ALUMINUM ALLOYS THEIR PHYSICAL AND MECHANICAL PROPERTIES

VOLUME I

CONFERENCE PROCEEDINGS

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DEVELOPMENT OF FINE-GRAINED 7075-0 SHEET FOR AIRCRAFT TAPER-ROLLED STRINGER

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Fine-grained 7075-0 sheets for aircraft taper-rolled stringers have been developed. The new material exhibits fine grain size (40 μm) and no grain growth after slight cold-reduction followed by solution treatment. Because of the fine grain size, the new material exhibits excellent properties compared with coarse-grained material (200μm) fabricated by conventional process. The new material is now massproduced and applied to taper-rolled stringers for the latest civil transports.

INTRODUCTION

The purpose of this paper is to describe the development of fine-grained 7075-0 sheet coil stocks for aircraft taper-rolled stringers. The fuselage of civil transports is composed of stringers, frames and skin sheets. The stringer is a structural beam in the longitudinal direction of the fuselage. The stringer was fabricated from 7075 alloy extrusions up to this time. With increasing tendency of weight saving, sheet-fabricated taper-rolled stringers whose thickness vary in the longitudinal direction of the fuselage were developed and applied to practical use.

In the fabrication of the taper-rolled stringer, 7075-0 sheets are taper-rolled, solutionized, water-quenched, roll-formed and aged to T6 temper. 7075 alloy sheets fabricated by a conventional process have some problems in application for the taper-rolled

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stringer, that is, cracking in the roll forming, and the decrease of fracture toughness and fatigue strength.
These problems of the conventional material are due to coarse grain size (~200μm) and marked grain growth (~300μm) after the slight taper-rolling reduction(10~30%) followed by the solution treatment.

Although many investigations (1)~(3) on grain refinement in 7000 series alloys have been carried out, fine-grained 7075-0 sheet coil stocks which exhibit no grain growth after the slight cold-reduction followed by the solution treatment have not been developed yet. The present study was carried out to develop the new fabrication process of 7075-0 sheet coil stocks for the taper-rolled stringer.

GRAIN REFINEMENT

Experimental procedure

A 6mm thick 7075 alloy plate produced by a conventional process was used for all of grain refinement tests described in this paper. The chemical composition of the alloy is presented in Table 1.

Fig.1 shows a thermomechanical process for grain refinement investigated in this study compared with a conventional fabrication process for 7075-0 sheet coil stocks. The new process includes deformation, rapid-heat annealing and low temperature re-annealing steps.

The plate was cold-rolled by 0 ~ 80%, heated to recrystallization temperature between 680K and 760K at the heating rate of $8 \sim 7 \times 10^3$ K/ks, annealed for 30~2400s and cooled at the rate of $8 \sim 1.6 \times 10^4$ K/ks

These annealed sheets were re-annealed at 475~725K for 3.6ks and slowly cooled at the rate of 8K/ks.

The re-annealed sheets were processed according to the fabrication process for taper-rolled stringer as

TABLE 1–Chemical composition of test alloy (mass%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.09	0.19	1.63	0.01	2.65	0.21	5.6	0.02	bal.

TABLE 2–Fabrication process for taper–rolled stringer.

(1) Material : 7075–O Sheet $(3\sim4^{t}mm\times150^{w}mm\times10^{\ell}m)$
(2) Taper Rolling : Cold Rolling by 0~80%
(3) Solution Treatment : 733~772K×2.4Ks→W.Q.
(4) Roll Forming
(5) Joggling
(6) Aging : 393K×86.4Ks

shown in Table 2. The solution treatment of the alloy was carried out by rapid heating using a salt bath. Grain size measurements and TEM observations were carried out at the main stage of the fabrication process for 7075-O sheets and taper-rolled stringers.

Experimental Results

Fig.2 shows the effect of cold reduction before the rapid-heat annealing on the recrystallized grain size of 7075 alloy. The grain size becomes fine with increasing the cold reduction. Fine grain size smaller than 60μm can be obtained by the cold reduction higher than 30%.

