Deformation Behavior and Microstructure Evolution of AA2024-H18 Aluminum Alloy by Hot Forming with Synchronous Cooling Operations

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Abstract: Hot forming with synchronous cooling (HFSC) is a novel technique for heat-treatable, high-strength aluminum alloys, which allows the alloys to acquire good formability, negligible springback, rapid processing and better mechanical properties. However, the deformation behavior and microstructure evolution of the alloys during HFSC are complex and need to be studied due to the temperature and strain rate effects. Uniaxial tensile tests in a temperature range of 250—450 ℃ and a strain rate range of 0.01—1 s^{-1} for AA2024-H18 aluminum alloy sheet are conducted with a Gleeble-3500 Thermal-Mechanical Simulation Tester. And based on metallography observation and analysis, AA2024-H18 aluminum alloy sheet in HSFC process exhibits hardening and dynamic recovery behaviors within the temperature range of 250—450 ℃. Strain rate shows different effects on ductility at different temperatures. Compared with traditional warm/hot forming methods, AA2024-H18 aluminum alloy achieves a better work-hardening result through HFSC operations, which promises an improved formability at elevated temperature and thus good mechanical properties of final part. After HSFC operations, the microstructure of the specimens is composed of elongated static recrystallization grain.

Key words: hot forming with synchronous cooling; AA2024 aluminum alloy; deformation behavior; microstructure evolution

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0 Introduction

The advantages of heat-treatable, high-strength aluminum alloy, including lightweight, high strength and stiffness, make it very attractive for aerospace[1-2] and auto[3-4] industries. However, forming the alloy sheets into complex contoured parts by traditional cold stamping processes is a challenge due to its narrow plastic deformation range, low cracking resistance and Young′s modulus[5]. As the ductility of aluminum alloy will improve at elevated temperatures[6], warm[7]/hot forming processes[8] can provide better formability, but in expense of grain growth, high energy consumption and low productivity. Therefore, hot forming with synchronous cooling (HFSC) technique which has been applied in forming high strength steels[9-12], is a promising way to facilitate the forming precision of the heat-treatable, high-strength aluminum alloys[13]. HFSC heats the alloy blank to solvus temperature and holds for a period of time to dissolve to α (Al) matrix, subsequently forms and quenches the alloy in cold dies[14]. Then the semi product with a supersaturated solid solution (SSSS) microstructure can be trimmed into the designed shape and aged to obtain full strength. Compared with traditional forming methods, HFSC produces can form parts with high formability, negligible springback, rapid processing and

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better mechanical properties[15].

The full image of deformation behavior and microstructure evolution of heat-treatable high-strength aluminum alloy in HFSC is essential for a reliable process design regarding the dimensioning of the forming die and the technological parameters. Studies on deformation behavior and microstructure evolution of the alloys in warm forming and hot forming given by published researches are very informative[16-20], but they are not applicable for HFSC as the blanks are formed in cooling process[21] instead of at a certain elevated temperature in traditional technologies[22]. This difference results in different microstructures as well as deformation behaviors. Therefore, to fully understand the deformation behaviors and microstructure evolution of heat-treatable high-strength aluminum alloys during HFSC, in this paper, a uniaxial tensile test for AA2024-H18 aluminum alloy by HFSC is conducted on a Gleeble-3500 Thermal-Mechanical Simulation Tester at a temperature range of 250—450 ℃ and different strain rates(0.01, 0.1 and 1 s^{-1}). And this study will also contribute to the HFSC process design.

1 Experiment

1.1 Materials

A commercial AA2024-H18 aluminum alloy sheet of 0.8 mm thick is selected. Its compositions are listed in Table 1. Specimens with an 8 mm long and 6 mm wide gauge, as shown in Fig. 1, are cut off from 2024-H18 aluminum alloy sheet. The gauge length is designed shorter than that required by the national standard to minimize the temperature difference in the gauge section and achieve a high strain rate.

For comparison, W temper AA2024 aluminum alloy specimens are employed for tensile test which are obtained by heating the H18 temper specimens to 495 ℃ and held for 300 s, and then cooled down to room temperature with a cooling rate of 40 ℃/s. The time interval between the solution treating and uniaxial tensile testing was within 10 min.

