

Research of Semi Solid Casting of Iron

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ABSTRACT

One result of the research on semi solid casting of iron is the development of parts having qualities that combine the superior material properties of iron with the dimensional accuracy of aluminum die-cast parts. In addition, this manufacturing method also improves the factory environment by eliminating the need for sand molds, and it utilizes the same equipment and facilities in an Al-thixo casting plant. To establish this technology, research was conducted on iron material (composition iron-carbon-silicon), molding methods using optimal billet heating speeds and copper die materials, and methods for the continuous casting of raw material billets for Fe-thixo casting. This manufacturing method was studied with an oil pump cover, in which the oil pump is directly driven by the engine crankshaft, and the same dimensional accuracy was obtained as the conventional aluminum die-cast product. Furthermore, an improvement in the volume efficiency of the oil pump was also confirmed due to the stiffness improvement and clearance reduction effects.

1. Introduction

Ferrous alloy die-casting has been researched in the U.S. and Japan⁽¹⁾, but there were issues with composition variance and handling of the high temperature molten iron and also with die life, so this particular research did not lead to practical applications. On the other hand, the semi solid casting method (hereafter “thixo casting”) uses semi solid billets with stable compositions, so the heated billets are easy to handle and the casting temperature can be set lower than normal die-casting temperatures, which results in less solidification latent heat. For these reasons, thixo casting is being researched as a method with relatively little thermal shock on the die for the pressurized casting of iron and copper alloys with high melting points, which result in a short die life that makes die-casting uneconomical. In addition, compared to conventional iron part casting methods, the thixo casting method also allows casting of thin and complex shapes similar to aluminum die-casting, making it suitable for parts requiring the strength of iron and the high degree of shape freedom (characteristic of aluminum die-casting). This research established Fe-thixo casting technology based on thixo casting method knowledge

obtained with aluminum⁽²⁾, and evaluated the manufactured parts.

The research was conducted in four areas: material composition, casting methods, raw material manufacturing methods, and applied parts.

2. Fe-thixo Casting Principle and Casting Method

2.1. Casting Principle

The Fe-thixo casting method heats an iron alloy to the semi solid state, and then performs pressurized casting into a die. Thixo casting combines the solid and liquid phases, so the following points are required to improve the material characteristics of the product.

- Laminar flow filling having liquid characteristics in the semi solid state and with few defects must be established.
- The composition must have a eutectic quantity (quantity of eutectic components present during final solidification) that provides superior molten iron feed characteristics during solidification.⁽²⁾⁽³⁾

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Fig. 1 shows a two-element status diagram for Fe-carbon (Fe-C). Semi solid regions exist around 1,500 °C (δ + Liquid) at carbon = approximately 0.2%, and around 1,200 °C (γ + Liquid) at carbon = approximately 2.0%.

The semi solid temperature range is wide and even heating of the billet is easy, so the thermal shock on the casting equipment and the die can be reduced. Therefore, the composition was evaluated by selecting the γ + L semi solid region, measuring the viscosity in the high temperature semi solid state, and measuring the solidification latent heat by the cooling method. The results indicated the following, and established that semi solid casting can be performed for Fe-carbon (Fe-C) in the same manner as Al-thixo casting.

- The solid phase forms globules in the semi solid state as shown in Fig. 2 and Fig. 3, so the relationship between the shear velocity and viscosity has linear characteristics. This allows handling as a liquid in the same manner as an Al-Si semi solid composition even in the Fe-C semi solid region.

