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Study of precision forging technology for complicated high strength aluminum alloy part

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In order to investigate forging feasible of SC100-T6 high silicon aluminum alloy, its plastic deformation behavior during high temperature was studied by isothermal compression of cylindrical specimens using Gleeble-1500. The experiment was carried out over of deformation temperature form 390 °C to 490 °C, strain rate form 0.006s^{-1} to 0.036s^{-1}. The result showed that the alloy had some plastic at high temperature, its flow stress was controlled by both strain rate and deformation temperature, which the flow stress decreases with the increase of temperature, while increases with the increase of strain rate. In order to prove alloy die formation, the die forming process with small flash for a complicated Al-alloy part was studied with theoretical analysis and experiment methods. Two steps die forming process was laid down, in which pre forming step the metal was distributed in accordance with the forging. Then in final step, the die cavity was filled easily with larger force. At last, the right heating process of material and die, the experiment was carried out at 800T hydraulic press successfully, and the qualified forge piece was obtained. The microscopic structure of raw material and forging material was investigated, the result showed that few Si blocks in raw material were broken small grain and structure was homogenized and improved to some extent, which improved the comprehensive mechanical property of the part to some extent.

Keywords: SC100-T6 al-alloy; hot compression experiment; preforging design; precision forging; micro-structure

Для исследования штамповки алюминиевого сплава SC100-T6 с большим содержанием кремния исследовалась пластическая деформация цилиндрических образцов при высокой температуре при изотермическом сжатии. Эксперимент проводился при температуре деформации от 390 °C до 490 °C, скорость 0.006 s^{-1} до 0.036 s^{-1}. Результат показал, что сплав имеет некоторую пластичность при высокой температуре, показано, что напряжение течения уменьшается с увеличением температуры и увеличивается с увеличением скорости деформации. Исследована микроскопическая структура материала до и после штамповки, обсуждаются возможные способы улучшения механических свойств сплава.

Дослідження технології штампування складного високоміцного алюмінієвого сплаву. *Цзюйвей Ченг, Сянчжан Фен, Ли Сиджун, Го Сяоцинь, Ся Цзюйчень.* Для дослідження штампування алюмінієвого сплаву SC100-T6 з великим вмістом кремнію досліджувалася пластична деформація циліндричних зразків при високій температурі при ізотермічному стисканні. Експеримент проводився при температурі деформації від 390 ° C до 490 ° C, швидкість 0.006 s^{-1} 0.036 s^{-1}. Експеримент довів, що сплав має деяку пластичність при високій температурі, показано, що напруження течії зменшується зі збільшенням температури і збільшується зі збільшенням швидкості деформації. Досліджено мікроскопічну структуру матеріала до і після штампування, обговорюються можливі способи поліпшення механічних властивостей сплаву.

1. Introduction

For die forming, it can be said that due to its improvement of material property, homogenous and small grain size, and good stress condition, it has become one of the most promising manufacturing technologies in the mass production of automotive components. Compared with the parts that are manufactured by machining or casting process, the forgings have such advantages as reasonable fibre, homogeneous and small grain size, and superior mechanical properties. Combined with the computer technology, plastic forming can not only save money, reduce the time of process and mold designing, but also can select the reasonable and feasible scheme in the scheme designing stage, and optimize the process and die structure.[1-8]

At some temperature range, some Al-alloy had certain plastic using which some simple or complex parts could be die forging. The parameters and laws of plastic flow of alloy could be defined by some drawing or compressing tests under certain conditions. Because of higher Si content, the SC100-T6 alloy was used to forming by casting. For some important parts such as piston and piston body parts in air-conditioner of car, die forging process was used to manufactured qualified parts. Then, the die forging process parameters should be investigated before studying.[1-9]

The finite-element method was employed for the preforming which was a key step in multi-stage die forging in which the metal was distributed preparing for final die forging according to the part's shape. For Al-alloy die forging, especially in higher temperature, friction between tool and blank was an important consideration which restricts movement of the material in die cavity and results in the difficulty of removing the forging from the die. In the paper, for the purpose of forging the part rightly, preforming scheme with rigid-plastic finite element analysis using Deform software was designed and the metal flow was analyzed.[10-16]

The aim of the present investigation was to determine experimentally the effects of deforming temperature and strain rate on compression. The die forging process for a complicated part in air-conditioner of car are also investigated and presented to proved the alloy forgeability.

