JMEPEG (2004) 13:55-59
DOI: 10.1361/10599490417632

1059-9495/$19.00

Effect of Applied Pressure and Heat Treatment Condition on Microstructural Characteristics and Mechanical Properties of the Thixoforged 357 Aluminum Alloy

C.G. Kang, S.W. Youn, and S.M. Park

(Submitted 22 April 2003; in revised form 11 November 2003)

The characteristics of the microstructure and mechanical properties of thixoforged 357 Al parts with an arbitrary shape were studied for microstructure and mechanical property variations as a result of changes in the applied pressure (110, 140, and 170 MPa) and the solution heat treatment aging time (4, 6, and 10 h).

Keywords applied pressure, high solid fraction, mechanical property, T6 heat treatment, thixoforging,

1. Introduction

Semi-solid forming (SSF) processes that produce component parts while in the semi-solid state are now becoming increasingly popular for the manufacturing of automotive parts. In addition, SSF has spread to the field of electric home appliances and hydraulic components because porosity is less of a problem due to the low deformation resistance of the semi-solid during forming.[1-7] Two SSF processes can be differentiated according to the solid fraction of the semi-solid material (SSM). One is thixocasting, which uses SSM with a solid fraction below 40%. It is the most common SSF process used industrially. Another is thixoforging that uses SSM with a relatively high solid fraction (f_s), i.e., between 55% and 60%. In the SSF process it is very important for the SSM to have a low viscosity and a high solid fraction. The low viscosity is necessary to obtain good fluidity, which is indispensable for filling up the die cavity, while the high solid fraction is effective in preventing various defects and obtaining a fine internal structure, leading to excellent product quality. From the point of view of solid fraction, thixoforging offers very interesting forming possibilities.

Thixoforging is a process similar to closed-die forging. A billet is placed between two open dies and then pressed into the desired shape by the movement of the upper die. In thixoforging, it is possible to fabricate parts having good inherent mechanical properties associated with alloy chemistry as well as the improvement in properties achieved from forging. In addition, thixoforging has some advantages over conventional hot forging, such as lower forming load, smaller scale forming equipment, wider materials selection, fewer product defects, and the possibility for near-net shape forming. Applications to automotive parts, such as engine brackets, steering knuckles, brake master cylinders for weight reduction, and structural frames such as rear suspension are being actively pursued.[5-8] To obtain high quality components with the thixoforging process, it is important to investigate the effects of the process forming parameters (e.g., the solid fraction of the material, punch velocity, applied pressure, die temperature, etc.) and post-forming heat treatment conditions on mechanical and microstructural properties.[8-10] However, compared with the thixocasting process, a lot of work is still needed in this field.

Consequently, the effects of aging time (4, 6, and 10 h) adopted for the T6 heat treatment and applied pressure (110, 140, 170 MPa) on mechanical and microstructural properties of thixoforged parts, constituted by A357 Al, were investigated.

2. Experimental Procedure

2.1 Reheating Experiment

For thixoforging it is important to reheat the SSM to a temperature between the solid and liquid states so as to have an adequate globular microstructure. The Al-Si7Mg6 (A357) alloy that was fabricated by EMS (Pechiney, France) was used. The chemical composition of A357 is shown in Table 1.

The SSM billet was machined to the height of 50 mm and a diameter of 76 mm and three holes (∅2 mm) were drilled to measure the temperature. Temperature on the transverse sec-

C.G. Kang, National Research Laboratory of Thixo/Rheo Forming, Engineering Research Center for Net Shape and Die Manufacturing (ERC/NSDM), School of Mechanical Engineering, Pusan National University, JangJun-Dong, Gumjung-Gu, Pusan, 609-735, South Korea; **S.W. Youn** and **S.M. Park,** School of Mechanical Engineering, Pusan National University, Pusan, 609-735, South Korea. Contact e-mail: wonny@hitel.net.

