An investigation of temperature effect on microstructure and mechanical properties of aluminum (A360) processed by thixoforging

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***Abstract*—**Thixoforging has some advantages over conventional forming processes such as die casting, squeeze casting, and hot/cold forging. Thixoforging can produce non-dendritic alloys for the semi-solid forming of complex-shaped parts in metal alloys. Since thixoforging takes place between liquidus and solidus temperature and liquid phase and solid phase exist at the same time, heating circumstances is more significant. In order to achieve homogenous microstructure during heating , eutectic must transformed to liquid completely to gain suitable mechanical properties .The solid phase percentage during forming process in semi-solid condition ,has a very important effect which is affected by heating temperature . In this research, the effect of temperature on thixoforging process and mechanical properties of the work piece was investigated. The lap, which is an external defect, was observed at higher initial work piece temperature. In hardness test, it was observed that the hardness decreased at higher initial work piece temperature.

***Keywords*—** Semi-solid forming, Microstructure, Thixoforging, Simulation, Mechanical properties

I. INTRODUCTION

Not only thixoforging reduces the essential forces for forming, but also causes the fewer defects such as porosity in work piece than die cast(Fig.1). In thixoforging process, to achieve homogenous solid phase distribution and spherical microstructure, the work piece must be heated in all section.

Because of some problems in electrical furnace such as irrepressible and time, usually induction coil is used. Induction coil could be controlled more precisely and also heated all section of work piece equally. In this process, specimen has low temperature and consequently low viscosity, so perhaps it couldn't fill the mould ideally. On the other side, in higher temperatures because of segregation between liquid and solid phase, the suitable work piece couldn't be achievable, regardless of complex movement of work pieces in high temperature and possibility of missing their shapes because of their weights. Furthermore, in high temperature lap phenomena could be happened.

In a study on the reheating process, Akbas and Turkeli[1]investigated the changing process of the globularization according to the heating temperature of Al7075 alloy. Midson et al. [2] proposed the necessity of coil design to prevent the electromagnetic end effect, and Garat et al. [3] proposed multi-capacity reheating conditions of A356 and A357 alloys. Witulski et al. [4] proposed that since with specimen heating, the stability of the specimen in its semi-solid state is a major consideration, the solid fraction control of the specimen to avoid its being excessively deformed by its own weight is necessary. Kouji [5] does this after heating the specimens in the semi-solid state by using induction heating system with several induction coils, feeding the specimens on the pressing punch by using a robot with six degrees of freedom. Then he filled the specimens into the die at lower pressure. Matsuura and Kitamura [6] carried out the reheating experiments to heat the specimens with 76.2 mm diameter and 170-180 mm length from room temperature to 843 K (570°C), $\pm$ 5 K.

In this research, the effect of temperature and heating on thixoforging was investigated and after induction coil design, some tests accomplished to reduce the thermal gradient and achievement of required microstructure and the effect of temperature on microstructure of piece were studied.

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II. Coil Design for Uniform Reheating

A. Aluminum and its alloy

The most operational and important characteristics of aluminum and its alloy are: lightness, workability, physical properties, mechanical properties and corrosion resistant. Aluminum is well known because of its lightness and corrosion resistance. Density of aluminum is about 2.7kg/m^3 which is about a third of steel, copper and brass.

It has a well resistance against corrosive agents such as atmosphere, salty water, oils and chemical materials. Thixoforming variants were shown in Fig1. Table 1 showed the chemical composition of aluminum alloy, A360.