Table 1 Chemical composition of 2024 %

Element	*W*
Si	0.4
Fe	0.3
Cu	4.1
Mn	0.67
Mg	1.52
Cr	0.03
Zn	0.18
Ti	0.06
Al	the rest

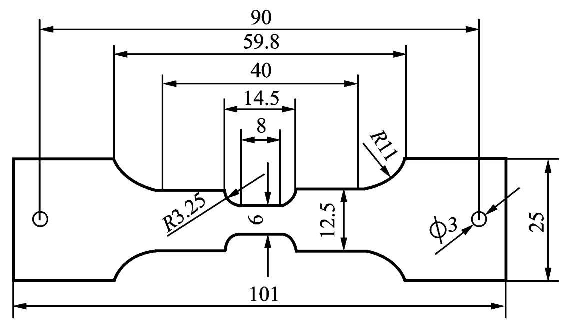


Fig. 1 Specimen used for uniaxial tensile test

1.2 Tensile tests

Referring to Ref. [17] and the temperature regime for aluminum alloys warm/hot forming processes, the test temperatures are set as 250, 300, 350, 400 and 450 ℃ and the strain rates are set as 0.01, 0.1 and 1 s^{-1}. The uniaxial tensile tests are carried out on a Gleeble-3500 Thermal-Mechanical Simulation Tester. And a specimen assembled in the Gleeble-3500 system is shown in Fig. 2.

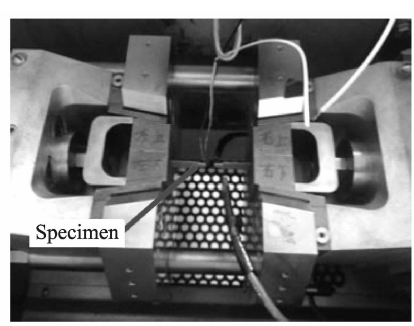
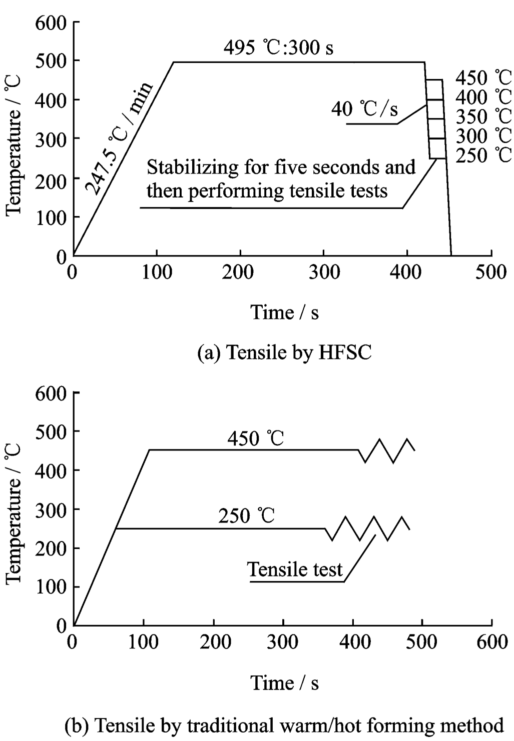


Fig. 2 Test device

As illustrated in Fig. 3(a), the specimens are first heated to the recommendatory solution treatment temperature of 495 ℃ within 120 s and soaked for 300 s at 495 ℃, so that the alloy phase is completely dissolved into the α(Al) matrix. And then the specimens are rapidly cooled down to a temperature between 450 ℃ and 250 ℃ at a rate of 40 ℃/s and stabilized for 5 s. The tensile tests are performed under isothermal environment.

For comparison, as-received (in H18 temper) and W temper AA2024 aluminum alloy specimens are employed for room temperature tensile test with strain rate 0.000 25 s^{-1} according to the national standard GB/T 228.1. And tensile tests by the traditional warm/hot forming method at 250 ℃ and 450 ℃ with strain rates of 0.01 s^{-1} and 1 s^{-1} are also conducted, and the heating history is shown in Fig. 3(b).