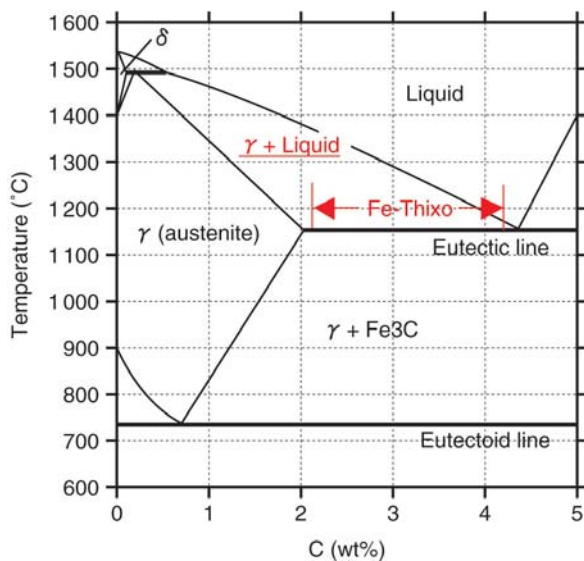


Fig. 1 Fe-Carbon

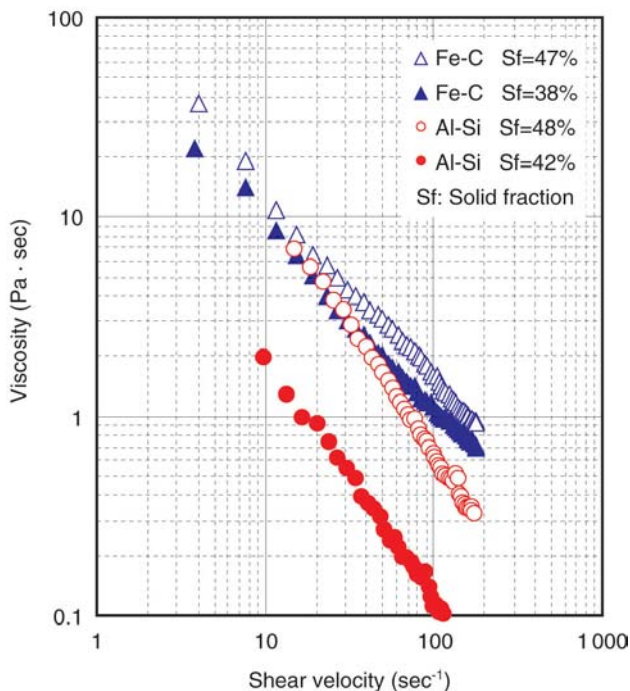


Fig. 2 Relationship between velocity and viscosity

- As shown in Fig. 4, the latent heat distribution has two steps in the same manner as Al-Si, and eutectic components are present during final solidification.

2.2. Casting Overview

Fig. 5 shows an overview of casting with the test apparatus. Fe-thixo casting was possible by following the procedure and using the facilities described below.

- a) When Fe-C materials are heated, the graphite in the structure forms a solid solution and the volume shrinks, causing deformation and making it difficult for the billet to stand on its own. Therefore, the billet is inserted into a SUS pallet and heated horizontally.
- b) The billet is heated inside an induction heating coil to a temperature of 1,180 to 1,220 °C.
- c) The pallet is transported using a fork and inserted to the injection port. An oxide film forms on the surface of the heated iron billet, so handling is easy.
- d) Casting is performed using a 200-ton horizontal injection die-cast machine for aluminum die-casting. Fe-thixo casting assumes heat treatment, so laminar flow filling is basically used to prevent blistering during heat treatment due to the inclusion of air. The injection system was improved to allow low-speed injection for laminar flow filling.
- e) Gates and distributors are established on the die to eliminate the oxide film that forms on the billet surface, and the product is removed from the die with a curing time of 5 s or less to prevent product cracking inside the die.

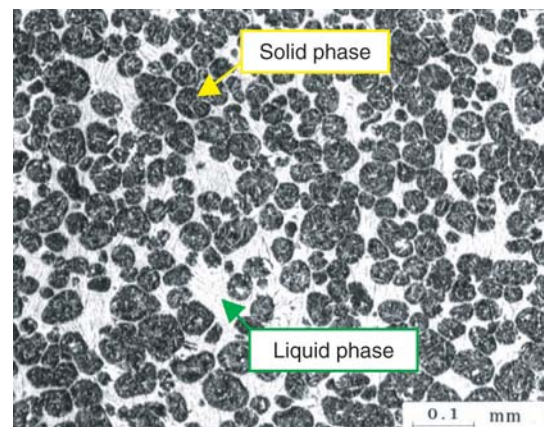


Fig. 3 Microstructure of Fe-thixo casting (etching)

