[Article ID] 1003- 6326(2002)02- 0218- 04

# Manufacturing of aluminum alloy ultra-thick plates by multidirectional forging and subsequent rolling ①

ZHANG Hui(张 辉)[1], LIN Gao-yong(林高用)[1], PENG Da-shu(彭大署)[1],
YANG Li-bin(杨立斌)[1], LIN Qi-quan(林启权)[1,2]
(1. Department of Materials Science and Engineering, Central South University, Changsha 410083, China;
2. College of Mechanical Engineering, Xiangtan University, Xiangtan 411105, China)

**[Abstract]** A combinatory large deformation model of multidirectional forging and subsequent rolling was proposed for producing high performance aluminum alloy ultra-thick plates. The results show that fine-grain (2~ 3 μm) structures were obtained when total deformation coefficient $\lambda = 32$ at 250~ 350 ℃ under a strain rate of about $0.1 s^{-1}$. The development of fine-grained structure can be characterized by the formation of strain-induced high energy dislocation and then transforms into new grain under large deformation at moderate temperature. The very fine secondary particles formed during large deformation play important role in retain the stability of the fine-grained structures.

**[Key words]** 7075 aluminum alloy; combination deformation model; forging; rolling
**[CLC number]** TG335.11 **[Document code]** A

## 1 INTRODCTION

Aluminum alloy ultra-thick plates of thickness more than 40 mm and with high mechanical properties are the main structural materials, which are extensively used in the modern aerospace industry and armor vehicles. Very fine-grained structures in aluminum alloys generally result in remarkable combinations of mechanical properties, for instance enhancing strength together with high levels of ductility, and large plastic deformation and recrystallization in many aluminum alloys can achieve grain refinement. Recently, several techniques have been proposed to provide very high plastic strains, including equal-channel angular pressing (ECAP)[1~ 4], torsion under high pressure (TUC)[5], cyclic-extrusion-compression (CEC)[6,7], multi-step forging (MSF)[8~ 11], and so on[5,11]. But it is impossible in the production of ultra-thickness plates to get very high plastic strains because of restriction of mill opening, therefore, , how to get enough deformation for industrial production of ultra-thickness plates has become a key fundamental research to be done. So far, only multidirectional forging seems to be a simple and practical method for industrial production because neither high working power nor special costly equipment is required. The 2024 aluminum alloy forgings with very fine grains (2 ~ 3 μm) and submicrophases (0.05~ 0.15 μm) were produced by a multidirectional large deformation (deformation coefficient $\lambda = 12$)[8,9]. The ultra-fine grained structures with grain sizes over the range from 0.5 μm to 5 μm were fabricated by multi-step forging of 2029 and 1420 aluminum alloys[11]. The present work is to put forward a combination deformation model with multidirectional forging and subsequent rolling, and to study the microstructural evolution during multidirectional forging and subsequent rolling of 7075 aluminum alloy, this can give guidance for the production of high performance aluminum alloy ultra-thick plates.

## 2 EXPERIMENTAL

A commercial 7075 aluminum alloy (Zn: 5.31, Mg: 2.19, Cu: 1.38, Cr: 0.29, Mn: 0.04, Fe: 0.21, Si: 0.14, and balance Al, mass fraction, %) with an initial grain size of about 200 μm was used as the samples, and the samples were machined with the starting dimension of $d$ 40 mm × 120 mm. Multidirectional compression tests were carried out with consequent changing of the loading direction in 90° through three mutually perpendicular axes (i.e. $x$ to $y$ to $z$ …) from pass to pass on an 3.5 MN servo-hydraulic press. The samples were deformed at 350 ℃ under a strain rate of about $0.1 s^{-1}$ with graphite powder as a lubricant. The deformed samples were quenched in water, slightly ground to a rectangular shape, and then reheated to 350 ℃ within 30 s and compressed approximately to deformation coefficient $\lambda = 2$ ($\lambda = H/h$, $H$ and $h$ are the specimen height of pre-deformation and post-deformation respectively) in each deformation pass. Subsequent rolling tests were kept in the same direction of the last compression at

① **[Foundation item]** Project (G1999064908) supported by the National Key Fundamental Research and Development Program
**[Received date]** 2001- 09- 18; **[Accepted date]** 2001- 11- 11

250~ 350 ℃, under a strain rate of about 0.1 $s^{-1}$ with machine oil as a lubricant on a $d$180 mm × 320 mm hot mill. The total deformation coefficient is considered as multiplication in the same deformation directions and summation in the different deformation directions.

Metallographic analyses were carried out on the mid-sections perpendicular to the last deformation direction using an Neophot-21 optical microscope (OM) and an H-800 transmission electron microscope (TEM). The average grain sizes are determined approximately by the mean of liner intercept method.

