Journal of Korean Powder Metallurgy Institute
Vol. 5, No. 4, 1998

Advancement in Powder Metallurgy of Aluminum Alloys

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(Received October 28, 1998)

Abstract Along with the growth of conventional ferrous powder metallurgy (PM), PM of aluminum alloys has been intensively investigated in Japan. Although rapidly solidified aluminum alloy powder was first used in the USA,[1] commercialization for consumer market was first realized in Japan.[2] In order to achieve the viable cost-performance including Near Net Shape (NNS) formability, we developed three processes, powder extrusion, powder forging and sintering. The new powder extrusion process does not use either capsulation or vacuum degassing. The new powder forging does not need lateral flow. The new sintering process does not use liquid phase. The performance achieved by the processes is outstanding mechanical or physical properties that has potential to substitute cast iron, steel, titanium Metal Matrix Composite (MMC) or Ingot Metallurgy (IM) aluminum alloys. Cooperation with customers, powder suppliers and research associations contributed to the advancement of PM aluminum alloys in Japan.

1. Introduction

It is well admitted that PM has two substantial merits, potential to create new materials that cannot be made by IM method, and cost saving as NNS formability. Ferrous PM is mostly depending on economics of NNS, and cemented carbide is, on the other hand, depending on the other one. Aluminum PM has both merit but each one requires completely different processing routes and raw materials. In this paper, new alloys along with three processing routes, extrusion, forging and sintering, for rapidly solidified prealloy powders are explained as industrially viable processes.

2. Rapidly Solidified (RS) Powder

The RS Al alloy powders are manufactured by atomization. Although there are numbers of exotic RS powder making processes, none of them is more suitable than the atomization from both practical handling and economical point of views. Among the requirements for PM, consistency of microstructure and chemistry is most important, because the merit of RS alloys is given mostly by it. And then compressibility and compactability are important because powders must be compacted and handled. Contamination either from molten metal or from ambient atmosphere should be minimized. Some possible impurity elements in mother alloys should be carefully inspected and eliminated if they are proved to be detrimental. Cross contamination is often not easy to be eliminated, because powder particles tend to stick somewhere in the production line, particularly in corners and bends. Therefore, every process from the beginning to the end, should be carefully cleaned and operated properly, otherwise serious quality problem may happen. The economics of raw powder is always recognized as the issue of "Chicken and Egg". The bigger the powder production lot, the better the economics of the powder. Therefore, it is recommended not to develop too many alloys for actual use.

3. Alloy Development

When RS Al alloys were developed in the USA, there were three major targets.[3] High strength alloys for aerospace structural application like Al-Zn-Co, heat resistant alloys for jet engine compressor rotor,

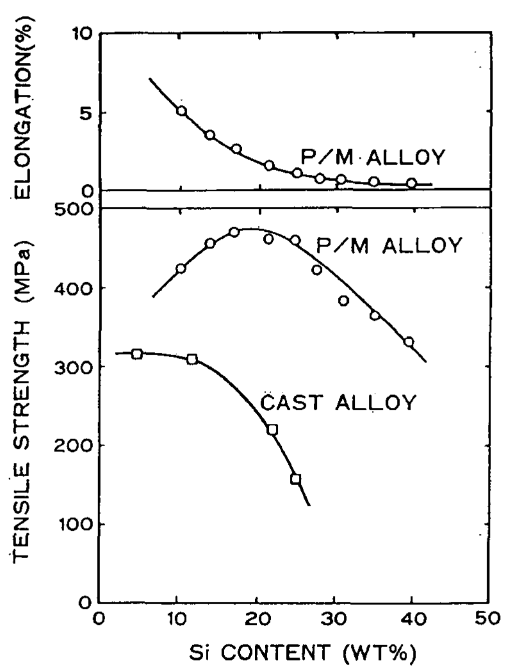

Fig. 1. Changes in tensile strength and elongation for Al-Si alloys.

like Al-Fe-Ce and high specific modulus alloys like Al-Li. All these targets are obviously intended only to use as aerospace application. In Japan, the market of high performance Al alloys was not expected in aerospace industry but in automotive and home appliance. They needed light materials as substitute for cast iron or steel. The major issues of Al alloys to substitute ferrous materials were wear resistance, thermal expansion and Young's modulus.