Fig.3 shows the effect of heating rates in the first step annealing on the recrystallized grain size of 7075 alloy. The grain size is much influenced by the heating rate in recrystallization process. The fine grain size smaller than 60μm can be obtained at the heating rate of 7×10^{2} K/ks or over. On the contrary, the coarse grain size (~180μm) is obtained in the case of slow heating rate (8K/ks) similar to that of the conventional process.

Table 3 shows the effect of annealing conditions in the first step annealing on the recrystallized grain size of 7075 alloy. The fine grain size smaller than 60μm can be obtained by the rapid-heat annealing at temperature higher than 700K regardless of the annealing time.

The effect of cooling rates after the rapid-heat annealing on the grain size of 7075 alloy was investigated. The hot-rolled plate was cold-rolled by 50%, rapidly heated (3.3×10^{3} K/ks) to 740K for 300s and cooled to room temperature at the rate of $8\sim1.6\times10^4$ K/ks. The grain size was fine (~40μm) and unchanged regardless of the cooling rate.

However, there existed a problem on the grain growth of the slowly cooled alloy after the slight cold reduction followed by the solution treatment.

TABLE 3–Effect of annealing conditions on grain size of 7075 alloy cold–rolled by 50%, rapid–heated (3.3×10^3K/Ks) to 680∼760K for 30∼2400s and quenched.

Annealing Temp.(K)	Annealing Time (s) 30	60	180	300	600	1200	2400
680	90	70	60	60	60	60	60
700	50	40	40	45	40	40	40
720	40	40	40	35	35	35	35
740	30	40	40	30	35	30	30
760	30	35	35	30	30	30	30

TABLE 4–Effect of cooling rate on grain size of 7075 alloy taper–rolled by 0∼80%, solutionized at 750K for 2Ks and quenched.

Cooling Rate (K/Ks)	Reduction of Taper Rolling (%) 0	10	20	30	50	80
8	35	40	180	60	35	30
160	35	40	180	55	35	30
480	35	40	150	60	35	30
1600	35	40	60	40	30	25
3200	35	35	40	35	30	25
8000	35	35	40	35	30	30
>16000	35	35	35	35	30	20

Table 4 shows the effect of the cooling rate on the recrystallized grain size of 7075 alloy after the taper rolling followed by the solution treatment.

Even if the grain size of the slowly cooled alloy was fine, marked grain growth occures after 20% taper rolling followed by the solution treatment. On the other hand, the rapidly cooled alloy (>1600K/ks) exhibits fine grain size and no grain growth after the slight taper rolling followed by the solution treatment. As mentioned above, the rapid cooling after the rapid heating is effective to keep the grain size fine after the taper rolling followed by the solution treatment.

However, the rapidly cooled 7075 alloy does not satisfy mechanical property limits for annealed sheet stocks because it age-hardens at room temperature.

Moreover, the taper rolling workability of the age-hardened alloy is not sufficient for the fabrication of the taper-rolled stringer. Consequently, re-annealing is required after the rapid cooling to control mechanical properties and to improve the taper rolling workability.

TABLE 5–Effect of re–annealing temp. on grain size of 7075 alloy taper–rolled by 0∼80%, solutionized at 750K for 2Ks and quenched.

Re–annealing	Reduction	of Taper	Rolling (%)			
Temp. (K)	0	10	20	30	50	80
300	30	30	35	35	26	15
475	30	40	40	35	30	15
525	35	30	40	35	26	20
550	35	40	40	40	30	20
575	35	35	40	40	35	25
600	35	45	45	45	30	25
625	35	35	150	55	35	30
675	35	35	180	55	35	25
725	30	40	180	65	30	25

Fig.4 shows the effect of the re-annealing temperature on the mechanical properties and the grain size of rapidly cooled 7075 alloy. The re-annealing at temperature higher than 550K is required to satisfy mechanical property limits for 7075-0 sheets. The grain size is almost constant regardless of the re-annealing temperature.

The re-annealed sheet was taper-rolled and solutionized at 750K for 2ks. Table 5 shows the effect of the re-annealing temperature and the taper-rolling reduction on the recrystallized grain size of solutionized 7075 alloy.

The fine grain size can be obtained in the alloy re-annealed at temperatur lower than 600K.
On the other hand, marked grain growth occures in the alloy re-annealed at temperature higher than 625K after 20% taper rolling followed by the solution treatment.

