Transactions of the Materials Research Society of Japan. Vol. 20

Recyclable Design and Heavily Plasticization for an Eutectic Al-Si Cast Alloy

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A new design concept for the recyclable material is proposed. Key idea is that heavy working plays an important role on building the fine microstructure for plural phases alloys. The Al-Si binary system has two phases and includes no dislike elements for the *ecomaterial*. The heavy cold-work, however, can hardly apply to the eutectic and/or hyper-eutectic Al-Si cast materials. A thermo-mechanical processing on Al-12 mass%Si cast material provides a refined microstructure where it shows the heavy plasticity such as 99% reduction. The tensile strength of the cold-worked material is higher than twice strength of the cast one.

1. RECYCLABLE DESIGN FOR SUSTAINABLE DEVELOPMENT

The products generally consists of many kinds of materials. On the other hand, it has been required to save resources and energy, and to recycle materials. Problems in scrap metal recycling were discussed from the viewpoint of metallurgy in the previous paper [1]. Engineering subjects for the ideal recycling system are to reduce impurity content from scrap melt, to immunize metals against impurities or make metals innocuous from impurities, and finally to replace metals with inherently recyclable metals. It means a built-in recyclability in materials design. As a design of the *ecomaterials* (environment conscious materials), Nagai *et al.* [2] proposed an approaching idea, recyclable design for sustainable development, where materials and products are in harmony with the earth environment and provide a simplified recycling. What kinds of design factors are required for alloys there ?

1.1. Recyclability and ecology for raw materials

Raw materials' choice has been depend on their cost or performance in the process and product. However, recyclable design introduces limitations for the raw materials' choice as follows.

(1) Recyclable resources/elements should be used predominantly.
(2) Regarding on the mostly exhausted resources /elements, we should use other exhaustless materials at first; restrict applications with scarce materials; use scarce materials in a recyclable state; and prohibit to use poisonous materials.

For an example, it is speculated that iron, aluminum and silicon elements are stocked in the earth well and they have good recyclability and ecology.

1.2. Simplification of recycling and scrapping on microstructural design

To simplify the recycling and scrapping the alloy compositions should be as simple as possible without any hardly removable element. However, the low alloy and simplest composition may lack the ability to provide the variety of properties. Then the material is designed with several alloying elements or with another material. In the case of the composite materials it is generally difficult to recycle.

Some alloys having plural phases with less solid solubility each other such as Al-Si system are able to design the metal-metal *in-situ* composite with high recyclability. Some materials including steel are able to vary their microstructural configurations without the compositions changing where different structure/phase are combined each other as a *mesoscopic complex* [1]. In both cases, the variability of microstructure could be utilized mainly in a sense that a different phase has a different nature.

1.3. Adequate balance with properties

Recyclable design should also consider the high performance of the material. But excess performance is unnecessary, because it is waste of resources and energy. To make balanced properties a combination of plural phases is considerable. For an example, Al-Si based cast material has medium strength, good wear and light weight. The heavy cold-work can not apply to the eutectic and hyper-eutectic cast materials. However, the eutectic Al-Si alloy having a fine microstructure exhibits a super-plasticity. Then the microstructural refinement might provide higher strength, toughness and ductility where good and adequate balance with each property could be design.

2. FINE MICROSTRUCTURE DEVELOPMENT IN PLURAL PHASES ALLOY

2.1. Prototype in steel

On the premise of recycling the design and arrangement for plural phases or partial structure difference, *hetero-structure* (heterogeneous microstructure), is a promised method to control adequate balance with properties as mentioned above. The balance between strength and ductility mainly depends on the type and configuration of structural combination in steels.[3] Basic concept of *hetero-structure* is almost the same with that of composite material. But the *hetero-structure* can be design from a simple alloy composition. If the alloy consists of recyclable elements, it is enough to remelt the scrap.

Ni addition in steels is effective for brittle fracture control, but interrupts recycling of steel. As a prototype of the *hetero-structure* control, there is a good example on the Ni-free steel.[4] The final hot-rolling process produced a fine microstructure only around surface layer for the Ni-free steel. The property arresting crack propagation of the plate was much improved as good as that of Ni-addition one.

