that has been studied extensively academically, into the manufacturing process, and this enabled the forging of magnesium alloy continuous cast bars that was previously not used as forging material. AIST bridged the basic academic results and the manufacturing process, and we believe this is an example of the practical application of the AIST's slogan "Technology to Society." In the future, we plan to join together the basic core technologies (microstructural control, analysis, and evaluation technologies of materials) of AIST and the manufacturing technologies of the companies through such joint research.

## References


[1] NEDO: "Maguneshiumu Tanzo Buzai Gijutsu Kaihatsu Purojekuto" Jigo Hyoka Shiryo (Follow-up Evaluation Report of the "Project for the Development of Magnesium Forged Parts Technology") (2012) http://www.nedo.go.jp/introducing/iinkai/kenkyuu_bunkakai_23h_jigo_12_1_index.html (in Japanese).

[2] M. Morinaga, T. Furuhara and H. Toda (eds.): *Kinzoku Zairyo No Kako To Soshiki* (Processing and Microstructure of Metallic Materials), Kyoritsu Shuppan, 71-72 (2010) (in Japanese).

[3] E. O. Hall: The deformation and ageing of mild steel: III Discussion of results, *Proc. Phys. Soc. B.*, 64, 747-753 (1951).

[4] N. J. Petch: The cleavage strength of polycrystals, *J. Iron Steel Inst.*, 173, 25-28 (1953).

[5] George E. Dieter, Jr.: *Mechanical Metallurgy*, McGraw-Hill, 119-123 (1961).

[6] F. J. Humphreys and M. Hatherly: *Recrystallization and Related Annealing Phenomena*, Elsevier, 373-382 (1995).

[7] M. Morinaga, T. Furuhara and H. Toda (eds.): *Kinzoku Zairyo No Kako To Soshiki* (Processing and Microstructure of Metallic Materials), Kyoritsu Shuppan, 150-153 (2010) (in Japanese).

[8] H. Watanabe, H. Tsutsui, T. Mukai, K. Ishikawa, Y. Okanda, M. Kohzu and K. Higashi: Grain size control of commercial wrought Mg-Al-Zn alloys utilizing dynamic recrystallization, *Materials Transactions*, 42 (7), 1200-1205 (2001).

[9] M. Sakamoto and H. Ueno: Energy savings in transportation systems by weight reduction of their components - Research and development of non-combustible magnesium alloys, *Synthesiology*, 2 (2), 127-136 (2009) (in Japanese) [*Synthesiology English edition*, 2 (2), 121-131 (2009)]

[10] AIST Press Release (2013/05/15): 200ºC ika no teion de magneshiumu gokin no tanzo o jitsugen (Realized the forging of magnesium alloy at low temperature of 200ºC or less), http://www.aist.go.jp/aist_j/press_release/pr2013/pr20130515/pr20130515.html (in Japanese).

[11] N. Saito, H. Iwasaki, K. Kanbara, T. Sekiguchi and N. Miyamoto: Magneshiumu gokin no kesshoryu bisaika o riyoshita tanzo purosesu no kaihatsu (Development of the forging process using the grain refinement in magnesium alloys), *Alutopia*, 43 (8), 26-32 (2013) (in Japanese).

[12] N. Saito, H. Iwasaki, K. Kanbara, T. Sekiguchi and N. Miyamoto: Magneshiumu gokin renzoku chuzozai no tanzo gijutsu no kaihatsu (Development of the forging technology for magnesium alloy continuous cast bars), *JFA* (PR Magazine of the Japan Forging Association), 45, 12-16 (2014) (in Japanese).

[13] N. Saito, H. Iwasaki, K. Kanbara, T. Sekiguchi and N. Miyamoto: Magneshiumu gokin renzoku chuzozai no tanzo gijutsu (Forging technology for magnesium alloy continuous cast bars), *Sokeizai*, 55 (6), 20-24 (2014) (in Japanese).

[14] AIST and Miyamotokogyo: Suekomi kako de kesshoryu o bisaika - 200ºC ika de seisansei kojo o nerau (Grain refinement by upset process - Aim for improvement of productivity at 200ºC or less), *Nikkei Monozukuri*, 711, 49-50 (2013) (in Japanese).