Consequently, the re-annealing at 550 ~ 600K is required after the rapid cooling for the grain refinement and the improved taper rolling workability.

To summerize test results, fine-graind 7075-0 sheets which exhibit no grain growth after the slight cold-reduction followed by the solution treatment can be obtained by the thermomechanical process as shown in Fig.5.

Discussion

The mechanism of the grain refinement in the new fabrication process is discussed in the following. The fine-grained 7075-0 sheet can be obtained by the special two-step annealing process which includes the rapid-heat annealing and the low temperature re-annealing.

In the first step of the annealing process, cold-rolled sheets are rapidly heated to solution temperature and recrystallized. In aluminum alloys, it is generally accepted that recrystallized grain size becomes fine with increasing heating rate. Wert et al(4)~(5) reported simillar results for 7075 alloy.

Therefore, the fine recrystallized grain obtained in the first step of the new process is due to the rapid-heat annealing.

In the second step, rapidly heated sheets are re-annealed at relatively low temperature to control mechanical properties. Even if the original grain size after the first step annealing was fine, the grain size after the slight cold-reduction followed by the solution treatment is much influenced by the re-annealing temperature.

Photo.1 shows TEM structures of 7075 alloy after the second step annealing. In the case of high temperature re-annealing (675K), large second-phase particles (~1μm) identified as AlCuMgZn phase and $MgZn_2$ phase, and small particles (0.1~0.2μm) identified as E phase ($Al_{18}Mg_{13}Cr_2$) are observed. Large particles precipitate during annealing at high temperature and slow cooling.

E phase precipitates during homogenizing and hot working of a ingot.

In the case of low temperature re-annealing (575K), small second-phase particles(0.1~0.2μm) and E phase are observed.

According to previous investigations (6)~(9), the recrystallization process of alloys containing second-phase particles is known to be much influenced by the size and the dispersion of particles. Dispersions of large particles accelerate recrystallization rates by the increase of nucleation sites for recrystallizing grains. On the other hand, dispersions of small particles decrease recrystallization rates by interfering with the formation of recrystallization nuclei and by retarding the growth of recrystallization grains.

Photo.2 shows the TEM structure of re-annealed 7075 alloy after cold reductions by 20% and 50% followed by the solution treatment. In the alloy cold-rolled by 20%, the alloy re-annealed at 575K don't recrystallize due to the dispersion of small particles and exhibits fine grain size, while the alloy re-annealed at 675K recrystallizes completely and exhibits marked grain growth as shown in Table 5, due to the low cold-deformation before the solution treatment.

On the other hand, the alloy cold-rolled by 50% recrystallizes completely regardless of the re-annealing temperature and exhibits fine grain size as shown in Table 5.

According to the results mentioned above, the cause of grain refinement in the new process can be explained as follows. In the first step annealing, fine recrystallized grains are obtained by the rapid-heat annealing. In the second step re-annealing, the alloy sheets are re-annealed at low temperature to precipitate fine second-phase particles which retard the growth of recrystallized grains. Therefore, the fine-grained alloy re-annealed at low temperature don't recrystallize after the slight cold reduction followed by the solution treatment. Consequently, the fine grain size produced by the rapid-heat annealing is maintained to the final stage of the fabrication process for the taper-rolled stringer.

In the case of the conventionally processed alloy and the slowly cooled alloy after the rapid-heat annealing in the new process, TEM structures of annealed sheets are similar to that of the re-annealed alloy at high temperature (675K) as shown in Photo.1.

Marked grain growth occures in these alloys after the slight cold-reduction (20%) followed by the solution treatment. The cause of marked grain growth of the alloys can be explained in a similar way of thinking to that of the re-annealed alloy at high temperature (675K) in the new process.

PROPERTIES OF NEW MATERIAL

To evaluate the properties of fine-grained 7075 alloy, 4mm thick 7075-0 sheet coil stocks were produced by the new process. The rapid-heat annealing in the new process was carried out by the use of a continuous annealing furnace.

Table 6 shows the mechanical properties and the grain size of new material compared with the conventional one.

The new material exhibits fine grain size (40μm), while the conventional one exhibits coarse grain size (180μm).