Table 1 Chemical Composition of A357 Alloy wt.%[11]

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Pb
Min	6.5	…	…	…	0.50	…	…	…	…
Max	7.5	0.15	0.03	0.03	0.60	0.03	0.05	0.20	0.03

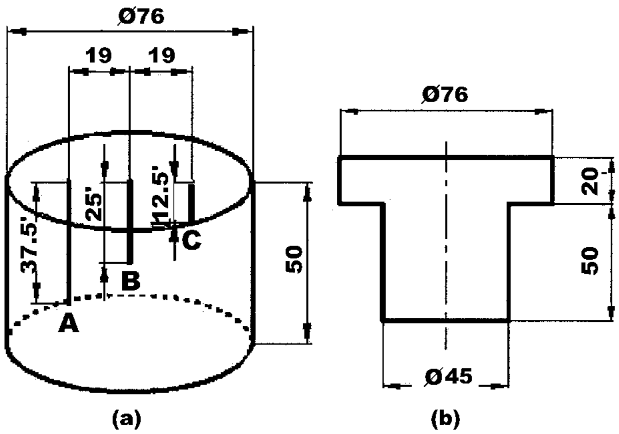

Fig. 1 Dimensions of **(a)** reheating billet, in which symbols A-C indicate the positions of temperature measurement and **(b)** thixoforging sample

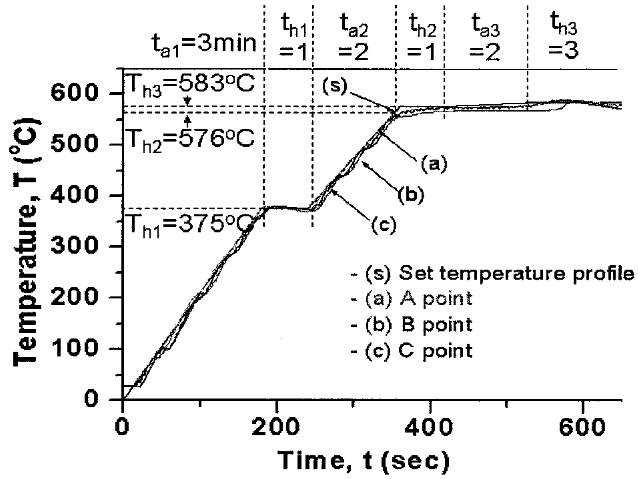

Fig. 2 Reheating conditions and temperature profile during the reheating of A357 to produce a sample part with semi-solid material

Table 2 A357 Reheating Condition ($\varnothing \times l$ = 76 mm × 50 mm) for Vertical Induction Coil

Holding Temp., T_h, °C			Reheating Time, t_a, min			Holding Time, t_h min		
T_{h1}	T_{h2}	T_{h3}	t_{a1}	t_{a2}	t_{a3}	t_{h1}	t_{h2}	t_{h3}
375	576	583	3	2	2	1	1	3

Table 3 Heat Treatment Conditions for A357 Thixoforged Parts

	Solutionizing		Aging	
Material	Temp., °C	Time, h	Temp., °C	Time, h
357	540	6	170	4
			170	6
			170	10

tion of the billet was measured at three positions: surface (Fig. 1a-A), half radius (Fig. 1a-B), and center (Fig. 1a-C), by using K-type chromel-alumel thermocouples of 1.6 mm diameter. The temperature of the position B thermocouple in Fig.1(a) was used to control the temperature of the induction heater. For a uniform temperature distribution throughout the billet, reheating experiments were performed using an induction heater with 60 Hz, 50 kW capacity using a three-step reheating scheme, as shown in Fig. 2.

To achieve the fine globular microstructure, the eutectic must be melted completely, and to achieve this, the reheating time must allow for complete eutectic melting. Therefore, the heating temperature of the second step (T_{h2}) was set at the eutectic temperature of each alloy to ensure complete eutectic melting. The final holding time (t_{h3}) is the most important factor in obtaining a fine globular microstructure and to prevent globule coarsening in the three-step reheating process. The reheating holding temperature of the final step (T_{h3}) was determined so as to obtain a proper solid fraction (55% by volume) and to achieve the homogeneous distribution of globular particles thereby reducing material loss. The reheating conditions that were investigated by the trial-and-error experimental method are described in Table 2.

2.2 Experiment for Thixoforging and Heat Treatment

To investigate the proper process condition, forging experiments were conducted for a variety of applied pressures (110 MPa, 140 MPa, and 170 MPa) by using a hydraulic press (maximum load 200 ton, maximum velocity 200 mm/s). Applied pressure was held for 20 s after completely filling the die to prevent defective filling due to shrinkage during solidification and liquid segregation both of which decrease part strength. The punch velocity was 200 mm/s. The geometry of the sample product is shown in Fig. 1(b). Cartridge heaters of $\varnothing$ 16 mm, 1 kW capacity were used to preheat and keep the die at between 200 and 300 °C. A graphite-base lubricant was used for the punch and a boron-nitride spray for the die cavity.