2 Mechanic behavior of SC100-T6 Al-alloy

(1) Test method

The material studied part was a commercial Al-alloy named SC100-T6 produced by Japan. Its chemical composition was given in Table 1.

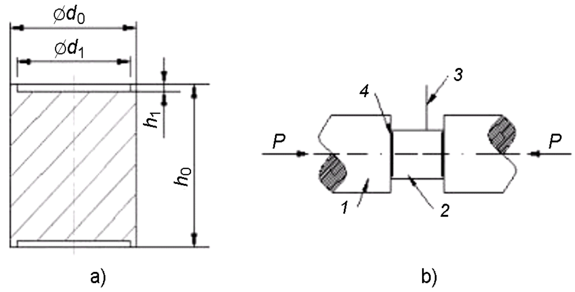


Fig.1 Schematic drawing of the specimen and hot compression experiment (a) Test Specimen (b) Compression diagrammatic sketch. 1-Pressure head 2-Specimen 3-Thermocouple 4-Graphite

In order to get the mechanic behavior of SC100-T6 at high deforming temperature to conform the temperature scope of die forming, the test specimens were isothermal compressed at Gleebl-1500 simulator at different temperature with different rate. The cylindrical specimens(shown in Fig.1(a)) were all machined from the homogenized billet which was homogeneously heat treated in a resistance furnace, which height h_0 and diameter d_0

Table 1 Composition of the tested alloy/ wt%

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Mass	9.50~11.0	<0.45	2.5~3.5	0.10~0.50	0.30~1.0	<0.10	<0.30	<0.15	other

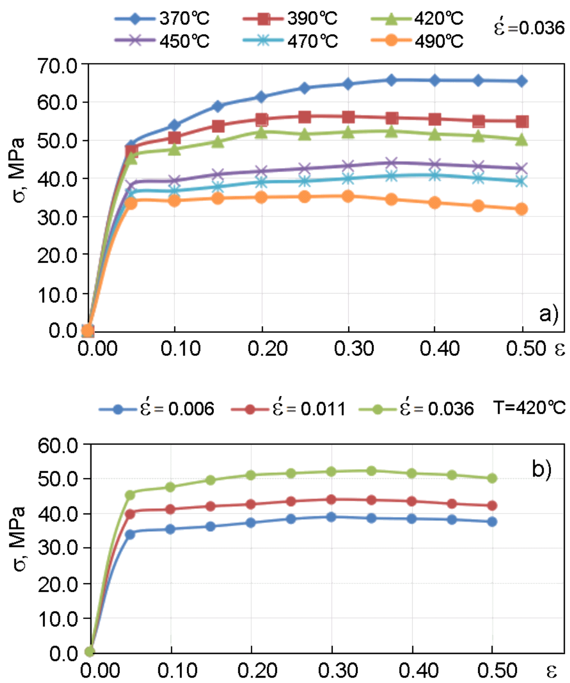


Fig. 2. True stress-strain curves of SC100-T6 Al-alloy for all of the temperature at the true strain of 0.5 (a) rue stress-strain curves at different temperature ($\dot{\varepsilon}$ =0.036) (b) True stress-strain curves at different strain rate(T=420°C)

were 12mm and 10mm. To minimize strain inhomogeneities, the ends of the specimens were recessed to a depth of 0.5mm to entrap the powdery graphite, as shown in Fig. 1(b). The specimens were water quenched to room temperature within 1s after deformation , making it possible to observe frozen microstructure during the deformation[12].