Fig.6 shows the effect of taper rolling reduction on the recrystallized grain size of the alloy after the cold reduction followed by the solution treatment. The new material exhibits fine grain size ($\sim$ 50 μm) regardless of the cold reduction.

On the other hand, the conventional material exhibits not only coarse grain size (180μm) but also marked grain growth ($\sim$300μm) after the slight cold-reduction followed by the solution treatment.

Formability of new material was evaluated by a bend test. The test was carried out within 1.8ks after the cold-reduction followed by the solution treatment.

Fig.7 shows the effect of cold reduction on 90° bend radius of the alloy after the cold reduction followed by the solution treatment. Because of the fine grain size, the new material exhibits superior formability compared with the conventional one.

Fabrication tests for taper-rolled stringer were carried out by the use of the new material. As the new material exhibits fine grain size and excellent formability, there existed no problems in the fabrication process.

The new material is now mass-produced and applied to the practical use for the taper-rolled stringer of the latest civil transports.

SUMMARY

A new thermomechanical process for the grain refinement of 7075 alloy for aircraft taper-rolled stringer has been developed. The new process in this study has two steps, that is, the rapid-heat annealing and the low temperature re-annealing. In the first step, cold-rolled alloy is rapidly heated to the solution temperature to obtain the fine recrystallized grain.

In the second step, the alloy is annealed at relatively low temperature to prevent the grain growth after the slight cold-reduction followed by the solution treatment. According to the new process, fine-grained 7075-O sheet coil stocks can be obtained.

The new material exhibits fine grain size and no grain growth after the slight cold-reduction followed by the solution treatment. Because of the fine grain size, the new material exhibits excellent properties for taper-rolled stringers compared with the coarse-grained material fabricated by the conventional process. As the new material exhibits optimum properties for taper-rolled stringers, it is now mass-produced and applied to the latest civil transports.

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TABLE 6–Mechanical properties and grain size of 7075–O sheet fabricated by new and conventional process

Process	T.S. (MPa)	Y.S. (MPa)	El. (%)	Grain size (μm)
New	233	118	20	40
Conventional	225	110	19	180