From the experimental process conditions, sample components were fabricated and heat treated for various aging times after solution treatment, as shown in Table 3. Microscopic observation and tension tests were performed. In the tension tests, a strain rate of 0.5×10^{-3} s^{-1} was used on the thixoforged samples both before and after heat treatment. For tension tests, cylindrical tensile specimens were machined following ASTM E-8M standard to a gage length of 20 mm with a diameter of 4 mm.

3. Results and Discussion

3.1 Temperature Profile of Billet During Peheating

The temperature of the billet at each point A, B, C as shown in Fig. 1(a) was measured during reheating. Figure 2 shows the temperature profile for reheating an A357 billet using the conditions in Table 2. The total reheating time was 12 min and is in good agreement with the three-step reheating scheme. In the real induction heater composed of coil and billet, the induced heat is normally not equally distributed over the length of the billet. Due to this "skin effect" approximately 86% of the

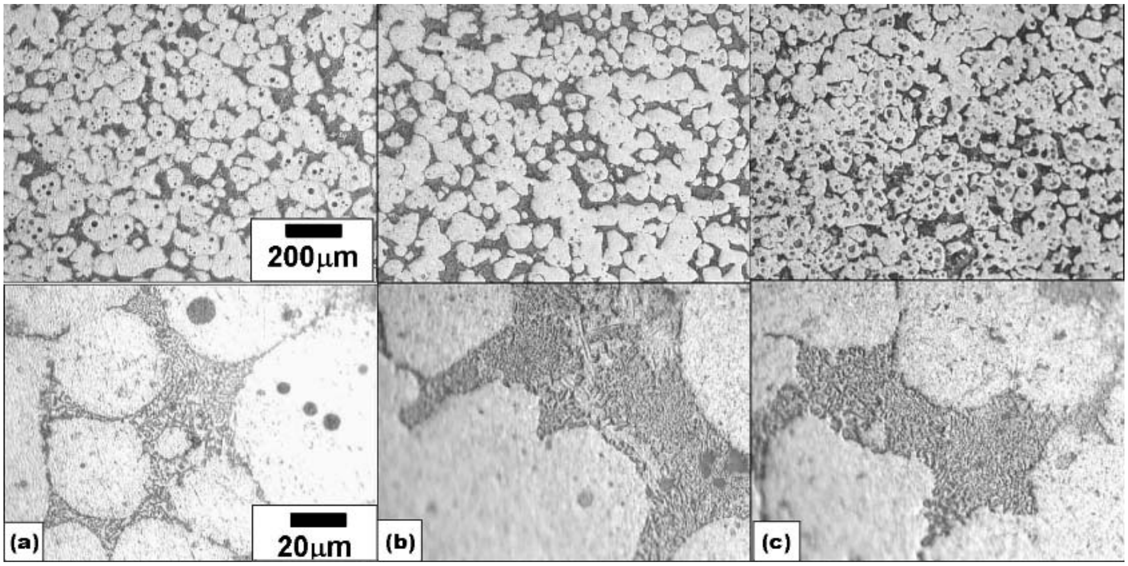

Fig. 3 Microstructure of thixoforged samples with applied pressure: **(a)** 110 MPa, **(b)** 140 MPa, and **(c)** 170 MPa (without heat-treatment)

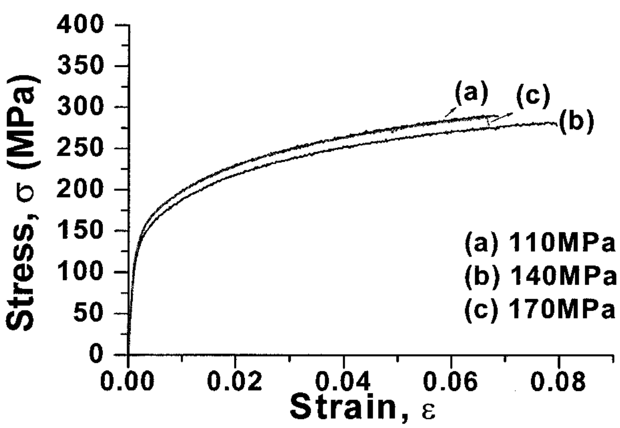

Fig. 4 Strain-stress curves of A357 with variations in the applied pressure

Table 4 Mechanical Properties of A357 Thixoforged Parts

Material	Applied Pressure, MPa	UTS, MPa	YS, MPa	Elastic Modulus, GPa	Elongation, %
357	110	290	162	108	7.0
(without T6)	140	282	150	103	8.2
	170	289	162	108	6.9