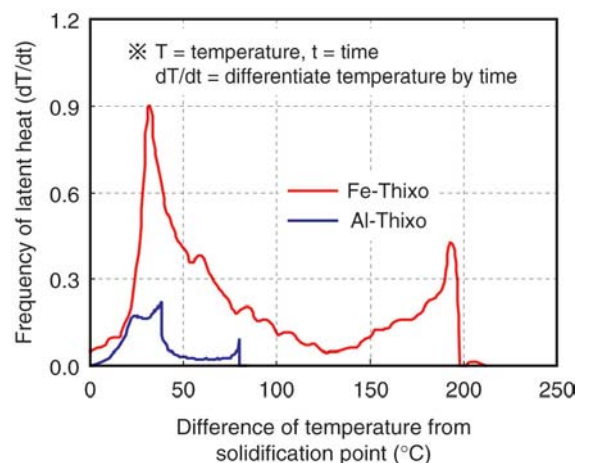


Fig. 4 Latent heat distribution

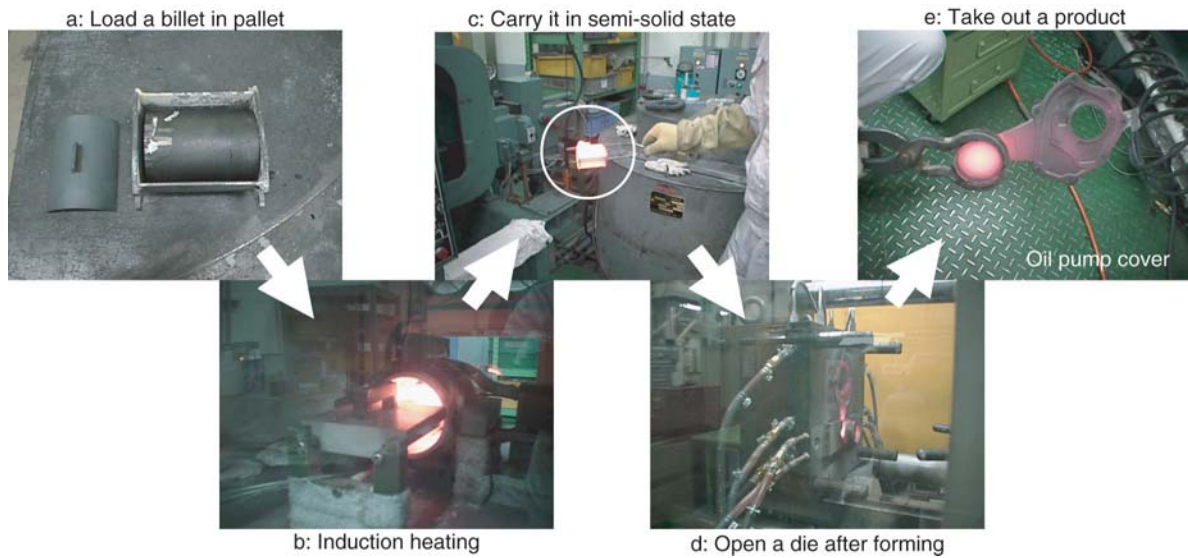


Fig. 5 Fe-thixo casting

3. Material Characteristics

3.1. Setting the Components

As mentioned above, the Fe-thixo casting method feeds molten iron during solidification by selecting a composition that has eutectic components present during final solidification, and this is effective for filling in the solidification shrinkage portions. The optimal eutectic component quantity (hereafter “eutectic quantity”) during final solidification for Fe-thixo casting was obtained, and the composition was set.

3.1.1. Setting the carbon and silicon quantities

The tension compression fatigue strength is sensitive to defects, and was evaluated to set the eutectic quantity. Bar-shaped test pieces with the eutectic quantity adjusted to 10 to 45% were cast, heat treated and cut to the test piece shape, then the tension compression fatigue strength (breakage probability 10% value at 10^7 times) was measured. Fig. 6 shows these measurement results plotted by fatigue/tensile-strength rate (value obtained by dividing the tension compression fatigue strength by the tensile strength). The results are divided into two areas with a boundary at a eutectic level of 30%, and the region with an eutectic quantity of 30% or more shows a fatigue/tensile-strength rate (0.45 to 0.60) equal to that of steel without internal defects. This indicates that molten iron feed during solidification is ensured by setting a eutectic quantity of 30% or more.