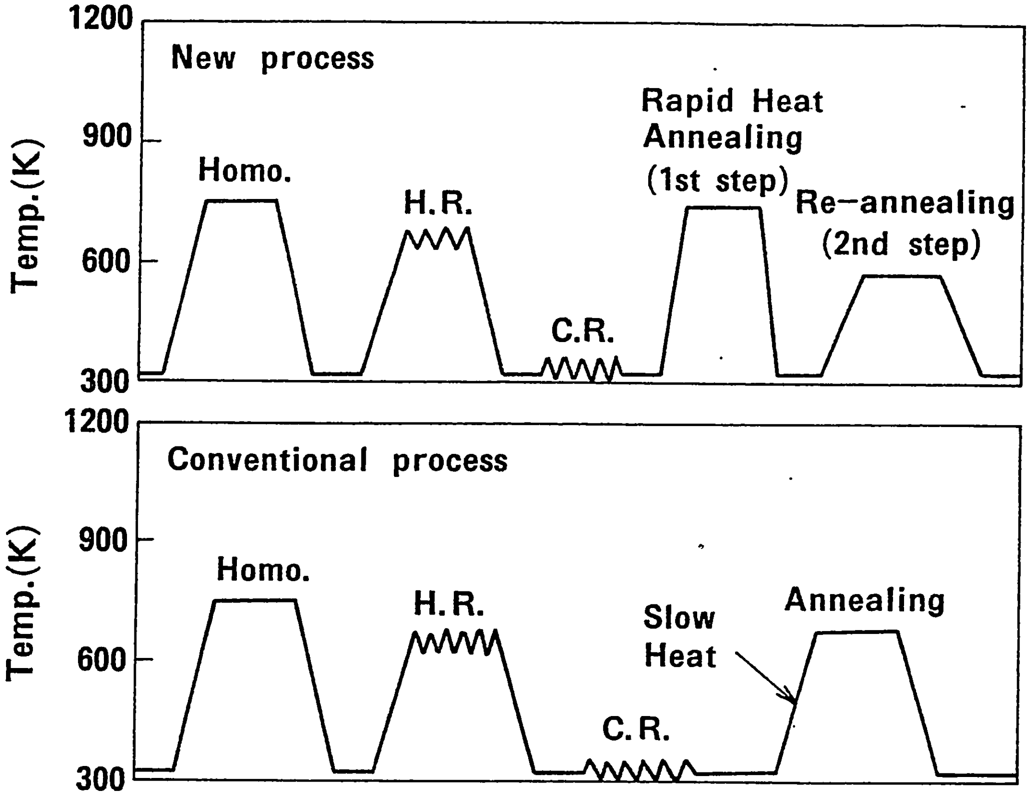


Fig. 1 Schematic diagram of grain refinement TMT

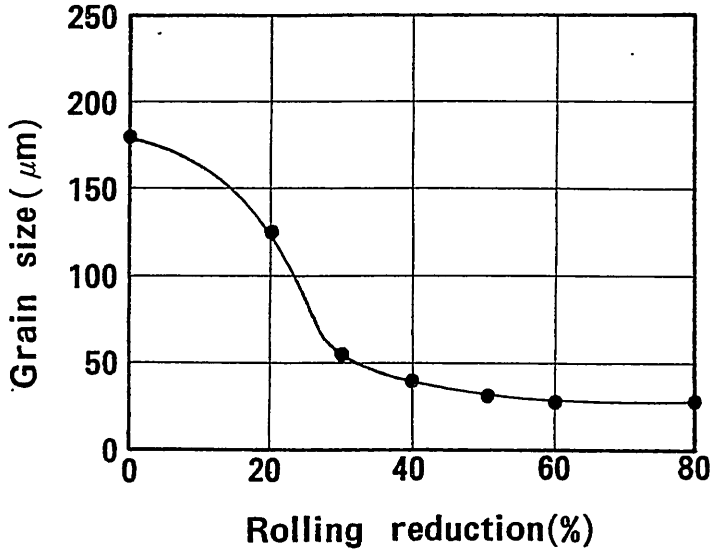


Fig. 2 Effect of cold reduction on grain size of 7075 alloy cold–rolled by 0∼80%, rapid–heated (3.3×10^3K/Ks) to 740K for 300s and quenched

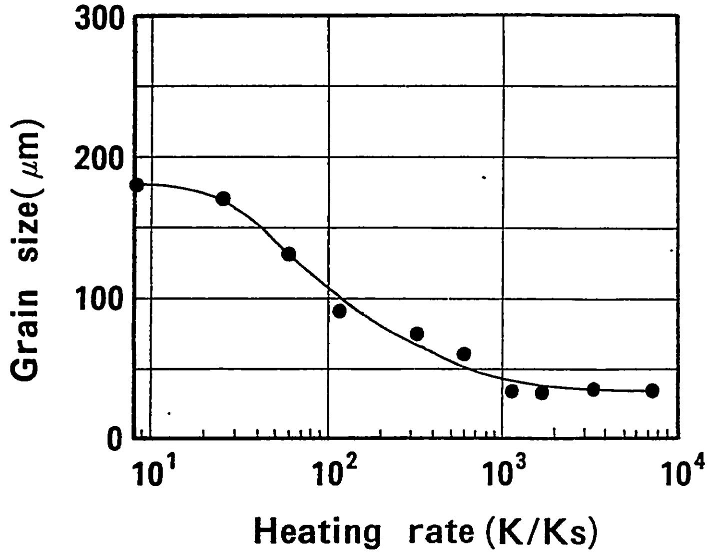


Fig. 3 Effect of heating rate on grain size of 7075 alloy cold-rolled by 50%, heated to 740K for 300s and quenched