(a) Tensile by HFSC

(b) Tensile by traditional warm/hot forming method

Fig. 3 Heat-up curves

1.3 Metallographic test

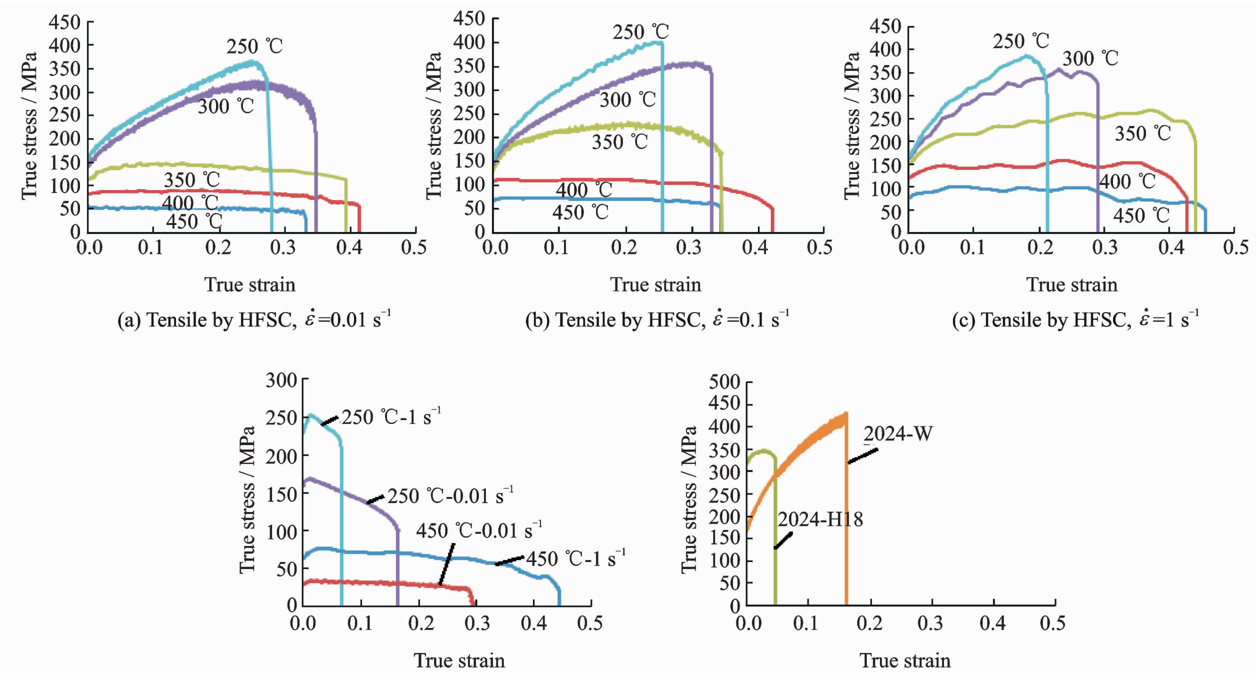
The microstructure near the fracture location of the tested specimens is observed with an optical microscopy. The cold-mounted AA2024 aluminum alloy metallography specimens are etched in the Keller's Etchant for 15—20 s, wiped by a cotton ball with nitric acid, and then thoroughly washed by water and dried. And the digital metallography is captured by a PME OLYMPUS TOKYO metallographic microscope.