## Authors

**Naobumi SAITO**

Graduated from the Department of Metallurgy, School of Engineering, Tohoku University in 1985. Obtained the doctorate from the Department of Materials Science, Graduate School of Engineering, Tohoku University in 1990. Doctor of Engineering. Joined the Metal Department, Government Industrial Research Institute, Nagoya, Agency of Industrial Science and Technology in April 1990, and engaged in the research of lightweight metal materials. Assigned to the

Materials Research Institute for Sustainable Development, AIST after reorganization in April 2002. In this research, was in charge of the microstructure analysis of magnesium alloy continuous casting bar, grain-refined materials, and forged prototype parts.

**Hajime IWASAKI**

Completed the doctor's course at the Graduate School of Engineering Science, Osaka University in 1969. Started teaching at the Department of Metallurgy, Himeji Institute of Technology in 1969; retired in March 2003. During that time, taught courses on plastic dynamics, plastic process science, and theories of material process science. Research field is high-temperature plasticity focusing on the superplasticity of lightweight metals. Visiting Professor for two years at AIST from 2004; and worked as Contract Researcher for five years at AIST Chubu from 2006, on NEDO "Project for the Development of Magnesium Forged Parts Technology." Currently, President, Y.K. High Process Research. In this research, was in charge of the evaluation and analysis of deformation behavior of the magnesium alloy continuous cast bars

**Michiru SAKAMOTO**

Graduated from the College of Natural Sciences, First Cluster of Colleges of the University of Tsukuba in 1980. Completed the Doctor's Program in Geoscience, Graduate School of Life and Environmental Sciences, University of Tsukuba in 1985; Doctor (Geology). Joined the Mechanical Metallurgy Department, Government Industrial Research Institute, Kyushu, Agency of Industrial Science and Technology in April 1985, and engaged in R&D of metal matrix composite materials. Assigned to the Materials Research Institute for Sustainable Development, AIST in August 2007, and transferred to AIST Chubu in November 2007. Transferred to AIST Kyushu in August 2011. In this research, engaged in the creation of overall plan and the management and administration of research for the NEDO Project.

**Kazuo KANBARA**

Graduated from the Department of Metal Processing, Special Engineering College of Kogakuin University in 1970. Joined the Technology Section, Miyamotokogyo Co., Ltd. in April 1970; Section Chief, Technology Section in 1979; Section Chief, Manufacturing Section in 1986; and Manager, Technology Section in 1990. Worked constantly on the development of cold forging technology for aluminum alloys and copper. Received the Special Technology Award for Aluminum Forging from the Japan Light Metal Association in 1994. Has been promoting the forging technology for magnesium alloys from 2000. In this research, was in charge of prototype forging of heat sink using the magnesium alloy continuous cast bar.

**Tsunehisa SEKIGUCHI**

Completed the master's course at the Department of Mechanical Engineering, Graduate School of Science and Engineering, Waseda University in 1969. Joined Showa Denko K.K. in 1969. Obtained doctorate (Mechanical Engineering) in 1993; received the Chairman's Award, Japan Institute of Invention and Innovation in 1984; Research Fellow, Kagami Memorial Laboratory for Materials Science and Technology, Waseda University in 1995; Joined Miyamotokogyo Co., Ltd. as Advisory Engineer in 2000; Lecturer (part-time, concurrent), Graduate School, Nihon University in 2005; and Researcher (concurrent), Japan Forging Association in 2006. Engages mainly in the development of aluminum (high silicon alloy) materials and forging technology. In this research, was in charge of prototype forging of heat sink using the magnesium alloy continuous cast bar.

## Discussions with Reviewers

### Overall

**Comment (Toshimi Shimizu, AIST)**

From the perspective of resource and energy saving, there is a social demand for weight reduction in a wide range of industrial products. This paper presents an example of the development of a low-temperature forging process for continuous cast bars that was conventionally considered impossible, using magnesium alloy that has the lightest weight among the structural metal materials. It describes the elemental technologies selected for the development of the forging process that greatly contributes to cost reduction, environmental load decrease, and workplace improvement, as well as its integration scenario, particularly focusing on the close collaboration between AIST's basic core technology and a company's manufacturing technology.

