Deformation Behaviors of 2219 Aluminium Alloy in Hot Multi-direcrional Forging Process

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Abstract. The hot multi-direcrional forging (MDF) process of 2219 aluminium alloy was simulated and the MDF test was carried out. The deformation behaviors of 2219 aluminium alloy were investigated in this paper, and the metal flow rule, temperature field variation and the strain variation were focused on. The results show that in the forging process, the metal flow velocity decreases gradually from top to bottom of the forgings. Meanwhile, on a horizontal section, the closer to four vertical edges, the smaller velocity of metal flow was obtained. After the forging process, the highest temperature appeared in the central area inside the forgings, followed by the four long edges, and the lowest temperature area is the eight sharp corners. The strain in each part of the forgings increased gradually with the increase of forging times. The maximum cumulative strain (12.5) and minimum cumulative strain (4.9) appeared in the central area inside the forgings and in the center area of the forging surface, respectively. In addition, in the whole MDF process, the highest temperature of 2219 aluminum alloy forging was 470 ℃, which is lower than their over burnt temperature.

Keywords: 2219 aluminium alloy; multi-direcrional forging; temperature field; cumulative strain; deformation behaviors.

1. Introduction

Owing to its high specific strength and fracture toughness, high mechanical properties at high temperature, and excellent stress corrosion resistance, 2219 aluminum alloy has been widely applied to aerospace field [1, 2]. At present, multi-direction forging (MDF) is regarded as the most promising large plastic deformation technology in industry due to its advantages of simple device, low cost and full deformation [3, 4], is the main technology for manufacturing large aluminum alloy components [5], and has attracted much attention from scholars [6, 7]. Wang et al. [8] analyzed the deformation characteristics and grain refinement behavior of 2A14 aluminum alloy based on the experimental study of MDF. According to the study of Joshi et al. [9], the multi-directional forging process can significantly refine the grains of 2014 aluminum alloy and improve the tensile strength of the material. Huang et al. [10] investigated the effects of cumulative strain variables on the microstructure evolution and properties of 2A14 aluminum alloy by using multi-directional forging process. However, at present, there are not many reports on the large plastic deformation technology of 2219 aluminum alloy, especially the research reports on the hot MDF technology of 2219 aluminum alloy are relatively few, and the feasible MDF process remains to be explored, which has a great impact on the development of high-performance manufacturing technology for large components of 2219 aluminum alloy. Therefore, the method of combining numerical simulation and experimental research are adopted to analyze the hot MDF process of 2219 aluminum alloy and study the characteristics and change rules of metal flow, stress change and temperature field of aluminum alloy, so as to obtain a feasible hot MDF process of 2219 aluminum alloy.

2. Numerical simulation

Deform-3D finite element software was used for modeling and numerical simulation. The poisson ratio, density, elastic modulus, coefficient of thermal expansion, specific heat capacity and heat transfer constant of 2219 aluminum alloy are 0.33, 2.71 ρ/g·cm, 68.9 GPa, 2.2e-05, 2.43328 kJ/kg·℃ and 180.195 W/m·K, respectively. The initial size specification of 2219 aluminum alloy blank is 130 mm×130 mm×210 mm. The initial temperature of the upper and lower molds is 400 ℃. The temperature of the billet removed from the furnace is 460 ℃, the friction coefficient between the billet and the mold is 0.3, and the upper die moves down along the Z axis at a speed of 5 mm/s. The displacement of each pass downward compression is 105 mm, that is, the deformation of the blank is 50%. The billet is set into a plastic deformable shape, the upper and lower dies are set into a rigid body, and the material is selected as AISI-H-13 die steel. There is heat transfer between the upper and lower die and the billet and the environment, so the upper and lower die are also divided into grids, and the billet is divided into solid grid form, the number of units is 24765, and the number of units of the upper and lower die is 15000. Material flow stress equation and other parameters select default values. Newton-Raphson method was used for iterative solution operations [11]. The established finite element model is shown in Fig. 1.

The simulation process is mainly divided into three stages. The first stage is the heat conduction process, the workpiece is heated and moved to the mold (the movement time in the air is 5 s). The second stage is the heat conduction process, the workpiece moves to the lower die, then stays on the lower die for 3 seconds before forging, and the heat conduction occurs between the workpiece and the lower die. The third stage is the MDF process, heat conduction and plastic deformation occur simultaneously in this process.