2 Results and Discussion

2.1 Stress-strain relations

The tensile load-displacement data are processed to true stress-true plastic strain data. Figs. 4(a—c) shows true stress-true strain curves obtained at three strain rates (0.01, 0.1 and 1 s^{-1}) and different temperatures (250, 300, 350,400 and 450 ℃) by HFSC. Figs. 4 (d, e) show the true stress-true strain relationship of the specimens tested by traditional warm/hot forming method and the specimens in H18 and W temper tested at room temperature, respectively. From Fig. 4, it can be seen that in HFSC process the flow stress of AA2024-H18 aluminum alloy increases with strain until necking at 250 and 300 ℃, this deformation behavior is in perfect accord with work-hardening model, similar to the AA2024-W aluminum alloy at room temperature (as shown in Fig. 4(e)). However, when conducting test by traditional warm/hot forming method at 250 ℃ (as shown in Fig. 4(d)), deformation behavior of AA2024-H18 aluminum alloy exhibits the characteristics of dynamic recrystallization model: The stress statistically increases and subsequently decreases monotonically with the increase of strain[23]. When HFSC is employed at 400 and 450 ℃, the stress first increases and subsequently becomes stabilized, which suggests that the work-hardening is counteracted by the thermal softening[20]. The deformation behavior of AA2024-H18 aluminum alloy at 350 ℃ changes from a balanced state between thermal softening and work-hardening to a work hardening dominated state with the increase of strain rate.

During HFSC operations, the deformation behavior of AA2024-H18 aluminum alloy mainly follows the work-hardening model. Usually, work-hardening behavior benefits the uniform plastic deformation as it can strengthen the defo-



(a) Tensile by HFSC, $\dot{\varepsilon}$=0.01 s^{-1} (b) Tensile by HFSC, $\dot{\varepsilon}$=0.1 s^{-1} (c) Tensile by HFSC, $\dot{\varepsilon}$=1 s^{-1}

(d) Tensile by traditional warm/hot method (e) Room temperature tensile

Fig. 4 True stress-true strain relationships of AA2024 aluminum alloy

rmed location and lead subsequent deformation at the undeformed location, which prevents deformation localization and therefore avoids plastic instability[24]. In addition, as the AA2024 aluminum alloy part only needs natural aging after HFSC operations, the effect of work-hardening will be retained in final part, which improves the mechanical properties by heat treatment. Therefore, compared with traditional warming/hot forming methods, HFSC technology can improve the formability of AA2024 aluminum alloy and the mechanical properties of final part.

2.2 Percentage total elongation at fracture

Fig. 5 shows percentage total elongation at fracture of AA2024-H18 aluminum alloy at different temperatures and strain rates during HFSC operations which is significantly improved compared with that at room temperature (about 5%). The maximum failure strain of AA2024-H18 aluminum alloy is more than 60%, occurring at 450 ℃-1 s^{-1}. When HFSC is employed, the amount of precipitates in the matrix significantly decreases during the cooling-down process, and therefore lowers down the possibility of crack-

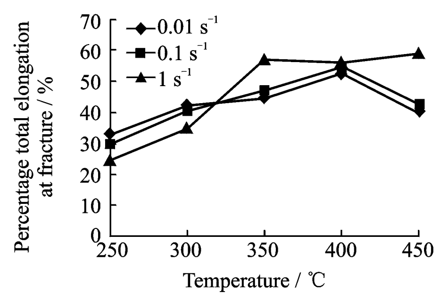
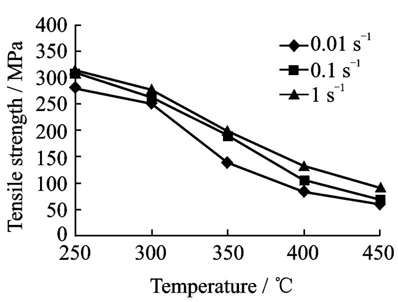


Fig. 5 Percentage total elongation at fracture of AA2024-H18 aluminum alloy (Tensile by HFSC)

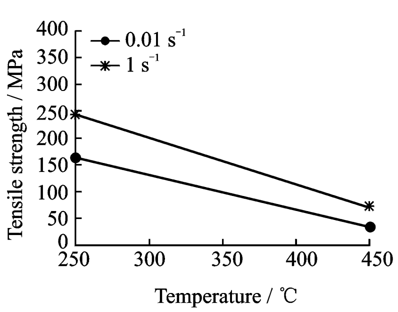
ing[25]. It can be seen from Fig. 5 that in HFSC, for a fixed temperature, the percentage total elongation at fracture of AA2024-H18 aluminum alloy decreases with the growth of strain rate when below 350 ℃, while it increases with strain rate when above 350 ℃. Compared with traditional warming/hot forming methods, HFSC improves the percentage total elongation at fracture of AA2024-H18 aluminum alloy, especially when forming the alloy at relatively low temperatures. Therefore, HFSC technology can improve the ductility of AA2024-H18 aluminum alloy at elevated temperature. The improvement of ductility can be attributed to the work-hardening behavior and microstructure transition of AA2024-H18 aluminum alloy.