## 3 RESULTS AND DISCUSSION

### 3.1 Microstructural evolution during multidirectional compression

Typical microstructures evolved under multidirectional compression at 350 ℃ to various deformation coefficients are shown in Fig. 1, indicating that grain sizes decrease with increasing deformation coefficient and grain sizes about 15~ 20 μm, 12~ 15 μm and 5~ 8 μm were obtained in 7075 aluminum alloy when multidirectional deformation to a total deformation coefficient of $\lambda$= 5.8, 12.2 and 21.5 respectively.

### 3.2 Microstructural evolution under multidirectional compression and subsequent rolling

Typical microstructures of deformed sample under a combination of multidirectional compression to a deformation coefficient of $\lambda$= 12.2 at 350 ℃ and then rolling to a deformation coefficient of $\lambda$= 5.5 at the range from 350 ℃ to 250 ℃ (total deformation coefficient $\lambda$= 17.7) are compared with an industrially hot-rolled microstructure prepared under deformation coefficient $\lambda$= 27.6 (rolled from 300 mm to 11 mm in thickness ) at the range from 450 ℃ to 350 ℃ is shown in Fig. 2, illustrating that grain sizes in the former are smaller than that in the latter, and the former structures absent of elongated grain formed in rolling direction, but more equiaxed due to deformation direction changed alternatively in three of mutually perpendicular axes during multidirectional compression, this very similar to the ECAP with changing extrusion direction[1~ 4]. Because the degree of energy accumulation in deformed samples increases as decreasing deformation temperature, lead to the formation of refined grains.


**Fig. 1** Microstructures of samples after multidirectionally deformed at 350 ℃
(a) —$\lambda$= 5.8; (b) —$\lambda$= 12.2; (c) —$\lambda$= 21.5

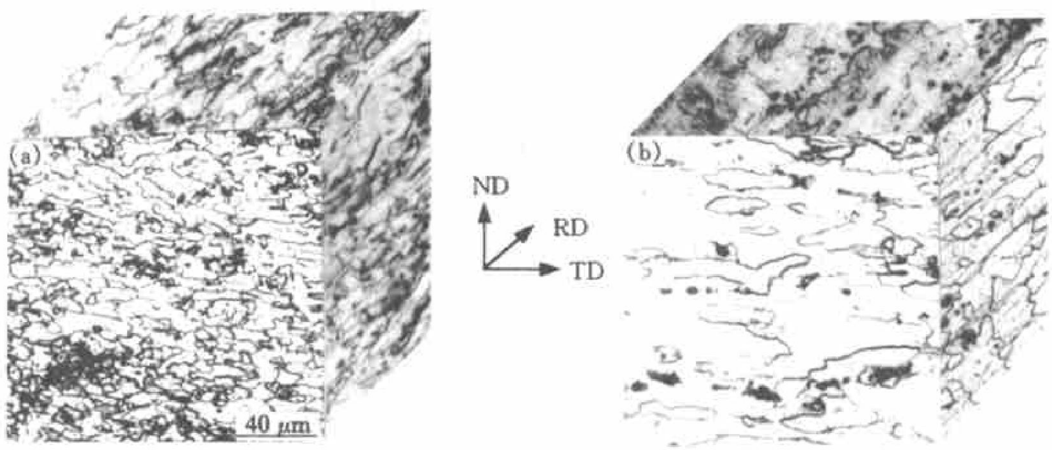


**Fig. 2** Comparison of optical microstructures after combination deforming and hot rolling respectively
(a) —Combination deforming; (b) —Hot-rolling

A progressive combination deformation of multidirectional compression to a deformation coefficient of $\lambda = 21.5$ at 350 ℃ and then rolling to a deformation coefficient of $\lambda = 10.5$ at the range from 350 ℃ to 250 ℃ was performed, very fine structures with 2~3 μm grains were obtained in aluminum alloy when total deformation coefficient $\lambda = 32$. The optical and TEM microstructures are shown in Fig. 3. An incomplete recrystallization structures are seen in Fig. 3(a), and a very interesting fact in Fig. 3(b) shows that both of the formation of high density dislocation congregation (notice *A*) and the formation of recrystallization nucleus (notice *B*), indicating that high density dislocation congregation may transform into new grain nucleus under large deformation at the temperature range from 350 ℃ to 250 ℃.