### 1 Structure of the scenario and elemental technologies

**Comment (Toshimi Shimizu)**

In the forging of magnesium alloys that has inferior corrosion resistance and plasticity, crystal grain refinement was achieved by actively utilizing the dynamic recrystallization, or changes in the microstructure. Moreover, the story is told of how the difficult low-temperature forging method was developed through joint research with a company using cast bars. However, the first draft seems to be no different from the report of the NEDO Project and the joint research report from the company, and this paper seems to be a mere combination of the two. This means that there is no detailed explanation or description on the details of elemental technologies or the integration scenario that are the essence of a *Synthesiology* paper. Putting it bluntly, it seems you are saying an optimal condition was found when doing investigations using the servo press pertaining to the conditions of major factors (temperature, processing speed, processing rate, etc.) for the dynamic recrystallization that was necessary for refining the grains of the continuous cast bar, and the development was accomplished easily when a company good at cold forging processes gave it a try based on the data you provided them. In your writing, you should present a compelling story including the setting of the social value as the goal, the working hypothesis that you established in doing the research and the verification results, the problems you ran into when integrating with corporate technology, the techniques to overcome them, and the logical development of technological integration, as well as the delineation of importance, difficulty, or urgency of the issues and technologies.

**Comment (Akira Kageyama, Research and Innovation Promotion Headquarters, AIST)**

When I read the first draft, it seemed that the technological issues and the ways to overcome them were already known, and as a result of patiently doing the experiments, you came up with a forging technology for high-strength magnesium alloy that can be formed at low temperature and is not likely to crack. In reality, I think there must have been parts where the authors' originality was involved in the concept design, hypothesis setting, and combination of the elemental technologies. Therefore, please review the paper by building up the discussion carefully for the processes and results, in line with the direction of *Synthesiology*.

**Answer (Naobumi Saito)**

I received similar indications from the two reviewers. In the first draft, I provided the description with importance placed on research after the NEDO Project. However, I do not think the readers could understand the meaning of this research unless the process of problem solving in the NEDO Project is described. Therefore, the entire composition of the paper was changed.

## 2 Integration diagram for the elemental technologies

**Comment (Toshimi Shimizu)**

I think you need a diagram on the integration and synthesis of the elemental technologies that is absolutely essential for *Synthesiology*. The reviewer added some content and created a rough diagram. It is strictly a proposal, so please use it as a reference only. Please refer to other papers in *Synthesiology* on material development, and do your own adjustment, addition, or correction. Of course, you can create your own original diagram.

**Comment (Akira Kageyama)**

The following keywords can be picked out from this paper: 1) improvement of mechanical strength, 2) direct forging from cast material, 3) review of manufacturing process of forging material = avoidance of extrusion process, 4) easy formability, 5) dynamic recrystallization, 6) grain refinement, 7) investigation from the perspective of cost reduction, 8) magnesium alloy composition, 9) forming temperature, strain speed, and reduction ratio as process conditions and the introduction of the servo press that can continuously change these conditions, 10) optimization of lubricant technology, and 11) reduction of work environment load. Here, 1) ~ 4) and 7) can be categorized as goals, 8) and 9) as specific items to be considered for achieving the goals, 5) and 6) as basic technologies that support the research, and 10) and 11) as reduction of environmental load in a wide sense. To put it in other words, the dynamic recrystallization and grain refinement were placed as the base of physical phenomena to achieve the goal, and careful R&D was conducted for the fluctuating factors 8) and 9). I think you can arrange the paper claiming you did your considerations with strong focus on the reduction of the environmental load. Using the above argument as your reference, please take on the challenge to build the logic of the paper in one diagram.