2.3 Tensile strength

Fig. 6 shows tensile strength of AA2024-H18 aluminum alloy at different temperatures and strain rates. The tensile strength decreases with the increase of temperature in HFSC which is consistent with the character of thermal activation: With increasing temperature, the thermal activation and the average kinetic energy of the atom increase, which boosts the activity of the dislocation and reduces the critical shear stress of the material, and therefore the tensile strength decreases. At a constant temperature, at higher strain rate the dislocation caused by deformation cannot be eliminated which leads to the work hardening and an improved tensile strength. Compared with the traditional warm/hot method, the tensile strength of AA2024-H18 aluminum alloy tested by HFSC is higher at elevated temperature, because of the reinforcement of the lattice distortion caused by solid solution treatment. At the same temperature and the same strain rate, the tensile strength of the material which goes through HFSC is higher than the traditional warm/hot formed material, which indicates that the HFSC operations need higher stamping force. However, thanks to forming at elevated temperature, the stamping force during HFSC operations is lower than that during cold forming operations. Since the tensile strengths of AA2024 aluminum alloy in W and H18 temper at room temperature are 362.3 MPa and 330.6 MPa, respectively.



(a) Tensile by HFSC



(b) Tensile by traditional warm/hot forming method

Fig. 6 Tensile strength of AA2024-H18 aluminum alloy

2.4 Strain hardening behavior

The true stress-true strain (ε-σ) relationships of AA2024-H18 aluminum alloy under HFSC operations (Fig. 4) can be fitted with a power law model. To determine the strain hardening index n, the analysis is dependent on constitutive stress-strain-strain rate-temperature correlation model shown as follows[26]

$$\sigma = k\varepsilon^{n}\dot{\varepsilon}^{m}e^{\frac{\beta}{T}} \tag{1}$$

where k, n, m and β are coefficients. The strain hardening index n was determined by multiple linear regression analysis of experimental data. Fig. 7 shows the n values at various strain rates which can be described as a function of test temperature and strain rate. For a fixed strain rate, the strain hardening index n decreases with the increase of temperature, and negative values appears at 450 ℃. And for a fixed temperature, n increases with the increasing of strain rate. It may be attributed to the higher dynamic recovery speed at elevated temperature and the sufficient dynamic recovery at low strain rate. Compared with traditional warm/hot forming methods[17], HFSC operations significantly increase the n value of AA2024-H18 aluminum alloy which leads to a

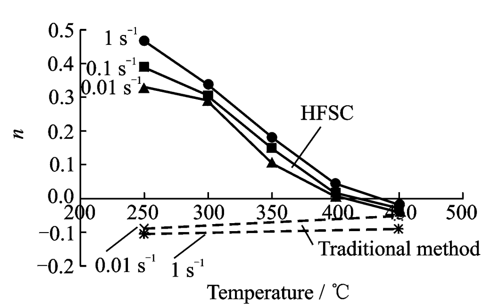


Fig. 7 Strain hardening index n of AA2024-H18 aluminum alloy under HFSC operations

more uniform material flow and reduces the fracture risk.

2.5 Strain rate sensitivity of flow stress

The strain rate sensitivity index of flow stress m is also determined by linear regression analysis, as shown in Fig. 8. The strain rate sensitivity index increases with the increase of temperature, which may be attributed to the higher activation energy at elevated temperature. The physical interpretation of strain rate sensitivity index is the affection of strain rate changing on the strengthening of the initial necking location. Generally, a higher strain rate sensitivity index will restrain necking and thinning during deformation[27]. Compared with cold forming method[5], HFSC operations can significantly increase m value of AA2024-H18 aluminum alloy, which also contributes to the improvement of forming performance.