Kassner[12] found that strong evidence of recrystallization existed in large-strain deformation of high purity aluminum at ambient temperature, the most prominent microstructural feature appeared to be small (0.9 μm), and relatively equiaxed subgrains formed from dislocation reaction during hardening by a strain of 1.7. This phenomenon of new grain evolution described above is similar to continuous dynamic recrystallization, which occurs in turn by the progressive accumulation of dislocations in low angle boundaries, leading to the increase of their misorientation and the formation of large angle grain boundaries when their misorientation angles reach a critical value as increasing strain. In the strain range from 0.5 to 3.0, the average misorientation angle ($\theta$) of strain-induced subboundaries can be approximated by a linear function of accumulative strain ($\sum\varepsilon$) as follows:

$$\theta = \alpha\left(\sum\varepsilon - \varepsilon_0\right) \qquad (1)$$

The slope has reported by Hughes[13] for an aluminum is 12°, and $\varepsilon_0$ is usually 0.2 to 0.4 and it is considered as a critical strain where geometrically necessary subboundaries are produced by lattice rotations. The development of fine grained structure can be characterized by the formation of strain-induced high energy dislocations and then transforming to new grain boundaries at high strains, that is essentially similar to a continuous dynamic recrystallization[14]. A strain-induced continuous dynamic recrystallization may lead to grain refinement under a combination of large deformation model of multidirectional forging and subsequent rolling at moderate temperature from 350 ℃ to 250 ℃.

### 3.3 Thermal stability

Thermal stability of the structure after deformed, with grain sizes over the range from 0.5 to 3 μm under a combination model of large deformation multidirectional forging and subsequent rolling was studied. Heating at 480 ℃ for 15 min resulted in dissolution of dislocation nets and little growth of grains due to boundary stabilization by secondary particles of strengthening phases formed before annealing. Fig. 4 shows the dissolution of dislocation nets but pinned by small particles with sizes over the range from 0.05 to 0.2 μm. it can be stressed here that some of these subgrains contain quite few dislocations in their interiors and their neat boundaries have higher angle misorientations. The average size of these (sub) grains is about 0.5 to 3 μm.

This mechanism has been used to promote superplasticity in Zr bearing or high Mg aluminum alloys summarized in Ref. [14]. These alloys are generally cold or warm rolled to increase their dislocation density, subgrains form very quickly but since the boundaries are pinned by small particles and continuously absorb dislocations, the subgrains transform into