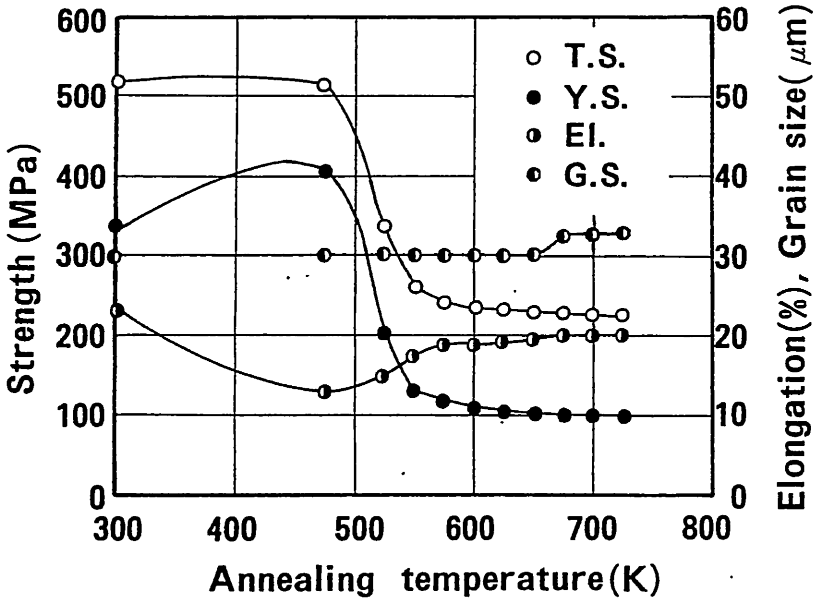


Fig. 4 Effect of re-annealing temperature on tensile properties and grain size of 7075 alloy cold-rolled by 50%, rapid-heated (3.3×10^3K/Ks) to 740K for 300s, rapid-cooled (6.6×10^3K/Ks) and re-annealed for 3.6Ks

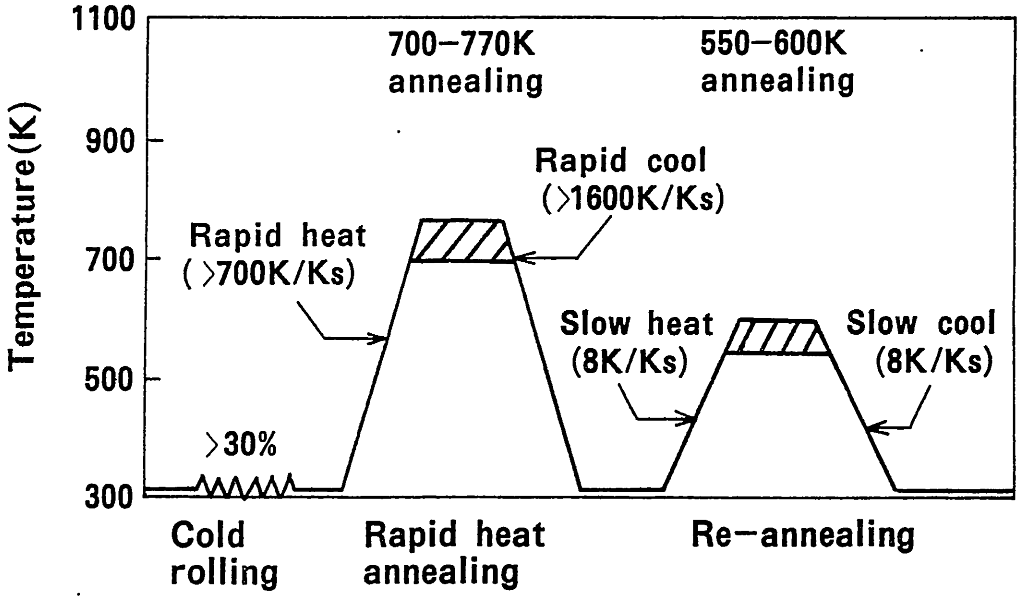
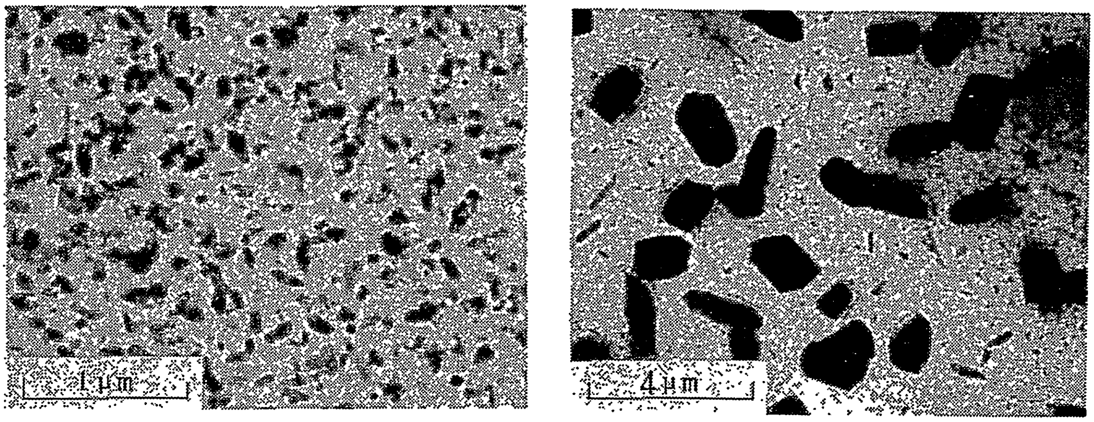
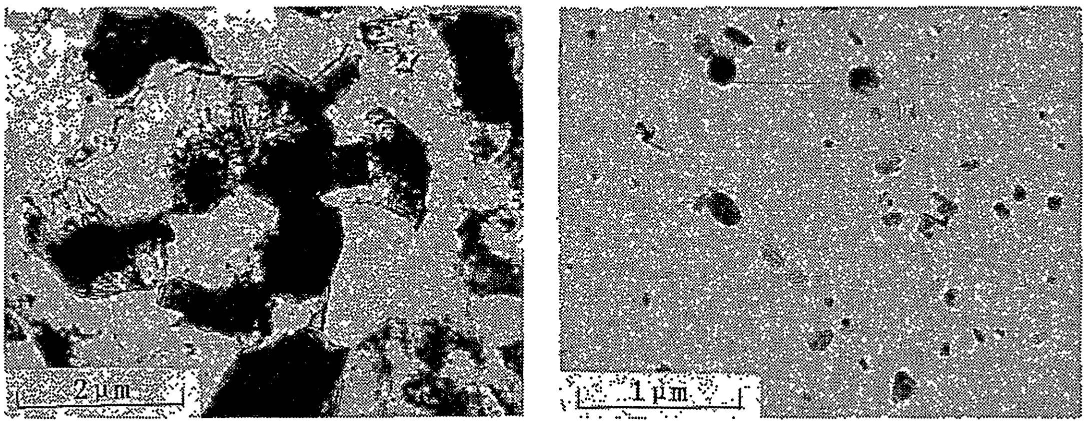