On the other hand, when the eutectic quantity increases, the heated material is in a near-liquid state, so the thixo casting merit of easy handling during heating and transport is lost. Also, when the eutectic quantity exceeds 50%, the amount of solidification shrinkage during final solidification increases, and surface splitting and cracking were observed. Therefore, the optimum eutectic quantity for Fe-thixo casting is from 30% to less than 50%.

Fig. 7 shows that the eutectic quantity varies according to the carbon and silicon quantities. First the eutectic quantity was set to 30% to 50% as noted above, then the carbon and silicon quantities were set with targets of a Young's modulus of 180 GPa which exceeds globular graphite cast iron that is competitive as an iron-based material, and an impact strength of 10 J/cm² (Charpy U notch, JIS3 test piece) which is equal or greater than FCD450 required of parts.

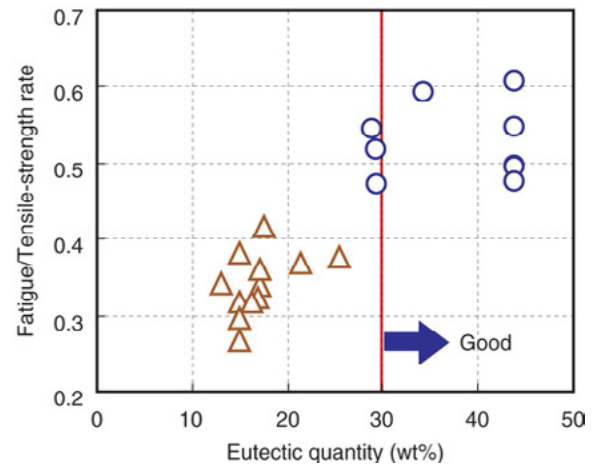


Fig. 6 Relationship between eutectic and fatigue/tensile-strength rate

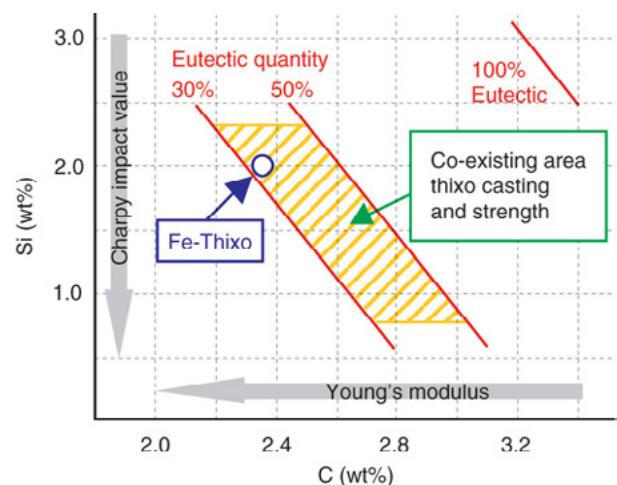


Fig. 7 Relationship between C-Si and eutectic quantity

When setting the carbon quantity, the composition of this casting method is such that a drop in the Young's modulus due to graphite precipitation after heat treatment of the cast product is unavoidable. Furthermore, the Young's modulus of Fe-thixo materials drops as the precipitated graphite area increases. Therefore, the added carbon quantity must be as low as possible.

In addition, increasing the added silicon amount generally produces hard and brittle silico-ferrite, and produces drops in both stretch and impact strength. The Charpy impact values of prototype materials having the silicon quantity adjusted between 1.5 to 6.5% were evaluated, and the results showed that the impact strength dropped markedly at an added silicon quantity of 3.0% or more.

Based on the above relationship between eutectic quantity and the carbon and silicon quantities, the applicable Fe-thixo casting range is the shaded region shown in Fig. 7. Taking into account component tolerance ranges when manufacturing raw material billets, the basic composition was set at carbon = 2.35% and silicon = 2.0%.