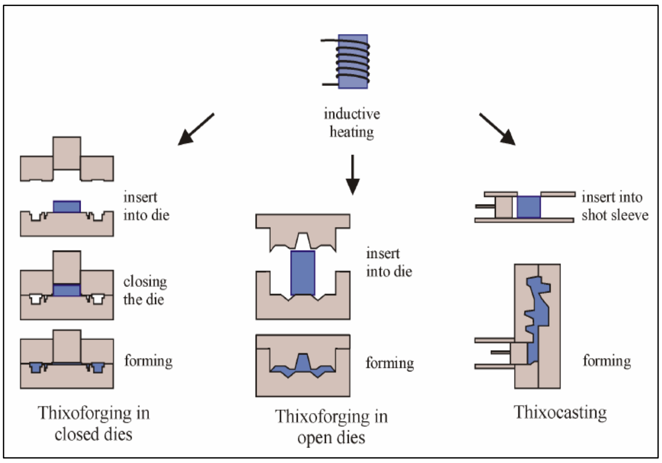

Fig. 1 Thixoforming variants

Table. 1 Chemical composition of A360

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ni	Sn
MIN %	9.0	-	-	-	0.40	-	-	-	-
MAX %	10.0	2.0	0.60	0.35	0.60	-	0.50	0.50	0.15

B. Work piece heating

For uniform reheating in this study, the optimal coil length and coil inner diameter of the induction heating system were designed as follows. Its importance is caused by the skin effect which is more than 86% of inducted thermal energy in specimen surface. The maximum acceptable tolerance for temperature was less than 1 degree.

The main points in coil design were the optimized relation between the length of specimen and coil [8, 9, 10].Regarding to mentioned points, the suitable coil was designed. In Fig2, schematic of designed coil was shown.

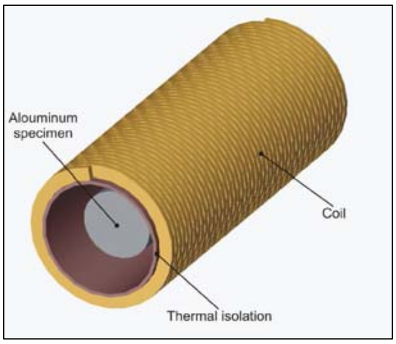

Fig. 2 Schematic of designed coil

C. The measurement of temperature in center of work piece

In order to measure temperature in center of work piece, a hole in order to setting the thermocouple sensor was made. The diameter of applied thermocouple was 1.6mm and the hole diameter and its depth were 2.5mm and 5mm respectively.

The following are the parameters of the globularization of the microstructure and a small temperature gradient: the capacity of the induction heating system (Q), the heating time (ta), the heating Temperature (Th), the holding time (th), and the reheating step.

In order to achieve the homogenous microstructure in a specimen for thixoforging process, the ratio between liquid and solid phase is very important.

Concerning to this matter, the percentage of solid and liquid phase was calculated.

D. The calculation of liquid and solid phase percentage

To determine the heating temperature of the SSM, the solid fraction is calculated using Scheil's equation [12].

$$f_L = \left(\frac{T_M - T}{T_{M-}T_L} \right)^{-1/(1-K)} \qquad (1)$$

Where TM and TL are the melting temperature and liquidus temperature of the pure metal, respectively and f_L is liquid fraction.

Fig3 showed the relation between temperature and solid phase percentage.

The test results showed that the suitable percentage for solid phase in thixoforging process was 55. Although lower percentages facilitated the process but the some problems could be occurred because of changed shape of pieces due to their weights and their movement for setting in mold.

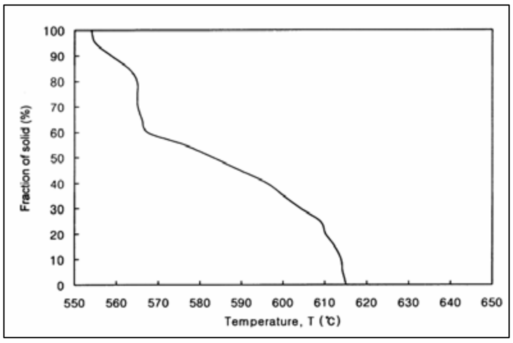

Fig. 3 Relationship between temperature and solid fraction for A360

III. Software simulation of temperature effect on thixoforging

In order to simulate the process, the software known as MSC.Super Forge, was used .One of the most noticeable agent which has a great effect on thixoforging is the primary temperature of work piece.