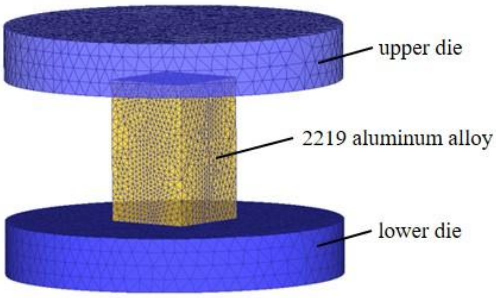


Fig. 1 Finite element model

3. Literature References

3.1 Metal flow characteristics

In the process of multi-directional forging, the velocity vector diagram of metal flow is shown in Fig. 2a and Fig. 2b. In the figure, the direction of the arrow indicates the direction of the metal flow and the direction of the metal deformation speed. Different colors of the arrow indicate different deformation speeds. As the color of the arrow changes from light to dark, the deformation speed gradually becomes smaller.

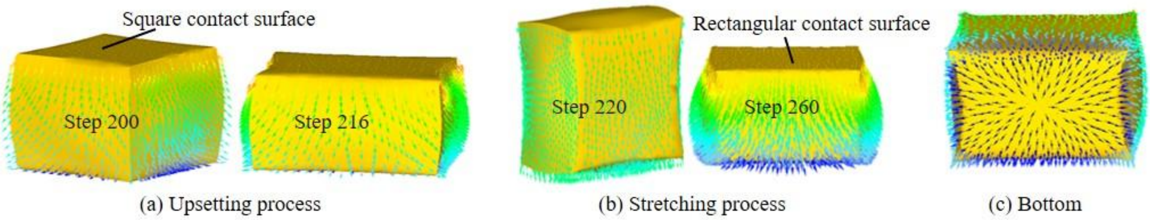
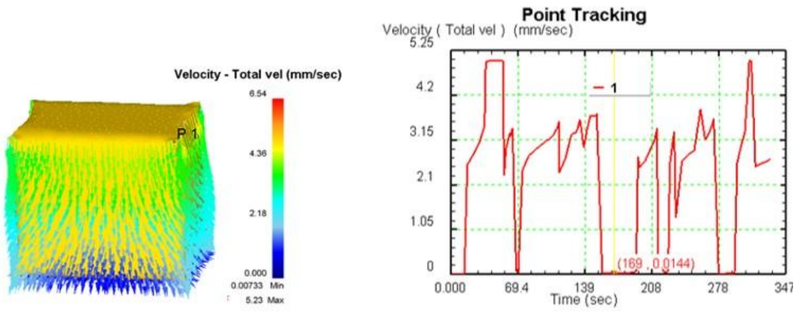


Fig. 2 Metal flow velocity vector diagram

It can be seen from the figure that the deformation speed of the metal on the billet gradually decreases from the upper surface to the lower surface. Due to the pressure from the upper die, the metals show a downward flow direction, but in the flow process, the outer metal is squeezed by the internal metal and gradually flows to both sides, which eventually results in the billet is drum-like. In addition, on the same horizontal section, the closer to the four vertical edges of the blank geometric vertical axis, the smaller the flow velocity of metal materials. Moreover, in the case of double-pass forging, the contact surface between the blank and the upper die is a rectangle rather than a square. According to the calculated data, the metal flow speed on the short side is larger than that on the long side. The fluidity of the metal at the lower end is more difficult and the speed is smaller. The metal on the contact surface with the lower die appears a certain flow speed, and its flow direction is as follows. The metal flows from the geometric center of the bottom surface to all sides, but the flow rate is very low, as shown in Fig. 2c. The main reason for the bottom metal to flow around is that the metal in the upper part of the billet is constantly flowing downward under the pressure of the upper die. When the metal flowing to the bottom, the metal will overcome the friction between the billet and the lower die and spread around due to the obstruction of the lower die. Due to the multi-directional forging process, the compression direction of the billet is constantly changing, which will cause the deformation speed of the metal in each area of the billet to change continuously during the entire forging process. When the metal is at the top surface, the flow speed of the metal is the largest, while when the metal is at the bottom center, the speed is the smallest, and the center is almost zero. The change curve of the deformation speed of the metal at point P1 is shown in Fig. 3.