**Answer (Naobumi Saito)**

Thank you for providing the diagram for the integration of the elemental technologies. The reason "increase in formability of the forging material" was necessary in this R&D was because the forging material was the continuous cast bar with grain diameter of 100 μm or more. In the extruded material that is used conventionally as forging material, efforts to achieve increase in formability is not necessary. Therefore, I added the phrase "development of the forging technology for continuous cast bars," corrected some parts of the diagram that you provided, and created Fig. 12. Other parts were also corrected. Chapter 6 was newly added along with Fig. 12, and the combination of elemental technologies was discussed therein.

## 3 Relationship with the NEDO Project

**Question & Comment (Akira Kageyama)**

I think this research is about utilizing the results of the NEDO Project and going on to do the advanced version of R&D. I think it is good to show both the results of the NEDO Project and the joint research, but please describe clearly from where to where is the NEDO Project and from where to where is the joint research. When I read the second draft, it seems that the results of the NEDO Project is to the end of chapter 4. If so, I think you should summarize the results of the NEDO Project at the end of chapter 4 (put the NEDO Project report in your references). Then, the introductory part of chapter 5 can be, for example, as follows: "We held careful discussion on the results of the aforementioned NEDO Project with Miyamotokogyo from the perspective of applying them to actual practice. As a result, we were able to share the recognition that it was important to set the goal of developing the forging technology to obtain high-strength, high-accuracy formed products at temperatures less than 200 ºC, and that the grain refinement was necessary to accomplish this. Setting these two as common goals, AIST and Miyamotokogyo conducted the joint research. In the course of discussion, the following points were proposed for the processing cost, environmental measures, and workplace environment, as merits of low-temperature forging."

**Answer (Naobumi Saito)**

As the reviewer indicated, up to the end of chapter 4 is about the NEDO Project. In the second draft, Reference [1] cited in chapter 2 is the explanation of the essence of the NEDO Project results, but I think it is more appropriate to cite the follow-up evaluation of the NEDO Project (published version). Therefore, the evaluation resources were cited in chapters 2~4, and I corrected the text so it would be clear that these are the NEDO Project results. In the third draft, Reference [1] is the follow-up evaluation of the NEDO Project (published version). For the goal setting of Subchapter 5.1, I followed your indication and corrected the text.

## 4 Comparison of the forged product

**Comment (Akira Kageyama)**

In the introduction, you mention that the magnesium alloys are not widely used compared to aluminum alloys. You mention the corrosiveness, plasticity processing, and total cost as reasons. Please consider showing the current situation of the magnesium alloys and the goal of this research, using the aluminum alloy as reference, in the form of a table. In that case, you should break the cost down into, for example, costs of material, manufacturing and processing, energy consumption, or size adjustment. Avoid the expression of high or low, but instead provide something like a cost index. By presenting this, I think the meaning of "promising candidate" that you describe in the abstract can be understood well by the readers who are not specialists of lightweight metal. In the market, people are looking at the total performance compared to aluminum, and if this is shown, the corrosiveness that is the main weakness of magnesium may be offset by its total performance.

**Answer (Naobumi Saito)**

I had coauthor Sekiguchi of Miyamotokogyo to provide the comparison table for magnesium and aluminum forged products, and added it as Table 1.

## 5 Table 1

**Question & Comment (Akira Kageyama)**

Is it correct that Table 1 shows the comparison of the properties between the magnesium and aluminum alloys in the preliminary stage before the start of this research?

1) Please add the density of the two metals (Mg = 1.738, Al = 2.70)

to the table. Since the magnesium alloy contains bits of Al and Zn, the density may be slightly higher than 1.738, but I think this will allow you to show the weight reduction to about two-thirds of the aluminum alloy. Also, for the weight reduction rate 30 % or 20 %, against what are they reduced?
2) I think you should show Table 1 at the end of section 5.2.6 again, and compare the magnesium alloy (conventional), aluminum alloy, and the results/data of this research as Table 3. This is because the superiority of the magnesium alloy against aluminum alloy in terms of weight reduction will be clarified in Table 1, while the comparison of conventional technology and result of this experiment for magnesium alloy will be understood in Table 3. I shall leave it up to the author to include the aluminum alloy in Table 3 again, but the reviewer thinks that you should do so from the following reasons:
- The comparison (competing technology) in the market is against aluminum alloy.
- While the conventional magnesium alloy was unlikely to replace the aluminum alloy in the points of strength, elongation, size accuracy, and cost of finished forged products, the possibility became apparent through this research. Of course, the conventional magnesium alloys used currently can be replaced relatively easily, but that alone will not expand the market for magnesium alloy.