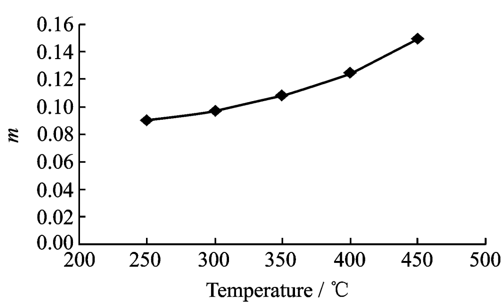


Fig. 8 Strain rate sensitivity index m of AA2024-H18 aluminum alloy under HFSC operations

2.6 Microstructure evolution

Fig. 9 shows the microstructure of AA2024-H18 aluminum alloy processed by HFSC. Although there is a high dislocation density of each initial specimen, dynamic recover, instead of dynamic recrystallization, appeared as the softening mechanism during tensile test by HFSC. This is because: (1) HFSC heats the specimens to 495 ℃ within 120 s and keeps at 495 ℃ for 300 s, static recovery as well as static recrystallization takes place, and a microstructure consisted of low dislocation density static recrystallization grain emerges; (2) in the rapid cooling stage, no phase

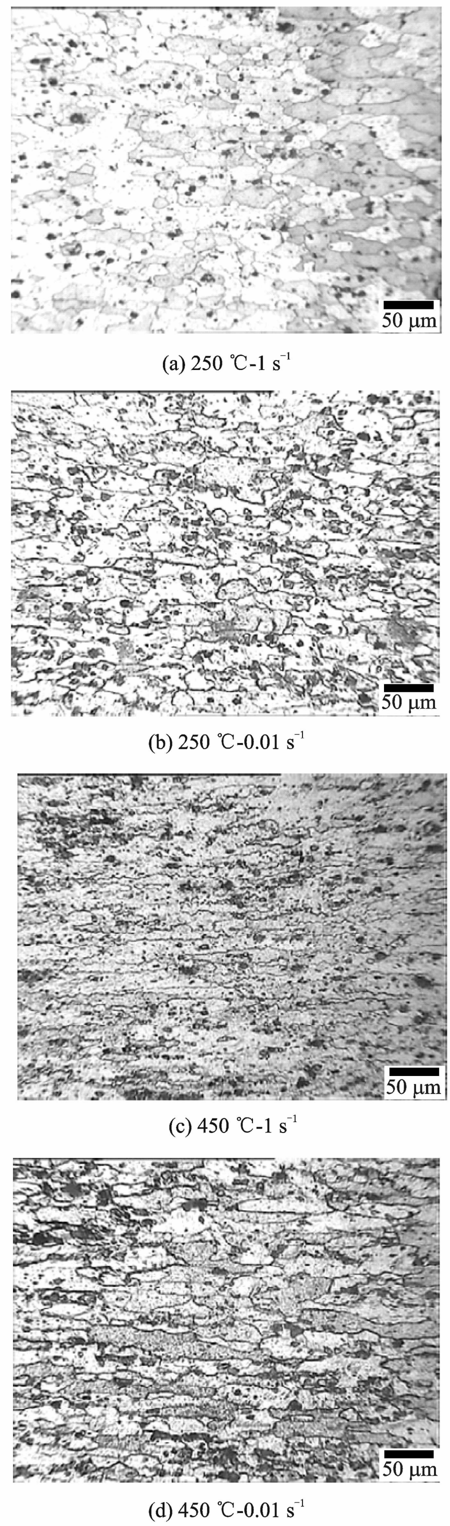
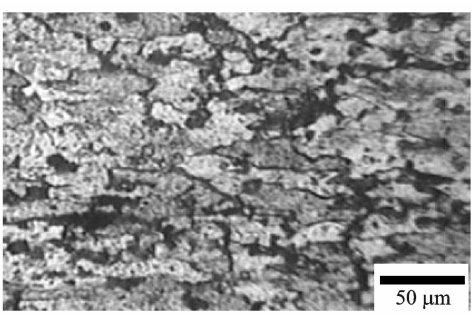
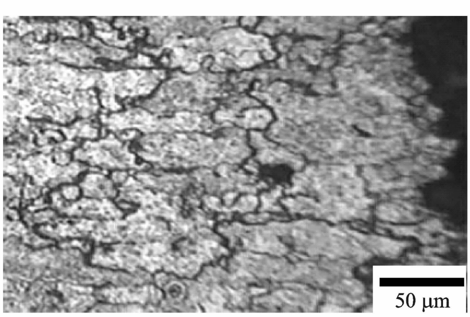