power is concentrated in a surface layer of the inductively heated billet. Therefore, the important process component is to optimize the coil design. This defines the optimal relation between the coil and billet length.[12-14] A maximum temperature difference of ±12 °C between points A and C was observed in only one certain section. However, a uniform temperature distribution was obtained to within ±1 °C for the last 1 min.

3.2 Effect of Applied Pressure

Figure 3 shows the microstructures of thixoforged A357 alloy parts for applied pressures of 110, 140, and 170 MPa. No remarkable reduction in the size of primary crystal was observed. Stress-strain curves of samples are shown in Fig. 4, and the mechanical properties are summarized in Table 4.

All properties show very much the same values regardless of applied pressure. For example, in the case of the ultimate tensile strength, the difference between the maximum and the minimum value was 8 MPa. It has been reported that the size of the globular structure decreases with increasing applied pressure, allowing an improvement of the mechanical properties.[9] However, in this study, this effect of applied pressure causing changes in mechanical properties and microstructure characteristics of the thixoforged part was not observed. This is considered to be due in part to the temperature drop of the billet during the feeding process. In the thixoforging billet handling portion of this study, it took 7-8 s to feed the reheated billet from the induction heater to the die. Therefore, the solid fraction in the reheated billet probably increased above the target 55% during feeding, and as a result, fast solidification may have occurred before the applied pressure fully affected billet microstructure. Also, the temperature difference between the reheated billet and die is another factor and may have resulted in a further temperature drop of the reheated billet. As a result of this research, it is considered that a higher punch velocity as well as a modification of the feeding device could lead to improved mechanical properties of thixoforged parts.

3.2 Effect of Ageing Time After Solution Treatment

The purpose of post-process heat treatment is to obtain a better combination of strength and ductility. Many Al alloys can be strengthened by solution heat treatment and precipitation hardening using successive quench cooling and hardening

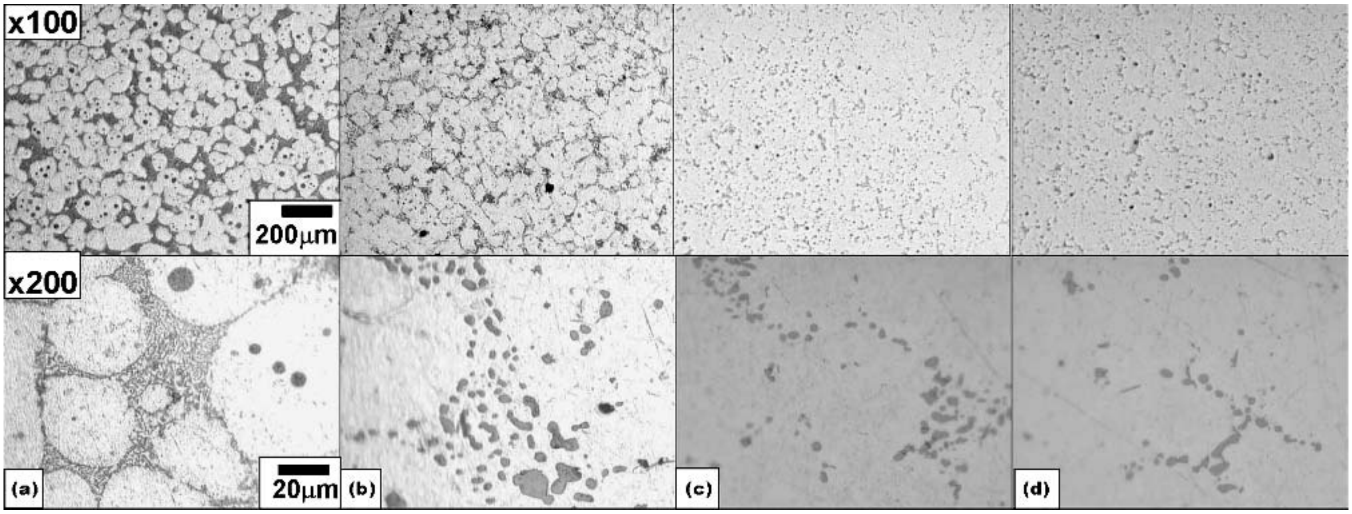

Fig. 5 Microstructure of A357 with variations in the aging time: **(a)** 0 h, **(b)** 4 h, **(c)** 6 h, and **(d)** 10 h