The isothermal compression tests were conducted in three strain rate values of $0.006s^{-1}$, $0.011s^{-1}$, $0.036s^{-1}$, at six temperature values of 370℃, 390℃, 420℃, 450℃, 470℃, 490℃, and with true strain up to 0.5 , by utilizing a Gleeble1500 thermal-mechanical simulator which can be programmed to simulate both thermal and mechanical industry process variables for a wide range of hot deformation conditions. The specimen temperature was monitored by using a Chromel-Alumel thermocouple that was welded at the center of the specimen. The heating rate of all tests was 1℃/s , which was followed by a 1 min soak at test temperature.

The experiment result

The true compressive stress-strain curves of SC100-T6 Al-alloy deformed at six temperatures under strain rates of $0.006s^{-1}$, $0.011s^{-1}$,and $0.036s^{-1}$, are shown in Fig. 2, respectively.

The flow stress as well as the shape of the flow curves were sensitively dependent on temperature and strain rate. With increasing strain ,especially at low temperature, the flow stress increases. It showed that dynamic hardening was dominant ,and hence the plastic deformation was difficult. Above 390 °C, for a specific strain rate and temperature, the flow stress did not increase markedly with increasing strain after a critical strain, and even a dynamic softening process appears. Comparing these curves with one another ,it was found

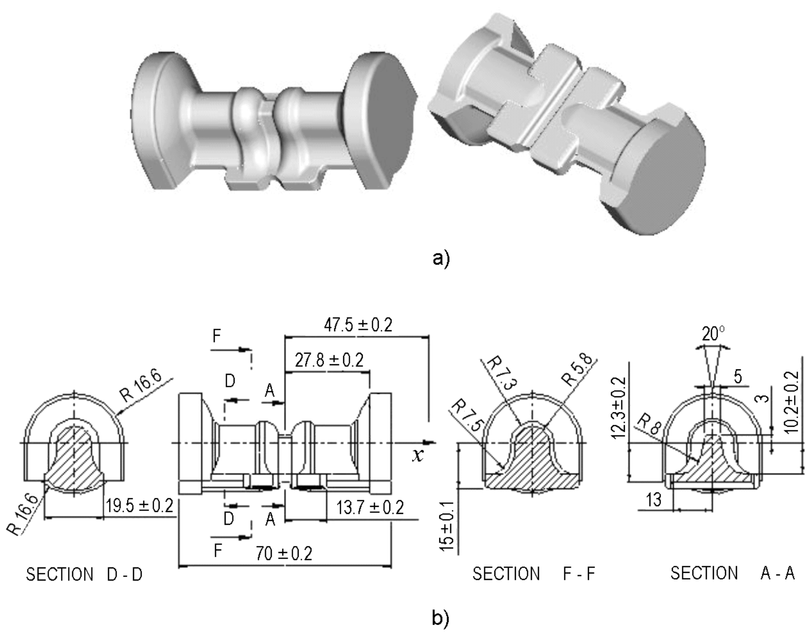


Fig. 3. The forging of piston SC100-T6 Al-alloy (a) 3D-Modeling of the forging (b) The main dimensions of forging

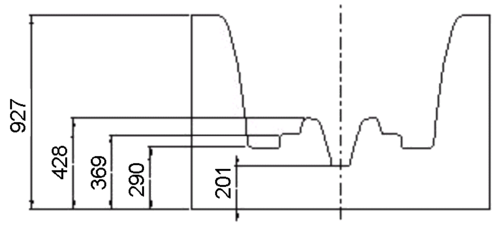


Fig.4. Schematic drawing of calculating blank of forging

that, for a specific temperature, the flow stress increases with the increase of stain rate. It shows that the strain rate sensitivity was positive for SC100-T6 Al-alloy, and for a fixed strain rate, the flow stress decreased apparently with the increase of temperature. With increasing strain rate and the decrease of temperature , the stress was required to reach a larger value. Further more , as shown in Fig. 2, at higher temperatures, the true stress-strain curves exhibited flow softening.

Then for the SC100-T6 Al-alloy, the appropriate forming temperate scope was form 390°C to 420°C and was formed in hydraulic press with heating device to maintain the forming metal's temperature.