Fig. 9 Microstructure of AA2024-H18 aluminum alloy processed by HFSC

transition occurs; (3) the face-centered (FCC) cubic structure of aluminum impedes the occurrence of dynamic recrystallization[28]. Therefore, the alloy's microstructure is composed of elongated static recrystallization grain after tensile test by HFSC. In HFSC, as shown in Fig. 9, both temperature and strain rate impact on the microstructure of AA2024-H18 aluminum alloy, but the latter affects more which can be attributed to the effect of percentage total elongation at fracture. When tensile test is conducted under 350 ℃, the fracture strain at 1 s^{-1} strain rate is smaller, so the grains of AA2024 aluminum alloy are thicker and shorter. In contrast, when the fracture strain with a 0.01 s^{-1} strain rate is larger, the grains are vimineous. However, the situation is opposite when carrying out the tensile test at a higher temperature. In addition, grain-boundary crack caused by overburning is observed in the tensile test specimens at 450 ℃ and strain rates of 0.01 s^{-1} and 0.1 s^{-1}, as shown in Fig. 10, which can lead to the drop of the percentage total elongation at fracture of AA2024-H18 aluminum alloy (as showed in Fig. 5). Therefore, the deformation condition must be avoided during HFSC operations.



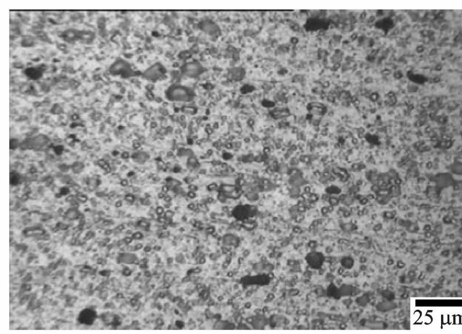
(a) 0.01 s^{-1}



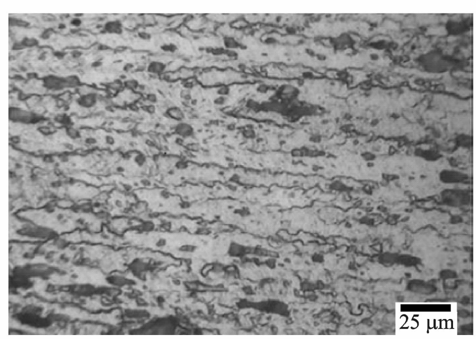
(b) 0.1 s^{-1}

Fig. 10 Grain-boundary crack of AA2024-H18 aluminum alloy processed by HFSC at 450 ℃

Fig. 11 shows the microstructure of AA2024-H18 aluminum alloy after tested by traditional warm/hot forming method. Compared with Fig. 9, the microstructure of the material tested by HFSC is significantly different from that of the isothermal tensile test. At low temperature (250 ℃), there are static recrystallization grains during HFSC(Fig. 9(a)), while there are only the original microstructure with which are distributed few dynamic recrystallization grains (as shown in Figs. 11 (a), 12) during traditional warm/hot forming process. At high temperature (450 ℃), lots of dynamic recrystallization grains appear in the specimens tested by the tradition warm/hot forming method, and the grain boundary is zigzagged and surrounded by necklace structure(as shown in Fig. 11(b)).