**Answer (Naobumi Saito)**

As the reviewer indicated, Table 1 is the comparison result of the stage before the start of R&D.
1) I added the specific gravities of pure magnesium and pure aluminum in Table 1. According to co-author Sekiguchi of Miyamotokogyo, the estimate of weight reduction was calculated for small automobile parts including the iron mount for rubber vibration isolator and the structural support materials such as engine mount and link arms. The figures for specific gravity do not entirely contribute to the weight reduction as the weight reduction is slightly lost since the stiffness (elastic coefficient) is insufficient.
2) I added Table 3 as you indicated in section 5.2.6.

## 6 Processing cost

**Question & Comment (Akira Kageyama)**

In chapter 5, you refer to the processing cost, environmental measures, and workplace environment. For processing cost, please indicate the following differences: 1) special furnace and infrared heater ≒ consumed electric power, 2) reduction in process, cost of cutting, and 3) mold lifespan. You say that the total of these is 20~30 %, but the reader cannot see which one is the largest contributor. Since the actual numbers may be a corporate secret, you can show them as indexes. Also, what kinds of worsening work environment and environmental load are there in using graphite? You also say “product accuracy increases by low-temperature process.” Is this related to the product of coefficient of thermal expansion and temperature difference?

**Answer (Naobumi Saito)**

Coauthor Sekiguchi provided us with the particulars of the processing cost, and I added this as Table 2 in the paper. However, he commented that the figures are not that precise. The worsening of the work environment and increased environmental load by graphite were explained in the paper. The reason for the improvement of product accuracy by low-temperature forging is as you indicated.

## 7 Basic core technology of AIST

**Question & Comment (Toshimi Shimizu)**

You mention that the structure control, analysis, and evaluation technologies of metal materials are the basic core technologies in which AIST excels. However, I think universities and other public research institutes have similar and equivalent potential. Can you explain in detail the potential that only AIST has? In relation to this, can you show by figures or tables the latest research trends of forging technology in Japan and overseas, and the relationship to AIST technology? In the first draft, you use a lot of photographs. Although they may be excellent proofs of direct evidence for readers in your field, the general reader cannot understand the difference. Can you show the results and proofs using numerical tables?

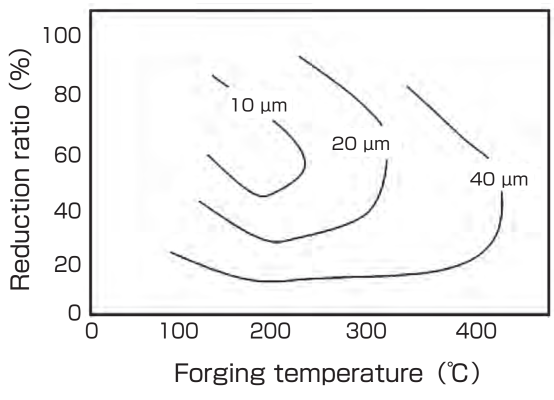
**Answer (Naobumi Saito)**

The point of this R&D is that the forging of magnesium alloy continuous cast bar that was never used before as forging material was made possible by actively incorporating the phenomenon of dynamic recrystallization, for which academic research has been done extensively, into the manufacturing process. It can be said that AIST bridged the basic academic result and the manufacturing process to enable such technology to be realized, and I think this is AIST’s potential. This is actual practice of the AIST slogan, “Technology to Society,” and I added these points to the conclusion. Concerning the latest research trends of forging in Japan and overseas, I will not add them because this paper centers on the results of joint research with a company, and the content will become too scattered if I discuss the overall forging technology. I added photographs and graphs in appropriate places to enhance the understanding of general readers.