3.1.2. Setting the chromium and nickel quantities

Table 1 shows the final composition with chromium and nickel added to prevent the surface cracking that occurs when casting thin parts with complex shapes. Chromium strengthens the chilled structure during casting, and nickel prevents surface cracking by transforming the solid phase into a tenacious γ structure. These added chromium and nickel quantities are also adjusted according to the mechanical characteristics required of the cast product. Chromium is not added and only nickel is added when emphasizing impact strength, and both chromium and nickel are added when emphasizing tensile strength.

Table 1 Chemical compositions of Fe-thixo casting (wt%)

C	Si	Mn	P	S	Ni	Cr
2.30/2.40	1.95/2.05	0.60/0.70	<0.035	<0.04	0.50/1.00	0.00/0.50

3.2. Heat Treatment and Mechanical Characteristics

With the Fe-thixo casting method, rapid cooling in the die causes the liquid phase portions to form a hard and brittle chilled structure with the carbon in solid solution, so annealing heat treatment is essential for ensuring the required impact strength. This research aimed to obtain a wide range of material characteristics by setting the optimum heat treatment conditions.

That is to say, i) the tensile strength σ_B = 400 to 600 MPa range as a replacement for globular graphite cast iron, ii) the σ_B = 600 to 800 MPa range as a replacement for unrefined steel, and iii) the σ_B = 600 to 1,000 MPa range as a replacement for high strength parts.

Table 2 shows the set heat treatment conditions, and Fig. 8a shows the tensile strength for each heat treatment performed on cast rod-shaped test pieces. (i) and (ii) can be separated by adjusting the cooling speed after annealing. (i) used furnace cooling with a cooling speed of 0.05 to 0.10 °C/s, and achieved a tensile strength of 500 to 700 MPa. (ii) used air cooling with a cooling speed of approximately 2 °C/s and two-step annealing, and achieved the target tensile strength of 600 to 900 MPa. In addition, (iii) performed heat refining as a high strength material, and a tensile strength of σ_B = 800 to 1,300 MPa was obtained by heat refining to increase the strength and impact strength, or by austemper

heat treatment to induce isothermal transformation at a temperature of 300 to 450 °C immediately after annealing. The results showed that Fe-thixo materials can be applied to a wide strength range. A Young's modulus of 180 GPa or more was also achieved as shown in Fig. 8-d.

Fatigue strength tests and Charpy impact tests were also conducted. As shown in the Fig. 8-b graph, the wide fatigue strength range of σ_B = 200 to 500 MPa was obtained. In addition, the Charpy impact values in Fig. 8-c show that the furnace cooled materials achieved Charpy impact values of 10 J/cm² or more, which is equivalent to FCD450.

Malleable iron must generally be cured at around 900 °C for 5 to 15 hours to anneal the chilled structure.⁽⁴⁾ In comparison, Fe-thixo can break down the chill with a curing time of 1 hour or less. The reason that chill breakdown is possible in a short time is thought to be that the graphite precipitation sites increase due to the following mechanisms, thus shortening the carbon diffusion distance.

- During heat casting, the solid phase portions transform into a martensite (M) + austenite (γ) structure with the carbon in a supersaturated solid solution. This increases the graphite precipitation sites during annealing, which shortens the diffusion distance and thus shortens the precipitation time.

Table 2 Heat treatment

Tensile strength	Heat-treatment (Hardness HB)
500 ~ 700MPa	i : Furnace cooling (HB 150-200) 950°C × 60min. Cooling rate = 0.05 ~ 0.10°C/sec.
600 ~ 900MPa	ii : Annealing/Annealing (two steps) (HB 200-350) 1000°C × 60min. Air cooling T °C × t min. Air cooling Cooling rate = 2.0°C/sec.
800~ 1300MPa	iii : Heat refining/Austemper (HB 250-350) 1000°C × 60min. Oil quench T °C × t min. T °C × 60min. Air cooling