Using RS, Si and TM(Transition Metal Elements) were added to have fine crystals or precipitates.[4] Si was selected as major alloying element. As shown in Fig. 1 and Fig. 2, it contributes to increases of Young's modulus, hardness and strength, to decrease of thermal expansion.

Si has very limited solid solubility and does not form intermetallic compound with Al. Therefore, the microstructure of Al-Si binary alloy consists only of alpha Al and Si crystals. It seems like a MMC. RS Al-Si alloys are distinguished by the size of Si crystals. It primarily depends on the RS rate during the

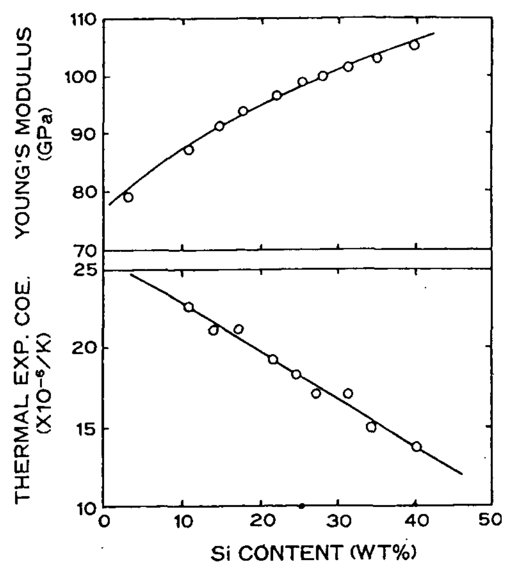

Fig. 2. Changes in Young's modulus and thermal expansion.

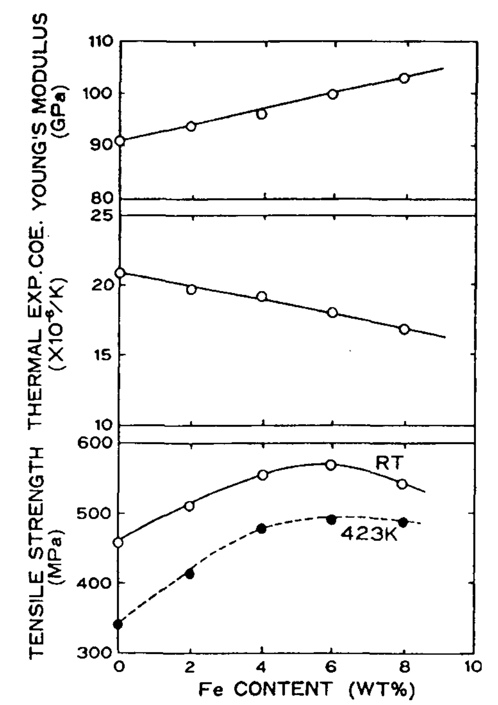

Fig. 3. Changes in tensile strength, thermal expansion coefficient and Young's modulus for Al-15Si-Xfe-3Cu-1Mg.

atomization. However, Si-modifier like P is also effective to refine Si crystals.[5]

The second alloying elements group is TM. It is chosen to form fine intermetallic compounds with Al and with some other third elements. As shown in Fig. 3, the second group of alloying elements must have enhancing effect along with Si. Fe, Ni, Mg, which are chosen to fit to each application. Age-hardening elements such as Cu and Mg are of ten used to obtain better strength or wear resistance at room temperature.

4. Extrusion

Wrought Al alloys developed in the USA were extruded at high reduction ratio. Furthermore, the powder was encapsulated and vacuum degassed at elevated temperatures, as shown in Fig. 4.