3 Analysis of precision die forming for piston tail forging

The forging's outer shape and main dimensions for totality and two typical sections were shown in Fin.3. The structure of the part was symmetrical about two central planes, then force exerted on the die was symmetrical as well. But the quantity of metal along horizontal axis was extremely nonuniform and the volume of metal at two ends in shorter length was much more than other part. The condition of the metal distribution was shown in Fig.4 clearly.

The complex coefficient of the forging defined by formula (1) clearly indicated forming difficulty level , and influenced the metal flowing and forming force strongly. The numerical value was more smaller, more difficulty of forming. The value of complex coefficient was ratio of volume of forging to volume of the simple part which was a six sided cube or cylinder and could contain the forging.[1-2]

$$C_V = V_F/V_C \tag{1}$$

Where C_V was complex coefficient, V_F was the volume of forging, V_C was the volume of parallelepiped or cylindrical container.

For the studied part shown in Fig.3, its volume V_F was about 32529mm^3, and the volume of six sided cube V_C which could contained the forging was 77157mm^3. According to the formula (1), the complex coefficient C_V of the forging was 0.42. Considering the calculating blank shown in Fig.4, the forging was belong to more complex part.[1-2]

Then, in order to make the metal fill the die cavity using reasonable force in final forging, pre-forging step was necessary for blank. The function of pre-forging was that the metal was transferred to the region needed more material, and in final step the deformation amount should be transferred as small as possible. For the studied object, the pre-forging schemes were shown in Fig.5.

According to the shape of the part, the right position of the forging was shown in Fig.5. The one forming way was shown in Fig.5(a) which the material was accumulated at the two ends by upsetting, and the other was extruding forming that the metal was extrude into the cavity at two ends from middle part shown in Fig.5(b). Though the upsetting forming was easily created compare to extruding, the die structure for upsetting shown in Fig.5(a) was more complex which had bevel slider structure changing the vertical movement to horizontal. For upsetting method, the stability of the blank exerted pressure must be considered. For the extruding scheme the problems mentioned above were non-existent and the metal was extruded into two ends cavities.

Then the scheme shown in Fig.5(b) was a reasonable way relatively.

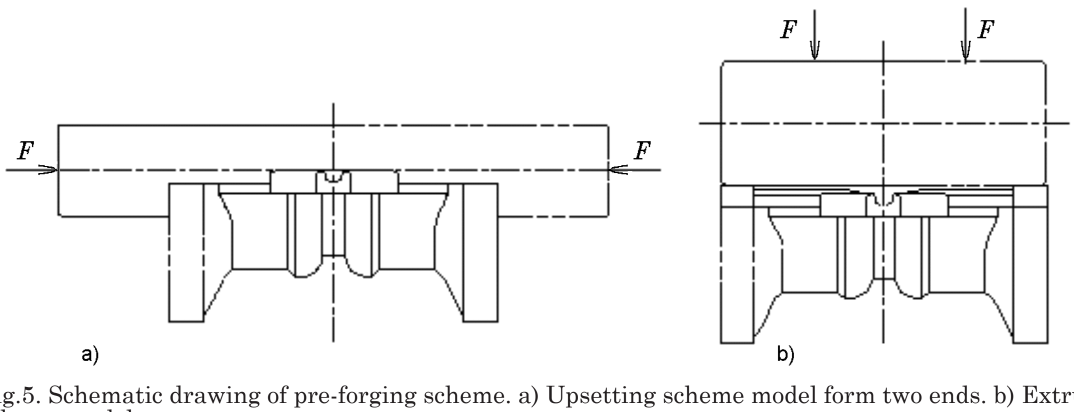


Fig.5. Schematic drawing of pre-forging scheme. a) Upsetting scheme model form two ends. b) Extruding scheme model