(a) Metal flow vector (b) Change curve of metal velocity at P1

Fig. 3 Flow law of metals at typical sampling points

From the second pass to the third pass, the drum face of the drawn-out blank needs to be forged again to reduce the drum error caused by the previous pass. In addition, the fourth pass to the fifth pass, the sixth pass to the seventh pass, the eighth pass to the ninth pass also need to do the corresponding forging trimming, and the vertical degree of the blank in the forging process needs to be adjusted in time, otherwise the blank will have serious irregular deformation, resulting in the failure of a complete multi-directional forging process, and even in the early forging due to serious distortion.

3.2 Temperature field

When the billet is taken out of the furnace, the temperature is 460 ℃. During the stage from taking out to placing on the lower mold, the billet conducts heat with the air, and the surface temperature begins to drop. Due to the large contact area with the air at the 8 sharp corners at top and bottom ends, the temperature in these areas drops by about 10 ℃, while the temperature at the center of 6 surfaces drops by about 4 ℃, and the internal temperature of the billet remains unchanged (460 °C). During the stage when the billet is placed on the lower die to the beginning of forging, heat conduction occurs between the billet and the air and the lower die. Since the initial temperature of the lower die is 400 ℃, the temperature at the four sharp corners of the contact end with the lower die drops slightly, the temperature is about 449 ℃, while the temperature at the other four sharp corners is about 446 ℃, and the temperature at the collection center of the upper surface is about 452 ℃.The temperature of the whole central area of the billet is still maintained at 460 ℃.

The temperature distribution of the billet after hot forging is shown in Fig. 4. As can be seen from the figure, the temperature at the eight sharp corners is the lowest, the lowest temperature is 427 ℃, followed by the edge region. As the material inside the billet is subjected to continuous extrusion deformation, the activation energy increases and the temperature rises, up to 470 ℃. In the process of multi-directional forging, the temperature variation of several typical regions of 2219 aluminum alloy blank is shown in Fig. 5.

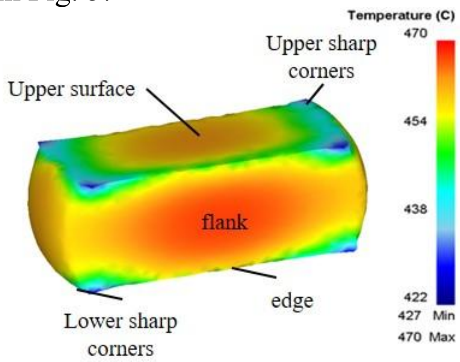
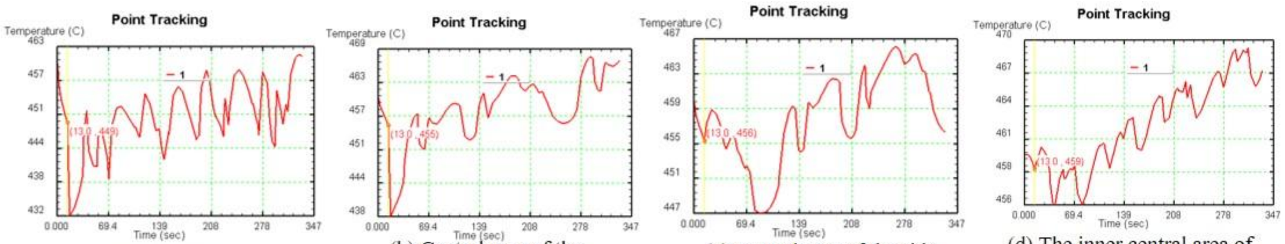