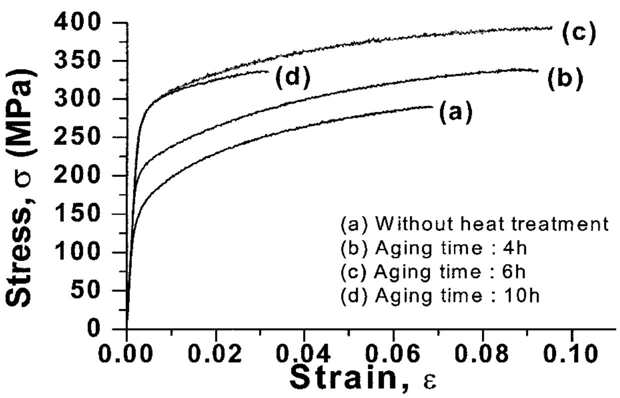

Fig. 6 Stress-strain curves of thixoforged samples with variations in the aging time.

ening steps. The precipitation hardening heat treatment is very effective for improving the general mechanical properties of aluminum, especially the fatigue resistance. The main precipitate in the T6 heat treatment is Mg_2Si for A357.[15-17]

To obtain the optimal T6 heat treatment condition, thixoforged parts were heat treated for a variety of aging times. For heat treatment experiments, sample parts were fabricated using a punch velocity of 200 m/s and an applied pressure of 170 MPa in a preheated die (about 300 °C).

The microstructural characteristics of the heat-treated parts are shown in Fig. 5. Figure 5(a) shows the as-deformed microstructure of the thixoforged part without post-process heat treatment. As aging time increases, the eutectic phase is well distributed leading to progressively finer and more well rounded Si particles Fig. 5(b-d).

Stress-strain curves and mechanical properties of thixoforged parts with and without post-process heat treatment are shown in Fig. 6 and Table 5. As shown in Table 5 mechanical properties improved significantly as a result of increased aging time. The best tensile properties were obtained for a 6 h aging time at 170 °C following solution heat treatment. The ultimate tensile strength was 394 MPa. Also, the highest percentage elongation of 10% was attributed to both the fine structure and the high Mg content. However, after the 10 h, 170 °C aging treatment, the ultimate tensile strength dropped to 336 MPa and was due to precipitate overaging. Moreover, in this case the percentage elongation decreased to 4%, which is lower value than for parts not given a heat treatment.

Table 5 Mechanical Properties for A357 After Post Process Heat Treatments

Material	Aging Time, h	UTS, MPa	YS, MPa	Elastic Modulus, GPa	Elongation, %
357	0	290	162	108	7.0
	4	339	214	102	9.0
	6	394	286	107	10.0
	10	336	286	106	4.3

4. Conclusions

Through the experiment of thixoforging with combinations of T6 heat treatments, a sample part with good mechanical properties was obtained. For a six-hour heat treat aging time, an ultimate tensile strength of 394 MPa was obtained. The percentage elongation for this sample was 10%. The following results were also discovered:

(1) The effect of applied pressure (110, 140, 170 MPa) on mechanical properties of thixoforged parts was not remarkable. It seems that the temperature of reheated billet dropped due to a delay in the handling time during the feeding process as well as temperature difference between the semi-solid material and die. As a result the solidification of the A357 alloy was completed before the applied pressure could affect the globular microstructure sufficiently.

(2) Among the different post-process heat treatments studied, (i.e., 4 h at 170 °C, 6 h at 170 °C, and 10 h at 170 °C), the

best mechanical properties were obtained by aging the parts for 6 h at 170 °C.

Acknowledgment

This work was supported by the Engineering Research Center for Net Shape and Die Manufacturing (ERC/NSDM), which was also financed by the Korean Science and Engineering Foundation (KOSEF).