The reasons why such processes were needed are detrimental effects of retained hydrogen that causes blistering and of surface oxides that block the sintering of powders. From economical point of view, encapsulation was definitely not acceptable for us, even though the extrusion was acceptable. The purpose of encapsulation is basically to remove hydrogen or crystallized water from the powder. In case of Al-Si-TM alloys, the vacuum degassing was not found to be necessary and then less expensive controlled atmosphere was adopted. The effect of reduction ratio on the mechanical properties was examined and our conclusion was 10:1 for the practical guideline of Al-Si-TM alloys.

Near Net Shape extrusion is also of consequence

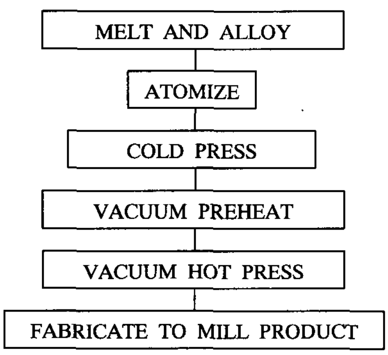

Fig. 4. The powder metallurgy process.

Fig. 5. Rotor shape extrudates.

for commercialization. Fig. 5 shows rotor shape extrudates. As Al-Si-TM alloys have high strength and high resistance to deformation, extrusion was not easy. Sometimes, billets were plugged in the extrusion die. Surface of extrudates was often tore. Too high pressure broke the tooling. Dimension and geometry were changed or scattered during a single extrusion. Distortion due to spontaneous twisting and bending often happened.

In short, these practical problems were solved by integration of know-how of operation, tailored equipment and toolings.

5. Forging

NNS-Extrusion is not always the best route for manufacturing components. Forging is sometimes more preferable than the extrusion.

Fig. 6 reveals scroll shape forging products. Hot forging of extruded bar stocks is a simple solution but it is not practical for both economic and technical reasons. The overall material yield of powder extrusion, cutting and forging sometimes reaches down to 50%. The hot forgeability of Al-Si-TM alloys is not comparable to conventional wrought Al alloys such as 2024 or 7075. However, the direct powder forging process had been considered not to be

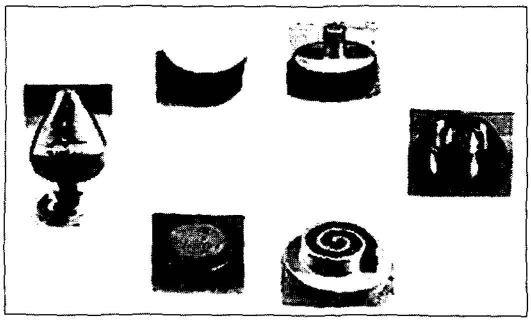

Fig. 6. Scroll shape forging products.

applicable because of oxide films on the powder surface that inhibit diffusion bonding. As shown in Fig. 7, what we invented is the direct powder forging method using specific preheating method that enhances decomposition of hydroxide and eliminates further oxidation.[6,7] It means that if powder surface is free from hydroxide, diffusion bonding happens under appropriate temperature and pressure conditions.

6. Sintering

MMC such as Al-SiC is an interesting material but it is not an easy material to use as industrial products. Its machinability is terrible and it is often too abrasive to materials mating with it. It originates from hardness of SiC, but also provides the merit of MMC. If we substitute SiC for AlN that is less harder than SiC but still has ceramic properties, Al-AlN composite could be a practical MMC. When high

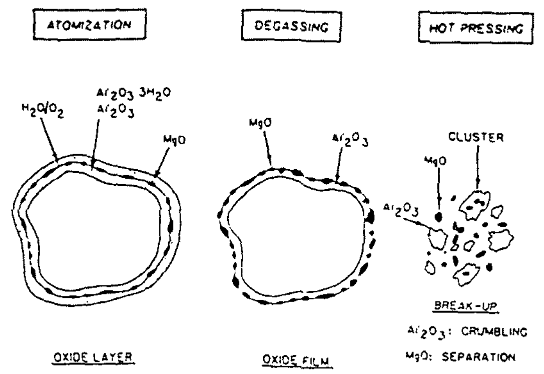

Fig. 7. The direct powder forging process.