Fig. 4 Temperature field of final forging

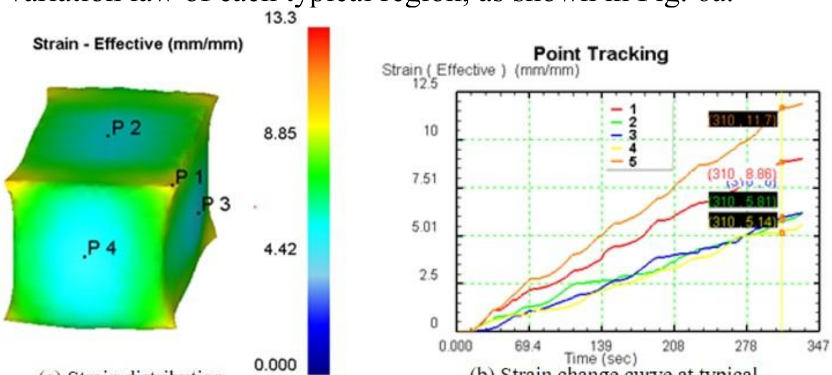


(a) Corner (b) Central area of the upper surface (c) Central area of the side surface (d) The inner central area of the forging

Fig. 5 Temperature curve of typical regions

3.3 Strain

The strain distribution cloud diagram after final forging of blank is shown in Fig. 6. After hot MDF, 2219 aluminum alloy is subjected to large deformation, plastic deformation occurs in the whole blank metal, but different parts have different degrees of strain, the maximum and minimum strain obtained are 12.5 and 4.94. A sampling point is taken in each of the typical regions, such as the sharp corner of the billet (P1), three surface center regions (P2, P3, P4) and billet center (P5), to analyze the strain variation law of each typical region, as shown in Fig. 6a.



(a) Strain distribution cloud map (b) Strain change curve at typical site

Fig. 6 Strain distribution characteristics of final forging

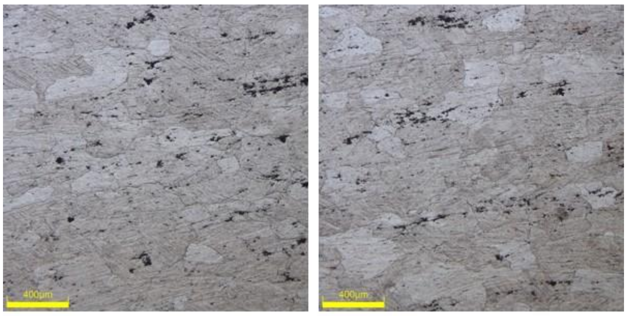
The variation law of typical regional strain with time is obtained, as shown in Fig. 6b. As can be seen from the figure, with the continuous progress of the forging process, the strain value of the metal in each area of the forging continues to increase, the largest strain value of the metal appears in the central area of the forgings, followed by the metal in the eight sharp corner area. The minimum strain is the metal in the central area of the six surfaces, and its strain changes are similar. With the increase of forging passes, both the strain difference between the center area and the sharp corner area and the strain difference between the sharp corner area and the surface center area gradually increased, that is, the strain in the center area show a largest increase value.

4. MDF test

Based on the process parameters in numerical simulation, the experimental analysis of 2219 aluminum alloy multi-directional forging was carried out. The single deformation was 50%, the die moving speed was about 25 mm/s respectively, the billet size was consistent with the numerical simulation, and the mold heating temperature was 400 ℃ and the billet heating temperature was 460 ℃. The experimental process was shown in Fig. 7. After 2219 aluminum alloy is removed from the heating furnace and placed on the punching machine, the temperature of the center area, the upper sharp corner area and the lower sharp corner area on the upper surface of the billet were measured respectively at 448 ℃, 440 ℃ and 443 ℃, as shown in Fig. 7a. 2219 aluminum alloy was multi-direction forged with three upsetting and three pulling, as shown in Fig. 7b and Fig. 7c. After the MDF, the temperature of each typical area of 2219 aluminum alloy forging was measured immediately (Fig. 7d), and the temperature of the surface center area, edge area and sharp corner area of the forging were measured to be 425 ℃, 415 ℃ and 410 ℃ respectively.

(a) Initial state (b) Upsetting (c) Drawing (d) Forging

Fig. 7 Multi-directional forging test process of 2219 aluminum alloy



(a) Sampling point 1 (b) Sampling point 2

Fig. 8 Microstructure of the central region of 2219 aluminum alloy forgings

According to the metallographic observation, the microstructure in the central area of 2219 aluminum alloy forging is relatively uniform, and no overburning is found (Fig. 8), indicating that the temperature in the central area of forging is always kept below the overburning temperature (545 ℃) during the MDF. In addition, the experimental results show that the temperature of the forgings is lower than that of numerical simulation analysis, whether it is before or after MDF. There are two possible reasons for the above phenomenon. One is that during the test process, the temperature of the tools used in the process of loading, handling and turning the billet is room temperature (26 ℃). The other is that when the billet is compressed at the end of each pass, the press show a low return speed, resulting in too long contact time between the mold and the billets. Therefore, in order to obtain a precise multi-directional forging deformation temperature for 2219 aluminum alloy, the handling time of the billet should be reduced, the temperature of the fixture and tool should be increased, and the contact time between the upper die and the billet should be reduced.