Fig. 5 Recommended annealing process for fine grained 7075–O sheet



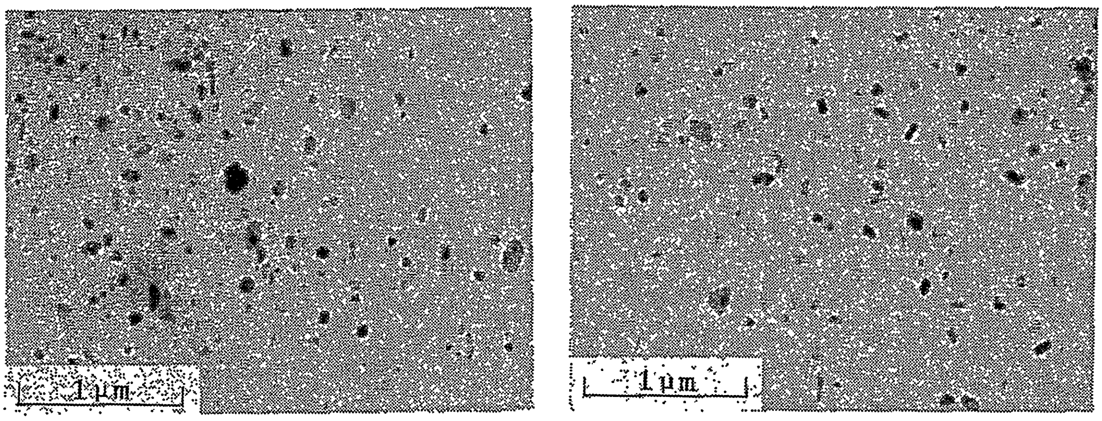
(1) 575K re–annealing (2) 675K re–annealing