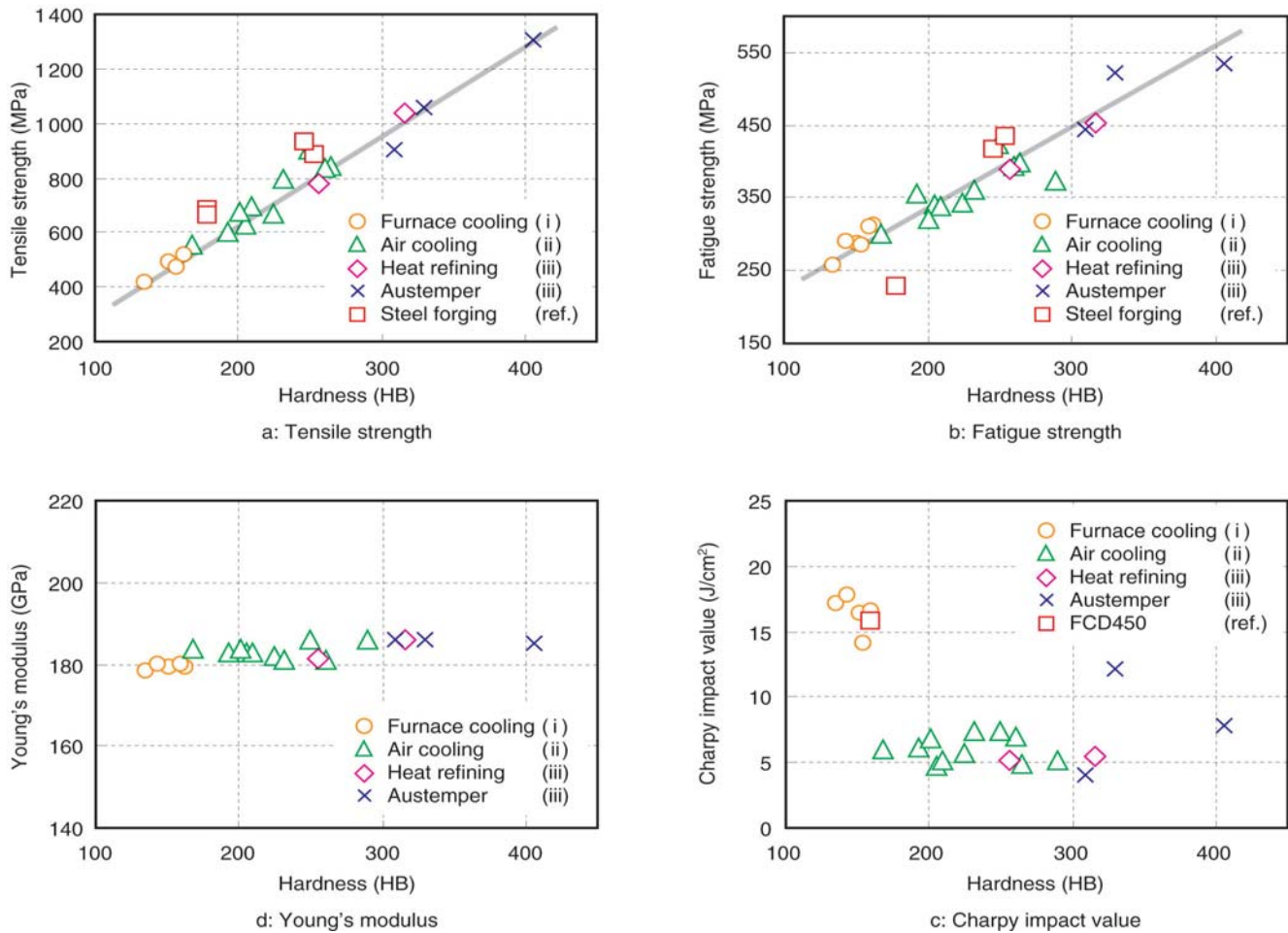


Fig. 8 Mechanical properties vs heat treatment

- The chilled portions that were liquid phase have wide boundaries with the solid phase, so strain is produced by the differences in thermal expansion between the solid and chilled portions during heat treatment, and these portions contribute as sites where the graphite can precipitate in an energetic and stable manner.

Horie et al. reported that the annealing time can also be shortened using atomized cast iron powder with surfaces having short diffusion distances that allow energetic and stable precipitation.⁽⁵⁾ However, the same principle is thought to be operating in this case as well.