Its importance related to its effective rule on relative percentage of solid and liquid phase. As shown in Fig3, by increasing the temperature, the solid phase percentage and consequently the forming forces reduced. Therefore, because of the significant rule of forming forces in thixoforging , piece temperature had a great importance .

Indeed, increasing the temperature had some limitation such as problems which could be occurred in specimen movement to mold before thixoforging process and occurrence of thermal cracks at the center of pieces.

The center track occurs because of over-increasing of primary temperature in the center of specimens. By fast heating the piece, the other defect, thermal crack, would have been appeared. This defect resulted by contraction, expansion and temperature difference between center and outer surface of piece.

A. The effect of primary temperature of work piece on lapping phenomena

Increasing of primary temperature caused the viscosity enhanced during thixoforging process. Increasing of work piece viscosity could raise the possibility of lapping phenomena.

In Fig 4 lapping phenomena in 500, 570, 600 ^{o}C in 80% of time, was compared. In this Figure, the lapping enhancement caused by temperature increasing, was shown.

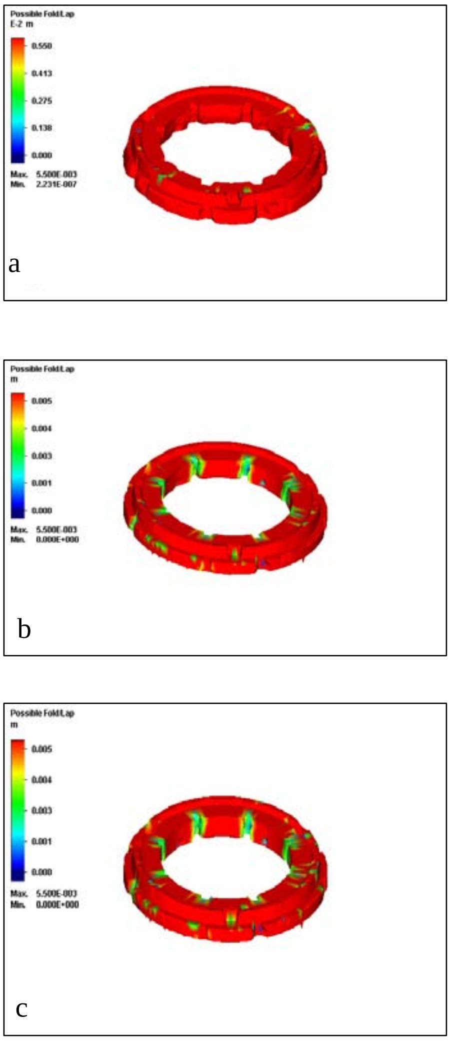

Fig. 4 Simulation of lapping in different temperature:
(a) 500^{o}C, (b) 570^{o}C, (c) 600^{o}C

B. The effect of temperature on the formation of sharp corners

After dislodging the work piece from coil, the piece temperature fell intensively. This reduction was intensified by setting the piece in mold.

The temperature reduction resulted in viscosity decrease and consequently during forming in thixoforging process, the formation of sharp corners was complicated. This matter was shown in Fig 5.

IV. The effect of temperature on piece microstructure

Microstructure of specimen before and after etching was shown respectively in Fig6,7,8and9. According to Fig6, material currency direction helped to distinguish the direction of specimen extrusion.

By increasing the heating temperature or marinating time in requested temperature, the grain size was raised. The grain size had a great effect on mechanical properties of the pieces.Therefore, the precise control of time and heating temperature in thixoforging were very important.