Photo. 1 TEM structure of 7075 alloy cold–rolled by 50%, rapid–heated (3.3×10^3 K/Ks) to 740K for 300s, rapid–cooled (6.6×10^3 K/Ks) and re–annealed for 3.6Ks



575K re–annealing 675K re–annealing

(1) 20% cold reduction



575K re–annealing 675K re–annealing

(2) 50% cold reduction

Photo. 2 TEM structure of 7075 alloy cold–rolled by 50%, rapid–heated (3.3×10^3K/Ks) to 740K for 300s, rapid–cooled (6.6×10^3K/Ks), re–annealed for 3.6Ks, cold–rolled by 20% and 50% and solutionized at 750K for 2Ks

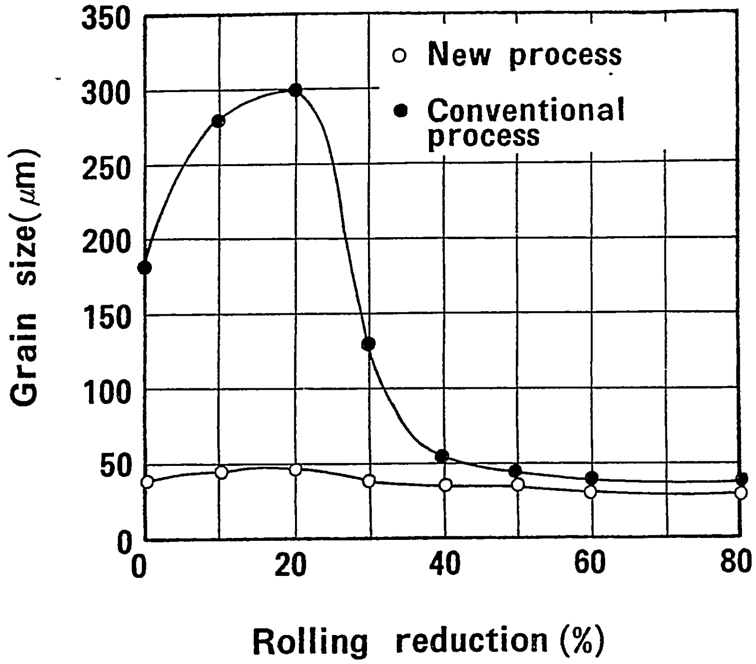


Fig. 6 Effect of taper rolling reduction on grain size of 7075 alloy taper–rolled by 0～80% and solutionized at 750K for 2 Ks

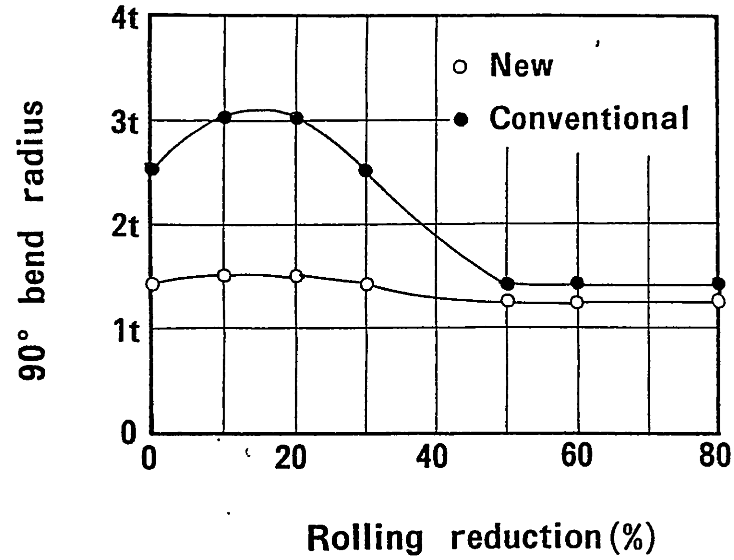


Fig. 7 Effect of taper–rolling reduction on bend radius of 7075 alloy taper–rolled by 0～80% and solutionized at 750K for 2Ks (t: thickness)

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