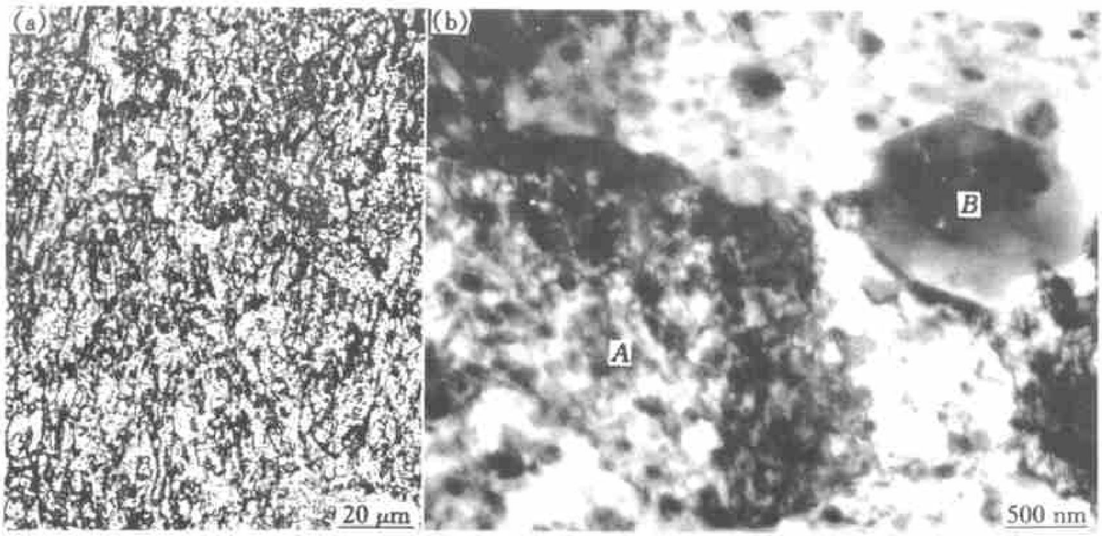


**Fig. 3** Microstructures after combination deforming at $\lambda = 32$
(a) —OM; (b) —TEM

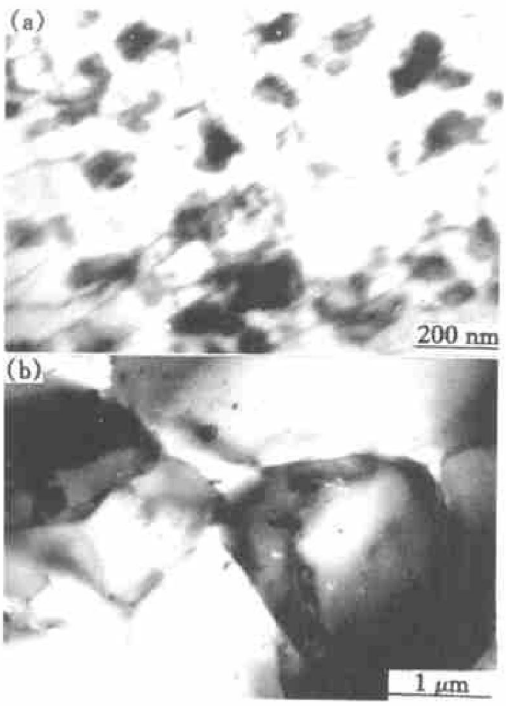


**Fig. 4** Deformed at $\lambda = 32$ and followed by annealing at 480 ℃ for 15 min

grains without obviously growing. A fine and equiaxed grain structure is thus obtained during heating due to the action of the very fine secondary particles formed in large deformation.

## 4 CONCLUSIONS

1) A combination model of large deformation multidirectional forging and subsequent rolling may provide a potential thermo-mechanical processing for producing high performance aluminum alloy ultra-thick plates (the thickness is more than 40 mm).

2) Very fine-grained (2 ~ 3 μm) structures are obtained in 7075 aluminum alloy when total deformation coefficient $\lambda = 32$ at the temperature range of 250 ~ 350 ℃ under a strain rate of about $0.1\,s^{-1}$.

3) The development of fine-grained structure can be characterized by the formation of strain-induced high energy dislocation and then transforming into new grain under large deformation at moderate temperature. The very fine secondary particles formed during large deformation play important role in retain the stability of the fine-grained structures.

## [REFERENCES]

[1] Valiev R Z, Korznikov A V, Mulyukoy R R. Structure and properties of ultra-fine grained materials produced by severe plastic deformation [J]. Mater Sci Eng, 1993, A168: 141- 148.

[2] LIU Zu-yan, LIANG Guo-xian, WANG Er-de, et al. Effect of equal-channel angular pressing on structure of Al alloy 2024 [J]. Trans Nonferrous Met Soc China, 1997, 7(2): 160- 162.

[3] Horita Z, Smith D J, Furukawa M, et al. Evolution of grain boundary structure in submicrometer-grained Al-Mg alloy [J]. Materials Characterization, 1996, 37: 285- 294.

[4] Pithan C, Hashimoto T, Kawazoe M, et al. Microstructure and texture evolution in ECAE processed A5056 [J]. Mat Sci Eng, 2000, A280: 62- 68.

[5] Chen W N, Ferguson D, Ferguson H. Severe plastic deformation techniques [J]. Acta Metallurgica Sinica, (English Letters). 2000, 13: 242- 253.

[6] Richert M, Liu Q, Hansen N. Microstructural evolution over a large strain range in aluminum deformed by cyclic-extrusion-compression [J]. Mat Sci Eng, 1999, A260: 275- 283.

[7] Terence G L, Furukawa M, Horita Z, et al. Using intense plastic straining for high-strain-rate superplasticity [J]. JOM, 1998(6): 41- 45.

[8] ZHANG Xin-ming, SONG Min, ZHOU Zhuo-ping, et al. Microstructures and mechanical properties of 2014 aluminium alloy forgings made by a new process [J]. Trans Nonferrous Met Soc China, 2000, 10(2): 139- 143.

[9] SONG Min, ZHANG Xin-ming, YANG Yang, et al. Heat-treatment of 2014 aluminum alloy forgings with intense strain [J]. Trans Nonferrous Met Soc China, 2000, 10(6): 721- 725.

[10] Belyakov A, Sakai T, Miura H. Fine-grained structure formation in austenitic stainless steel under multiple deformation at 0.5$T$m [J]. Materials Transactions, JIM, 2000, 41: 476- 484.

[11] Markushev M V, Bampton C C, Murashkin M Y, et al. Structure and properties of ultra-fine grained aluminum alloys produced by severe plastic deformation [J]. Mat Sci Eng, 1997, A234- 236: 927- 931.

[12] Kassner M E, McQueen H J, Pollard J, et al. Restoration mechanisms in large-strain deformation of high purity aluminum at ambient temperature [J]. Scripta Metallurgica et Materialia, 1994, 31: 1331- 1336.

[13] Hughes D A, Liu Q, Chrzan D C, et al. Scaling of microstructural parameters: misorientations of deformation induced boundaries [J]. Acta Mater, 1997, 45: 105- 112.

[14] Gourdet S, Montheillet F. An experimental study of the recrystallization mechanism during hot deformation of aluminum [J]. Mat Sci Eng, 2000, A283: 274- 288.

**(Edited by HUANG Jin-song)**