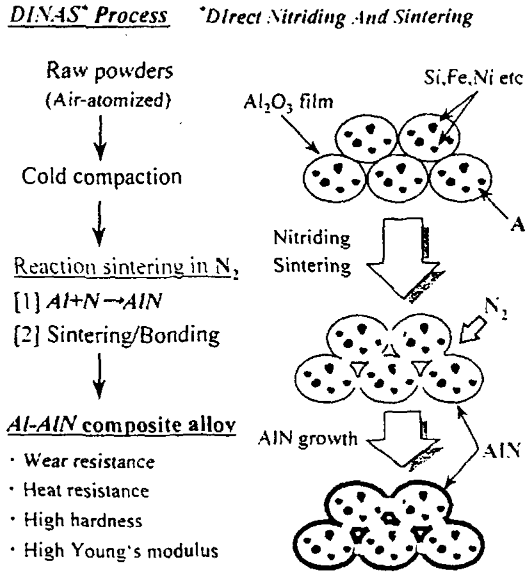

Fig. 8. The direct nitriding and sintering process.

strength is not required and non-seizure property is required, Al-AlN composite made by press and reaction-sintering method is a good candidate material.

As shown in Fig. 8, the method of AlN formation from Al-Mg alloy under nitrogen atmosphere was invented. The in-situ formed AlN from Al matrix gives us segregation-free distribution of AlN and ideal bonding to the matrix. Mg acts as deoxidizer of alumina and enhances the sintering of reduced aluminum. The process is applicable to various Al alloy systems that contains certain level of Mg as alloying elements.[8]

7. Conclusion

The advancement of aluminum powder metallurgy since late '70 was reviewed in Fig. 9. New processes and alloys were developed to meet the market demands. The first innovation was the encapsulation-free powder extrusion process for Al-Si-TM alloys. The second innovation was the direct powder forging process for 3-D shape. The third one was reaction sintering of Al-AlN. Excellent material properties were fully utilized as PM components that

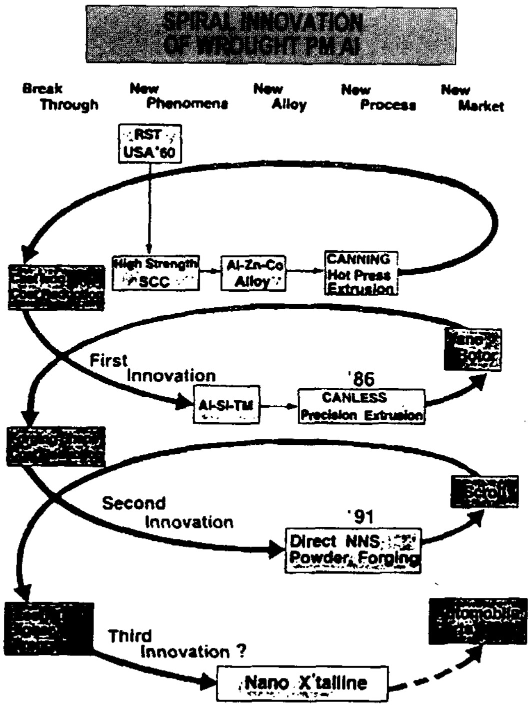

Fig. 9. The advancement of Aluminum Powder Metallurgy since late '70.

were formed by Near Net Shaping processes.

Acknowledgement

Commercialization of new Al PM components required not only PM manufacturer's own effort but also collaboration of customers, powder suppliers, equipment manufacturers and subcontractors. The author would like to express his best appreciation for all of those who contributed to the commercialization. The author also would like to thank to colleagues who worked out with challenge spirit and patience.

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