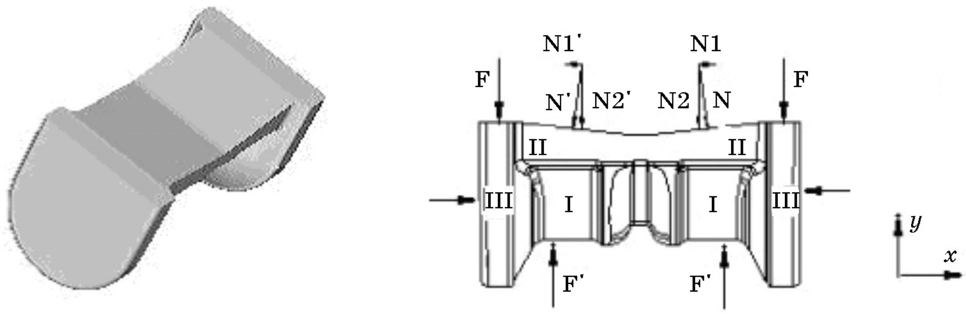


Fig.6. 3D-model of pre-forging and force sketch map in pre-forging process

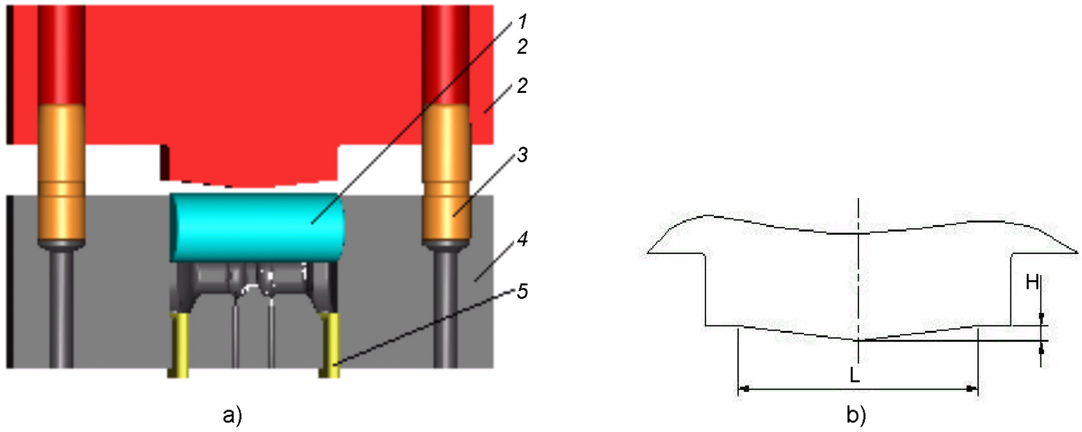


Fig.7. Schematic drawing of pre-forging die. (a) The structure of the pre-forging (b) The shape of working part of punch. 1-blank, 2-punch, 3-guide pillar, 4-die, 5-push rod

4 Die forging Process

The 3D-model of pre-forging was shown in Fig.6, and its top surface was designed "V" shape. The pre-forging should be put into the final die cavity easily and the deformation in final step should be upsetting mainly, and was small as far as possible.[4-5,7]

The schematic drawing of pre-forging die was shown in Fig.7, and the blank was deformed in closed die. Apparently, the two ends of pre-die need material to fill and a great deal of metal was extrude to ends from the middle part. The blank metal got in touch with the working surface of punch form begin to end, and contact state between them would affect the metal flow. At high forming temperature, the friction coefficient between steel and Al-alloy was bigger and friction force strongly prevented the metal flow. Then, the structure of punch working part should be designed to reduce friction force or contribute to the metal flow. The "V" shape surface of punch working part was designed to replace the flat surface. Punch surface was contact with metal gradually, and the force exerted the forming metal by punch slant surface which shown in Fig.6 contributed the material flow. At the end, compare to flat surface the more material was transferred to two ends which was advantage for final forming. The depth of the cavity at the ends was machined deeper than the designed to contain more metal in order to avoid vertical flash.

The schematic drawing of pre-forging die and the shape of working part of punch was shown in Fig.7 respectively. According to the dimensions of forging, the value of H was equal to 55mm, and the value of H was decided by experiment finally. The initial value of H could be 3mm.

According to the feature of the forging and pre-forging, the final die was adopt small flash open die forging in which surplus metal was extruded out of the die with small round and got qualified forging.