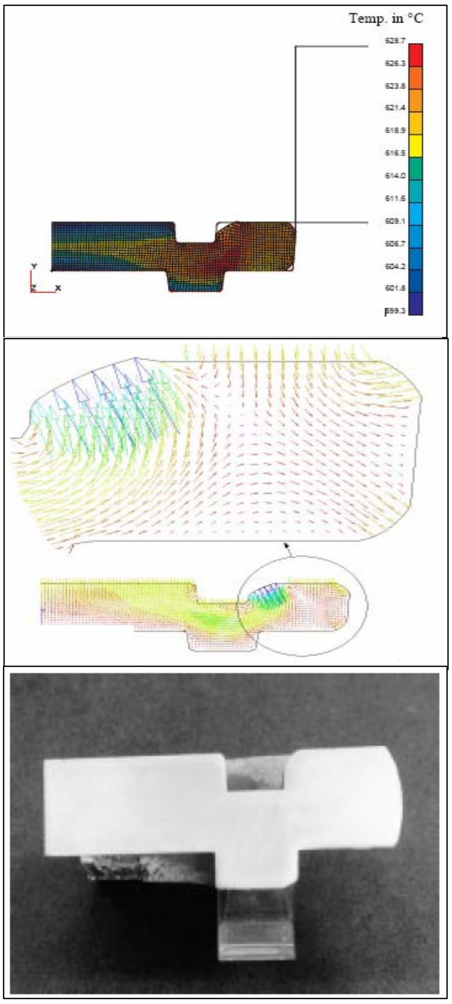

Fig. 5 Effect of viscosity on die filling in sharp corners

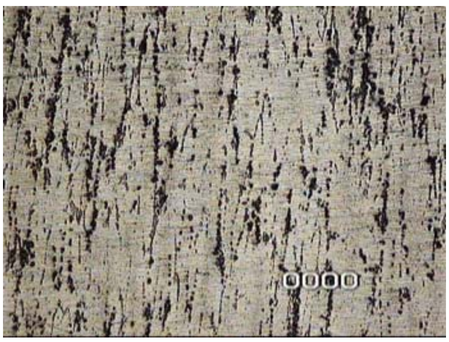

Fig. 6 Microstructure of extruded specimen before etching(100X)

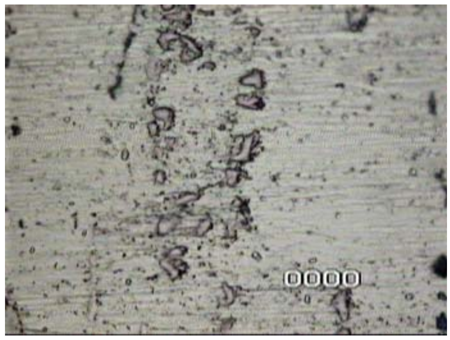

Fig. 7 Microstructure of extruded specimen before etching(1000X)

Fig. 8 Microstructure of extruded specimen after etching(100X)

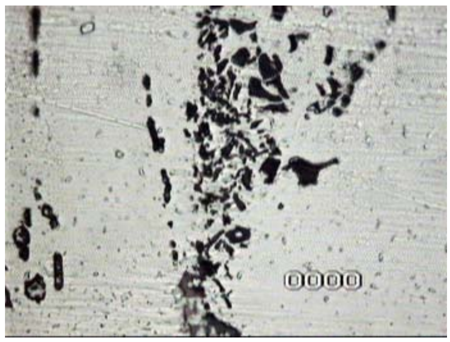

Fig.9 Microstructure of extruded specimen after etching(1000X)

V. INVESTIGATION OF HEATING TEMPERATURE ON DEPOSIT INTEGRATION IN GRAIN BOUNDARIES

Metallic contents such as zinc, copper, magnesium at 350^{o}C were distributed in grains equally. Recystallisation started at 500^{o}C and the copper amount in grain boundaries increased. This increase of copper in grain boundaries was raised up in higher temperature such as 590 ^{o}C as pasting temperature.

The existence of metallic contents in grain boundaries decreased strength of the piece. In order to solve this problem, after thixoforging, the pieces processed by heat treatment known as T6. This heat treatment resulted in equal distribution of metallic contents such as copper, zinc, magnesium. Fig 10 showed the accumulation of metallic contents.