2.2. Basic concept of the *hetero-structural* design and control

Mechanical properties can be generally controlled by changing microstructures. Basic ideas for the design and control of the heterogeneous structure, where the second phase basically are distributed in matrix with high density and fine structure, are mentioned in the following. In those the heavy working plays an important role on building the fine microstructure.

(1) Microscopic distribution of second phase:

When second phase is deformable, the increase of plastic strain leads to the decrease of lamella spacing.

When second phase can not be deformed, the plastic strain cause the cracking of second phase.

(2) Deformation of matrix and a role of second phase as pinning site:

The rapid increase of plastic strain in matrix makes a dynamic recovery and recrystallization in fine scale grain size.

The second phase is a site for local deformation and a pinning site for the dynamic recovery in matrix.

3. PLASTICIZATION FOR AN EUTECTIC AL-SI ALLOY

Al-Si binary alloy might be a suitable system in the *ecomaterials* with sustainable development as mentioned above. Therefore, an idea of the *hetero-structure* design and control applied to the microstructural refinement and plasticization of an eutectic Al-Si alloy.

3.1. Refinement of Si crystal and microstructure

The microstructural modification and mechanical properties of Al-12 mass%Si cast alloy have been investigated.[5] The alloy contains the both primary and eutectic Si crystals which are the second phase and unable to deform at room

Table 1 The chemical compositions of an eutectic Al-Si binary alloy in the present study.

Element	Si	Cu	Fe	Ni	Ti	Mg	Zn	Mn	Al
mass%	12.60	0.01	0.14	0.04	0.05	0.00	0.00	0.00	bal.

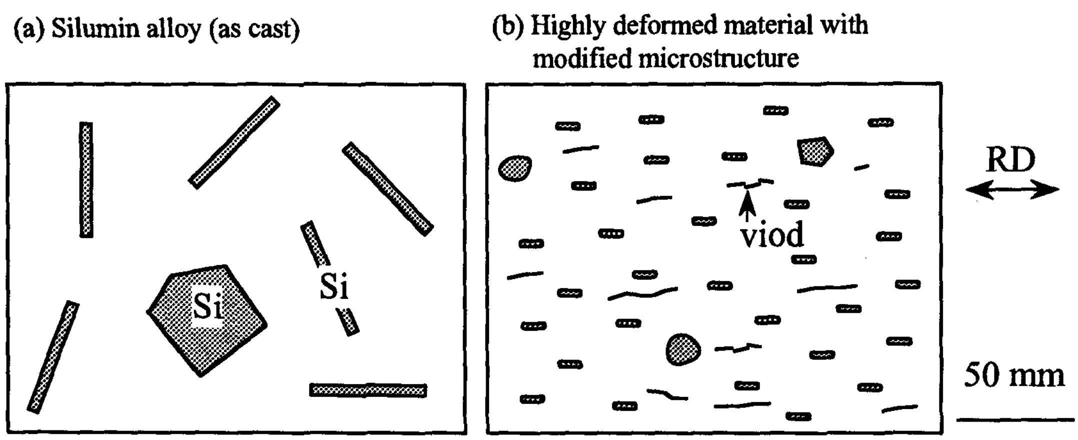

Fig.1 Illustration of microstructural feature for Al-12 mass%Si materials; (a) as cast, and (b) 90% cold-rolled following the thermo-mechanical treatment.