References

1. M.C. Flemings: " SSM: Some Thoughts on Past Milestones and on the Path Ahead" in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites*, G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 11-13.
2. D. Apelian: "A Roadmap for Semi-Solid Processing" in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites,* G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 47-54.
3. A. Witulski, A. Winkelman, and G. Hirt: "Thixoforming of Aluminium Components for Lightweight Structures, in *Proc. of 4th Int.Conf. on Semi-Solid Processing of Alloys and Composites*, D.H. Kirwood and P. Kapranos, ed., Sheffield, June 1996, Univ. of Sheffield, UK, SRP Ltd., UK, 1996, pp. 242-47.
4. W. R. Loué and M. Suéry: "Microstructural Evolution During Partial Remelting of Al-Si7Mg Alloys," *Mater. Sci. Eng. A.,* 1995, *A203,* p. 1.
5. R. Kopp, D. Neudenberger, and G. Winning: "Different Concepts of Thixoforging and Experiments for Rheological Data," *J. Mater. Proc. Technol.* 2001, *111,* p. 48.
6. R. Kopp, G. Winning, J. Kallweit, H. Knissel, J.P. Cabathuler, and R. Quast: "Comparison of Thixocasting and Thixoforging Using a Unique Demonstrator Part" in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites*, G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 687-92.
7. R. Kopp, D. Neudenberger, M. Wimmer, and G. Winning: "Thixoforging – Basic Experiment and Optimized Tool Design" in *Proc. of 5th Int.Conf. on Semi-Solid Processing of Alloys and Composites*, A.K. Bhasin, J.J Moore, K.P. Young, and S. Midson, ed., Colorado School of Mines, Golden, CO, 1998, pp. 165-172.
8. C.G. Kang and P.K. Seo: "The Effect of Gate Shape on the Filling Limitation in the Semi-Solid Forging Process and the Mechanical Properties of the Products," *J. Mater. Proc. Technol*, 2003, *135,* p. 144.
9. W.G. Cho and C.G. Kang: "Mechanical Properties and Their Microstructure Evaluation in the Thixoforming Process of Semi-Solid Aluminum Alloys," *J. Mater. Proc. Technol.,* 2000, *105,* p. 269.
10. K.C. Sharma, J.H. Ferreira, G. Govender, and O. Damm: "Effect of Process Variables on A356 SSM Castings" in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites*," G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 253-258.
11. ALTHIX Billets: *Aluminium Pechiney*, Pechiney, France, 1996.
12. J. Keist and D. Apelian: "Induction Heating of SSM Billets: Processing Issues" in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites*, G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 203-208.
13. H.K. Jung and C.G. Kang: "An Induction Heating Process with Coil Design and Solutions Avoiding Coarsening Phenomena of Al-6 pct Si-3 pct Cu-0.3 pct Mg Alloy for Thixoforming," *Metall. Mater. Trans. A,* 1999, *30A,* p. 2967.
14. H.K. Jung and C.G. Kang: "Induction Heating Process of an Al–Si Aluminum Alloy for Semi-Solid Die Casting and Its Resulting Microstructure," *J. Mater. Proc. Technol.,* 2002, *120,* p. 355.
15. M. Rosso, P. Giordano, and L. Chiarmetta: "Study of the Influence Heat Treatment Cycles on Properties of Thixoformed Automotive Parts," in *Proc. of 6th Int. Conf. on Semi-solid Processing of Alloys and Composites*, G.L. Chiarmetta and M. Rosso, ed., Edimet, Brescia, Italy, 2000, pp. 325-30.
16. H.K. Jung, P.K. Seo, and C.G. Kang: "Microstructural Characteristics and Mechanical Properties of Hypo-Eutectic and Hyper-Eutectic Al–Si alloys in the Semi-Solid Forming Process, *J. Mater. Proc. Technol.,* 2001, 113, p. 568.
17. S.H. Juang, S.M. Wu, and C.Y. Ma: "Study on Mechanical Properties of an A356 Aluminium Alloy With Thixotropic Properties," in *Proc. of 6th Int. Conf. on Semi-Solid Processing of Alloys and Composites*, G.L. Chiarmetta and M. Rosso, Edimet, Brescia, Italy, 2000, pp. 705-10.