Comparison between Figs 10 and 11 showed that in higher temperature of forming, the accumulation of metallic contents in grain boundaries was increased and caused to piece strength decrease. The increase of grain size in higher temperature helped the strength decrease. When the grain size was lower than 100 µm, the microstructure was more homogenous and mold was filled very rigorously [13, 14, 15 and16].

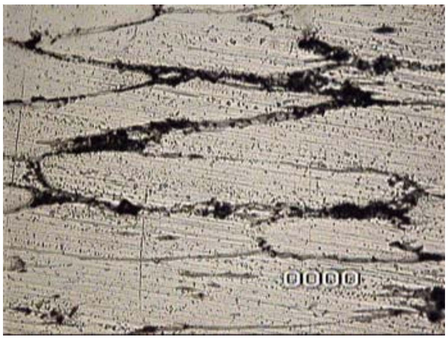

Fig. 10 Thixoforged part in 590 ^{o}C(500X)

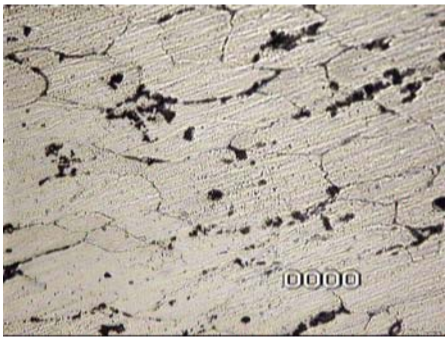

Fig. 11 Thixoforged part in 500 ^{o}C(500X)

VI. Investigation of temperature on hardness

As were stated before, the metallic contents accumulated in grain boundaries in pieces after thixoforging. These precipitations decreased the strength and the heat treatment was necessary. One of the most common heat treatment was T6.

This process for aluminum alloy (A360) contained 8 hr heating in 500^{o}C, quenching and keeping 160 ^{o}C for 5hr. The decrease of hardness derived from temperature increase was shown in Figs 12 . Fig 12 emphasized on the necessity of heat treatment.

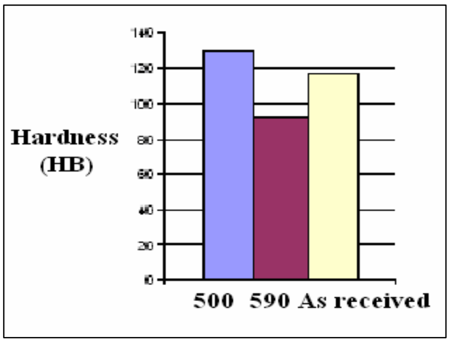

Fig. 12 Hardness with various thixoforging temperature

VII. Conclusions

1-Thixoforging used as new method to produce pieces with so complex shapes. It also reduced energies, required equipments, pieces defects and also machining significantly.

2-Software simulations for thixoforging were so useful to decrease the try and error faults in order to better selection.

3-By using software analysis, some investigation such as friction, mold temperature, the rate of strain, the effect of blank piece temperature on forming forces, material flux, existing stresses on piece and mold, yield stress and lapping phenomena could be accomplished.

4-The grain size raised up by increasing the heating temperature and in situation which grain size was lower than 100 µm, the microstructure in more homogenous and the mould could be filled precisely.

5-In comparison with the casting piece, the thixoforging piece had a lower hardness. By increasing the primary temperature, the mentioned difference was more significant. The reason of this distinction was the accumulation of metallic deposits in grain boundaries. These metallic deposits made the heat treatment necessary. One of the most common heat treatments on aluminum alloy had known T6. After thixoforging, the hardness of piece was much more than the casting piece.

6-At 350 ^{o}C, some contents such as copper, zinc, magnesium were distributed in grains equally. Recystallisation started at 500 ^{o}C and the amount of copper increased. This enhancement in grain boundaries was raised up at higher temperatures such as pasting temperature. The existence of metallic contents in grain boundaries caused to decrease the material strength.

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