4. Casting Methods

4.1. Formation of Solid Phase Globules by Heating

For the material to have fluid characteristics in the semi solid state, the solid phase must form globules. In aluminum semi solid casting, the dendrites in the material billet structure are severed during the material manufacturing process and form globules. This research established a method for dividing a normal dendrite structure material billet such as shown in Fig. 9-a into globules by controlling the heating rate.

Figs. 9-b and 9-c show the structures obtained by heating the billet to 1,200 °C at different heating rates in the temperature range of the austenite transformation point or higher, and then water cooling the billet. When the billet is

heated at high speed (80 °C/min), the dendrites are severed and the structure is suitable for thixo casting. However, when the heating rate is slower (44 °C/min), the solid phase portions join and form larger, coarser structures. Fe-C material dendrites are thought to form globules because the carbon solid solution is wide at 2.1%, so differences in the carbon concentration occur within the dendrites during rapid heating. The high concentration portions are thought to transform into the liquid phase, and the low concentration portions remain in the solid phase, causing the dendrites to divide. Further, as shown in Fig. 10 it was also determined that the heating rate at which division is possible depends on the dendrite arm spacing (DAS II, see Fig. 9-a). When the DAS II is small, the carbon diffusion distance becomes shorter, so division is possible even at a slower heating rate.

4.2. Die Materials

In Fe-thixo casting, 1,200 °C semi solid molten iron flows into the die, so the die is subject to thermal shock. However, copper materials were used for the die as a countermeasure to suppress the die temperature rise and thermal stress. The thermal stress produced by die thermal shock under two-dimensional constraint conditions is expressed by equation (1) below.⁽⁶⁾

$$\sigma = \frac{\alpha E (T_m - T_d)}{l - \gamma} \quad (1)$$

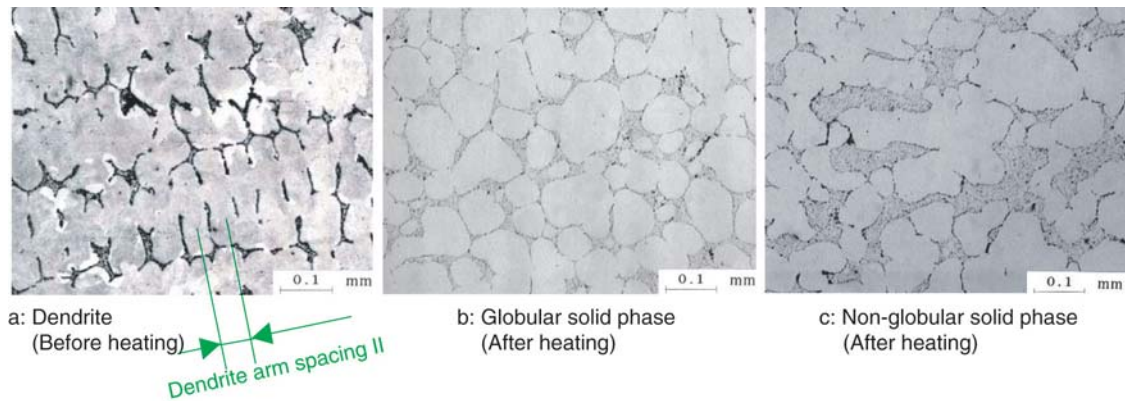


Fig. 9 Microstructure of Fe-thixo casting

Here, σ is the thermal stress, α is the thermal expansion rate, E is the Young's modulus, T_m is the maximum measured temperature value, T_d is the die preheating temperature, and ν is the Poisson's ratio of the die materials. If the thermal stress when the molten iron flows into the die exceeds the compressive yield stress of the die materials, tensile stress remains in the die when the temperature drops after the product is removed, and this stress accumulates and leads to cracking. Therefore, in contrast to the ferrite dies used for aluminum die-casting, copper (NGK INSULATORS, LTD. MC-9) dies were used for Fe-thixo casting. Copper materials have a high density and thermal conductivity, so the temperature rise during molten iron inflow is small and little thermal stress is produced. Fig. 11 shows the compressive thermal stress produced by thermal shock in each part as calculated from measurements made using thermocouples located at a depth of 1 mm from the surface that contacts the molten iron. The only portions exceeding the compressive yield stress of the copper mold were the gates for removing the oxide film. The stress produced on the runner and the product portion was below the compressive yield stress of the copper mold. This indicated that copper dies can be used for the runner and the product portion by making the gates periodic replacement parts. Test pieces were cast using a copper die for 1,200 shots, and there was no heat cracking.