(a) 250 ℃-1 s^{-1}



(b) 450 ℃-1 s^{-1}

Fig. 11 Microstructure of AA2024-H18 aluminum alloy tested by traditional method

The different microstructures can result in significant differences in deformation behavior of AA2024-H18 aluminum alloys by the two different methods. For HFSC, due to the solution treatment at 495 ℃ before forming, the amount of alloy phase distributed within the α(Al) matrix is less than that of traditional hot/warm forming

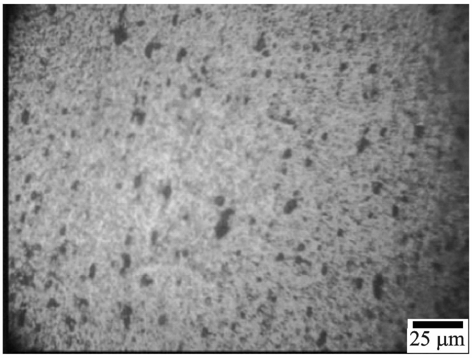


Fig. 12 Microstructure of the material as-received

methods. The disappeared alloy phase is dissolved into the α(Al) matrix as solute atoms, leading to lattice distortion of α(Al) matrix and the improvement of the critical shearing stress for plastic deformation. Therefore, at the same temperature and strain rate, the forming stamping force during HFSC operations is higher than that during traditional hot/warm forming operations. And the interaction between the diffusive solute atoms and the moving dislocation further enhances the forming stamping force. With the increase of temperature, the solubility of solute atoms is increased, and the amount of alloy phase distributed within the α(Al) matrix during traditional warm/hot forming method is decreased. Therefore, compared with low temperature deformation behaviors, the differences of flow stress and tensile strength at high temperature are relatively small during the two different forming methods.

During HFSC operations, the AA2024-H18 aluminum alloy specimens consist of low dislocation density static recrystallization grain when the plastic deformation started, so the dislocation density increases. And the pinning effect of the solute atoms on the dislocations is enhanced by the increase of solute atoms within the α(Al) matrix, which can lead to dislocation increment during forming operation. Dynamic recover appears as the softening mechanism during tensile test by HFSC. The ability of elimination dislocation is not as well as dynamic recrystallization. For these reasons, the alloy′s ability of dislocation increment is better during HFSC operations, and which will enhance the effects of work hardening[24]. Therefore, compared with traditional warm/hot forming methods, HFSC operations can significantly improve the work-hardening effect of AA2024-H18 aluminum alloy.

3 Conclusions

In this paper, uniaxial tensile test of the AA2024-H18 aluminum alloy specimen is conducted on a Gleeble-3500 Thermal-Mechanical Simulation Tester, the deformation behavior and microstructure evolution are investigated at a temperature range of 250—450 ℃ and different strain rates by HFSC. The following remarks can be concluded:

(1) For HFSC, the deformation behavior of AA2024-H18 aluminum alloy shows the character of hardening and dynamic recovery. Under 350 ℃, the true stress-true strain relationship of studied material can be described by hardening model, while above 350 ℃, it can be described by dynamic recovery model. And the deformation behavior changes from dynamic recover to work hardening with the increasing of stain rate at 350 ℃.

(2) In different temperature ranges, the effects of strain rate on percentage total elongation at fracture of the alloy are different. For a fixed temperature below 350 ℃, the percentage total elongation at fracture decreases with an increasing strain rate. However, when above 350 ℃(including 350 ℃), it increases with an increasing strain rate.

(3) Compared with traditional warm/hot forming methods, HFSC significantly increases the strain hardening index n of AA2024-H18 aluminum alloy. Therefore, the work-hardening effect of AA2024-H18 aluminum alloy is more significantly under HFSC operations, which can further improve the formability of AA2024 aluminum alloy at elevated temperature and the me-

chanical properties of finally part.

(4) The microstructure of AA2024-H18 aluminum alloy is composed of elongated static recrystallization grain after deformation by HFSC. And dynamic recrystallization takes place during HFSC.

(5) At high temperature and low strain rate (450 ℃/0.01 s^{-1} and 0.1 s^{-1}), there are grain-boundary cracks caused by overburning within the AA2024-H18 aluminum alloy, so material forming should be avoided under the state when using HFSC.

Acknowledgment

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