5. Summary

(1) The deformation rate of 2219 aluminum alloy billet gradually decreases from the upper surface to the lower surface. Due to the extrusion of the inner metal, the outer metal flows down and to both sides at the same time, resulting in a drum-like billet. On the same horizontal section, the closer to the four vertical edges, the lower the flow speed rate of the metal material.

(2) Plastic deformation occurs in the whole billet, and the maximum accumulated strain is 12.5 and the minimum accumulated strain is 4.94. With the continuous increase of forging passes, the strain values in each region of the billet continue to increase, and the largest strain value appears in the central region of the billet, followed by the sharp corner region, and the smallest strain value appears in the central region of the surface.

(3) The metal at the eight sharp corners of the billet has the fastest heat transfer rate and the lowest temperature, followed by the four long edges. The metal in the center area of billet show a slow heat transfer rate, a large amount of deformation heat energy is accumulated, so the highest temperature with 470 °C appears in this area, which is lower than its overburning temperature, indicating that the MDF process is feasible.

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References

[1] Yin Xuni, Zhang Lihua, Zhao Jun. Establishment of steady creep constitutive equation of 2219 aluminum alloy [J]. The Chinese Journal of Nonferrous Metals, 2014, 24(9): 2250-2256.

[2] H.J.Liu, H.J.Zhang, L.Yu. Effect of welding speed on microstructures and mechanical properties of underwater friction stir welded 2219 aluminum alloy [J]. Materials and Design, 2011, (32): 1548-1553.

[3] Zhang Yunfei, Wang Liang, Zhao Xiaodong, et al. Numerical simulation and experiment research on mlti-directional free forging of Al-Zn-Mg-Cu high strength aluminum alloy [J]. Forging & Stamping Technology, 2013, 38(4): 167-171.

[4] He Hailin, Yi Youping, Huang Shiquan, et al. Effects of deformation temperature on second-phase particles and mechanical properties of 2219 Al-Cu alloy [J]. Materials Science & Engineering A, 2018, 712: 414-423.

[5] Ye Shuaiqi, Cai Yujun, Li Guohe, et al. Study on Mechanical Properties and Constitutive Equation of 6014 Aluminum Alloy at Room Temperature [J]. Machinery Design & Manufacture, 2022, (3): 41-44.

[6] O. Sitdikov, T. Sakai, A. Goloborodko, et al. Kaibyshev. Effect of pass strain on grain refinement in 7475 Al alloy during hot multidirectional forging [J]. Materials Transactions, 2005, 45: 2232-2238.

[7] Hou L, Wang T, Wu R, et al. Microstructure and mechanical properties of Mg-5Li-1Al sheets prepared by accumulative roll bonding [J]. Journal of Materials Science & Technology. 2018, 34(2): 317-323.

[8] M. Wang, L. Huang, W. Liu, et al. Influence of cumulative strain on microstructure and mechanical properties of multi-directional forged 2A14 aluminum alloy [J]. Materials Science & Engineering A, 2016, (674): 40-51.

[9] A. Joshi, N. Kumar, K.K. Yogesha, et al. Mechanical properties and microstructural evolution in Al 2014 alloy processed through multidirectional cryoforging [J]. Journal of Materials Engineering & Performance, 2016, (25): 3031-3045.

[10] Wang M, Huang L, Liu W, et al. Influence of cumulative strain on microstructure and mechanical properties of multi-directional forged 2A14 aluminum alloy [J]. Materials Science and Engineering: A. 2016, (674): 40-51.

[11] Ma Linwei, Sun Lemin, Zhang Qiaofang, et al. The Key Techniques of FEM Simulation in Metal Forging [J]. Metal Forming Technology, 2003, 21(6): 17-20.