5 Number simulation

Pre-forging process which model was shown in Fig.7(a) was simulated by Deform software, and the effective strain at main steps was shown in Fig.8. The part was symmetrical about left-right and front-back symmetrical plane. Obviously modeling one quarter of the model was advantageous because 3D analysis was so intensive on computational time. Due to geometrical and computational considerations,

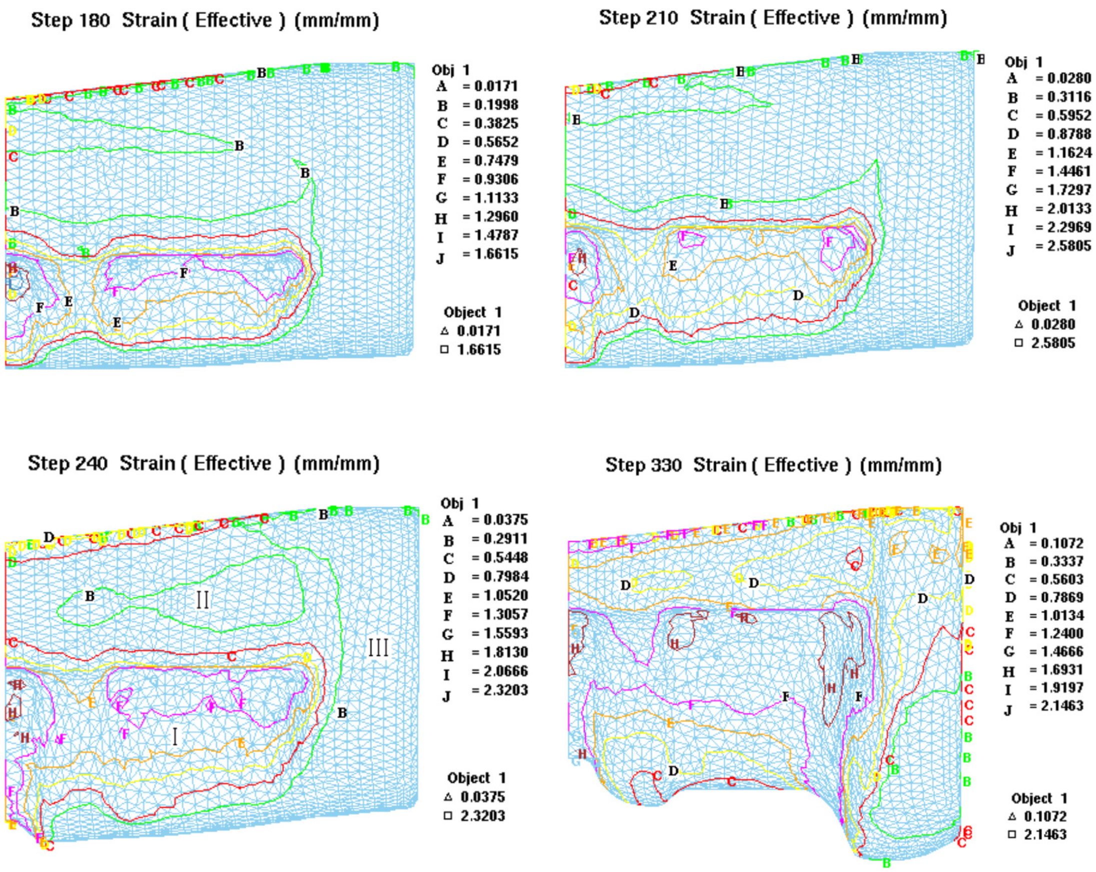
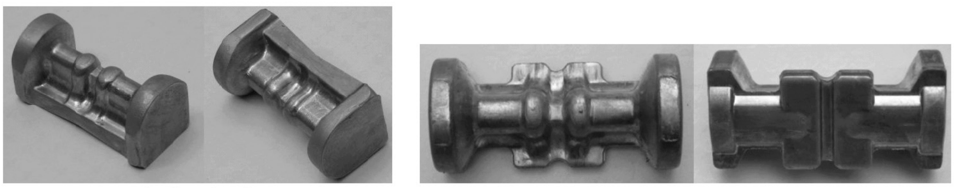