## 8 Contour map showing the effect of dynamic recrystallization as basic core technology

**Question & Comment (Akira Kageyama)**

The major point of the technology in this paper is to decrease the grain diameter by one digit through dynamic recrystallization. If temperature and reduction ratio affect the dynamic recrystallization, I think you should consider expressing this phenomenon using a kind of contour map where the grain diameters of the crystals are shown on the X-Y two dimensional coordinates. For example, from the data that the authors have, using the AZ91 alloy or AZX91 + Ca alloy, can you use temperature as the x-axis and reduction ratio as the y-axis to show the obtainable grain size? (The figure shown below is only for reference.)

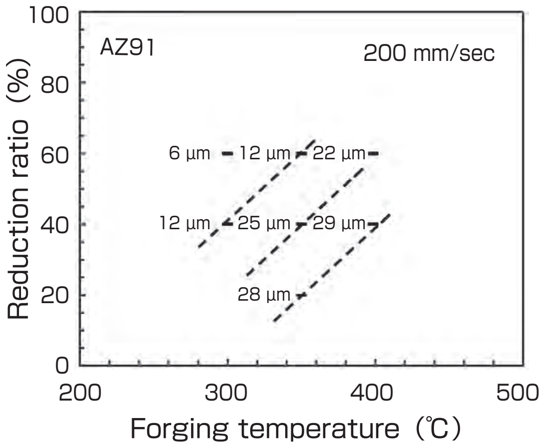



**Conceptual diagram of the relationships among forging temperature, reduction ratio, and grain diameter**

This data will be the process window itself, and is extremely important in realizing the technology. Also, does the strength of the formed parts increase if the grain diameter decreased from the order of 100 µm to 5~20 µm? If so, please state the mechanism of strength improvement (this can be partially hypothetical). If you continue this discussion, we come to the question that how many µms is the optimal grain diameter. If you discuss this point also, I think it will further help the verification of AIST’s basic core technology (composition control, analysis, and evaluation technologies).

**Answer (Naobumi Saito)**

The point you indicated had an important meaning in the R&D for the NEDO Project. Therefore, we attempted creating a figure just like the one you indicated based on the data in Fig. 3, in the discussion of ideation, hypothesis setting, and combination of elemental technologies for the NEDO Project. However, we did not have sufficient quantity of data, and the figure was not very convincing. Therefore, we used Fig. 3 as it is shown in the paper. For reference, I show you the figure that we tried to create.




**Reference: Relationship between the forging temperature, reduction ratio, and grain diameter created from the experimental result**

The fact that the strength increases at room temperature by refining the crystal grains of metal materials is already known as the Hall-Petch Relation. We added this in the text of subchapter 3.1.

## 9 Forged prototype

**Question (Toshimi Shimizu)**

The company selected the square pin heat sink as the forged prototype, and conducted the low-temperature forging process based on the forging blanks and basic data provided by AIST. In the first draft, only the results where the forging temperature was altered was shown, but didn't you come across other issues that you had to overcome during the prototyping and development? It seems that contrary to the background where "it was difficult to satisfy the mechanical property by the conventional forming process for the magnesium alloy" that you mention in the beginning of the paper, the issues were very easily overcome.

**Answer (Naobumi Saito)**

During the prototyping and development, we did not hear from the company about any new issues that had to be overcome. Also, the prototype (heat sink) is not an item that requires strength, so we did not conduct the evaluation for mechanical property. However, through the microstructure observation of the pin part of the heat sink, we confirmed that the grains had been refined to 10 µm or less. Therefore, we think it has high strength. The idea of realizing grain refinement by dynamic recrystallization during the forging process was the "Columbus' egg" or seemed difficult but was easy once it had been done. Although it is now taken for granted, we never thought of it when the Project started, and I would like to emphasize that after discussing a lot with the companies and universities, it was proposed by AIST. Also, the magnesium alloy is a material that easily undergoes grain refinement by dynamic recrystallization, and the development of this research whose key point was grain refinement went relatively smoothly as a result.