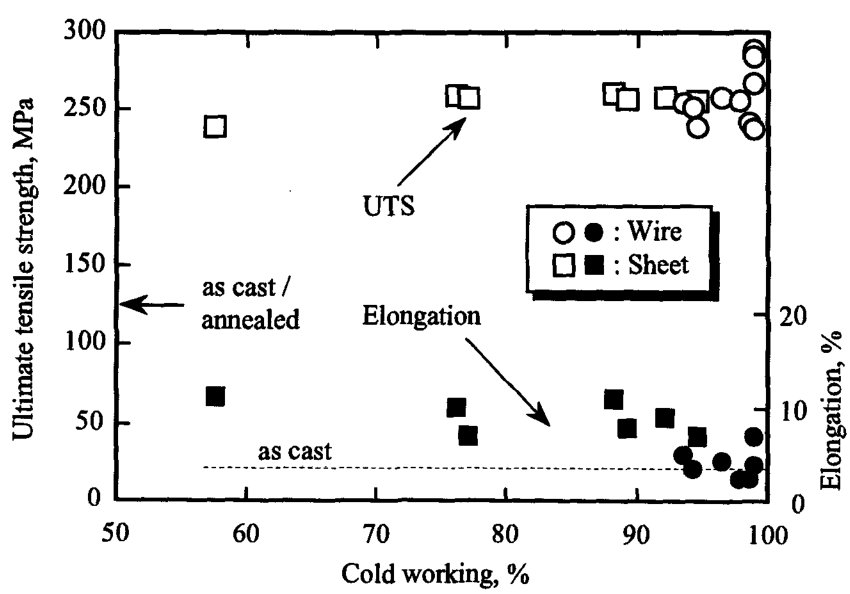

Fig.2 Tesile properties of cold-worked Al-12 mass%Si materials following the thermo-mechanical treatment.

temperature. The chemical compositions are listed in Table 1. The primary Si forms like a hexagon and about 50 μm diameter in average. The eutectic Si exhibits a needle or plate type form and about 5 x 50 μm in size. Fig.1(a) illustrates for the cast microstructure. The cast material shows a low ductility such as less than 23% cold-rolling reduction at room temperature.[5]

We developed a thermo-mechanical processing for the Al-Si alloy where the cold-work within limitation and the annealing heat treatment are multiply combined.[5] The flat-rolling, grooved-rolling and swaging are available for the work. By the cold-working each primary Si cracks into a few pieces and decreases the size itself. The void formed by the cracking heals up with the annealing. Then the thermo-mechanical treatment resulted in a fine microstructure as illustrated in Fig.1(b), and the alloy is fully annealed. The primary Si is almost refined less than 10 μm in diameter. Mostly Si crystals are about a few micron-meter and aligned along rolling direction. Therefore, the second phase is distributed in the matrix with high density and fine size. In addition Si crystals are spheroidized. Then the size of each second phase is lower than one fifth that in the cast material.

3.2. Plasticity and tensile properties

The Al-12 mass%Si alloy with the refined microstructure exhibits a good workability, tensile strength and elongation. The ultimate tensile strength of the thermo-mechanical treated material is almost the same with that of the cast one which is about 125 MPa. The elongation of the treated material is much higher than that of the cast one.

Fig.2 shows the relationship between tensile properties and reduction of cold-working for the thermo-mechanical treated material.[5] In both sheet and wire forms the heavy plasticity such as over 90% reduction is available. The tensile strength of the cold-worked materials with over 60% reduction is higher than twice strength of the cast one. Even in heavily cold worked samples the stress-strain curves showed a good ductility and elongation with about 3%. The work hardening of Al matrix might be responsible for the higher strength in the cold worked materials.

In the matrix of the cold worked materials the highly dense dislocation structure has not been observed for the heavily worked materials, but the sub-grains structure with about 200 nm in diameter was detected [5]. The increase of plastic strain in the matrix might make a dynamic recovery, because the fine second phase gave a pinning site efficiently. Furthermore, many voids were observed in the matrix as illustrated in Fig.1(b).

4. SUMMARY

A new concept of the *ecomaterial*, recyclable design for sustainable development, was discussed from its design factors. The eutectic Al-Si cast alloy has no dislike elements for the *ecomaterial*, but poor ductility. From the viewpoint of the *hetero-structure*, a thermo-mechanical processing applied to an Al-Si cast alloy and produced a refined microstructure. It showed the heavy plasticity up to 99% reduction. The cold-worked material exhibited much higher the tensile strength than the cast one. In recently the recyclable materials might establish superiority over other low cost or high performance ones.

The present work is sponsored by the special coordination research fund of the Science and Technology Agency, Japan.

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