Fig.8. Distribution of effective strain



a) Pre-forging b) Forging

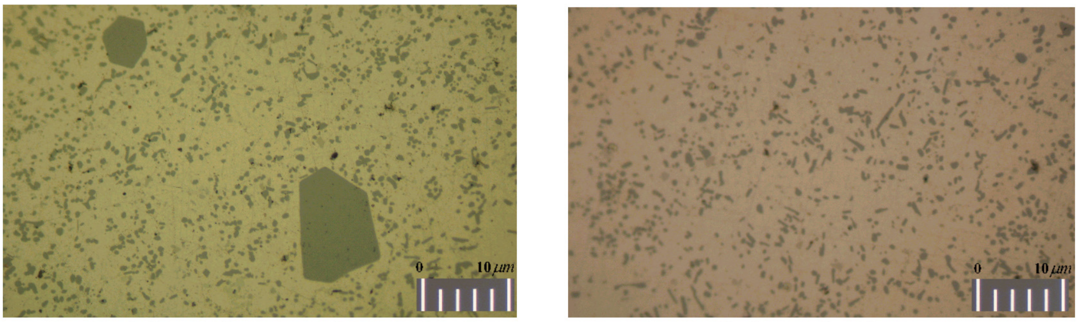
Fig.9. Photos of pre-forging and forging

some assumptions were given as follows. The simulation type is considered as rigid-plastic which dies could not be deformed and wrecked in the forging process. There was no heat interchange occurring between the billet and the dies, and the temperature of billet was set to 480 °C at which the material has higher formability. The die velocity of 20mm/s, obtained from industrial condition, was applied to the punch. The shear friction coefficient is set up 0.30 between the dies and the billet which is near to the real value.

It was shown in Fig.8 that the metal in the middle part was easier to flow to the two ends to fill the die cavity by the side force which the slant surface of punch applies to the billet. At the same time, the friction force between the punch and billet was greatly weakened because of smaller normal force applied to the billet and the metal under the punch was deformed earlier. It was more proper to distribute the metal along the horizontal axis direction which there need much more volume of metal in two ends for final forging.

6 . Experimental

The experiment die device was installed in 800T hydraulic press, and pre-forging and final forging had same die carrier. According to isothermal compression experiment done before, heating plate was fixed the die outer to maintain the blank temperature 450±20 °C. The electric oven was pre-heated 300 °C and 30 minutes firstly, and the blanks were put



a) Sample from raw material   b) Sample from forging

Fig.10. Microstructure photos of Al-alloy

into the oven to heat 480 °C, maintaining 60 minutes. The die was lubricated using colloidal graphite mixed with water.

The photos of pre-forging and forging which was cut of the flash were shown in Fig.9. In the two ends of pre-forging, the shape was not done, which reduced the forming force and avoided vertical flash. Form forging photos, the shape of forging was very well-stacked, and had no flaws. It was verified the pro-forging designed right.

The microstructure of Al-alloy was shown in Fig.10. In the raw material, few Si elementary substance blocks were scattered in the metal, which could degrade mechanical properties of material. For the forging, the samples were cut from the ends of the part, the Si elementary substance blocks were broken to pieces in forging process and scattered uniformly in the metal, which could improve the forging mechanical properties. It was proved that the forging process done in paper was feasible. The qualified forging was got and the mechanical properties of Al-alloy was elevated.

7. Conclusion

From theoretical analysis and experiment for the al-alloy and the forging process above, some conclusions had got as follows:

In the high temperature range 420~470°C, the SC100-T6 alloy had certain plastic, and temperature and strain rate had strongly effects on its effective stress.

For a complicated forging with SC100-T6 alloy, at forging temperature rang the qualified forging could be achieved by feasible forging process.

For the studied forging, the preforging was key step and the preforging part designed could solved the problem of material accumulating successfully. The right die forging process was designed and qualified forging was gotten.

Through die forging process, the microstructure of the alloy had improved to some extent, the Si blocks scattered in the alloy had been bracken small grain.

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