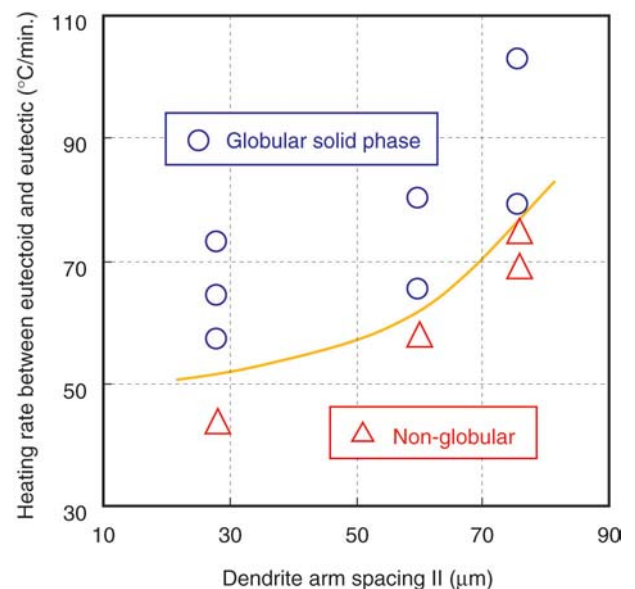


Fig. 10 Relationship between dendrite arm spacing II and heating rate

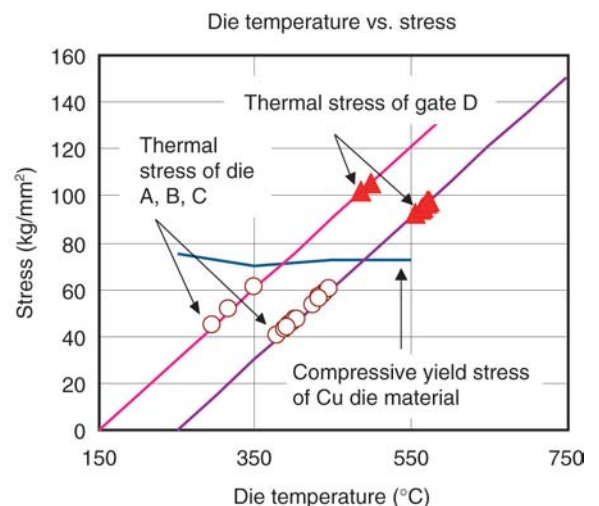
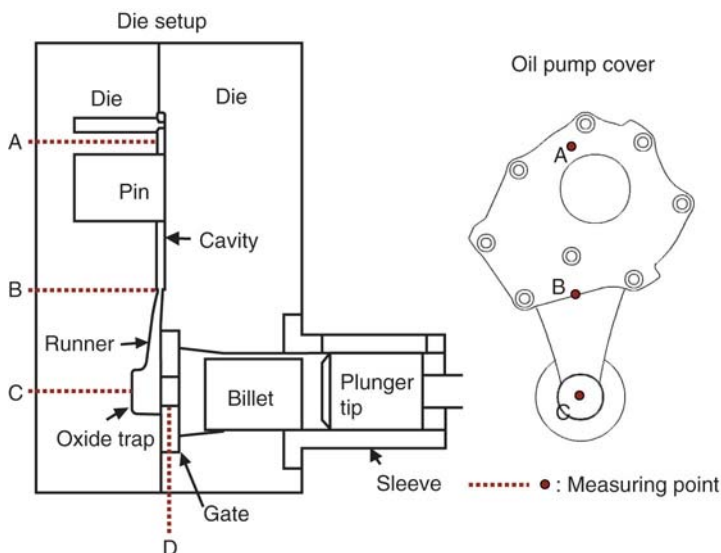


Fig. 11 Measuring points of die temperature and calculated thermal stress

4.3. Casting Size and Flow Length

The Pokorny equations for the product flow length (2) and the maximum filling time (3) in the die-casting method are expressed by the following equations.⁽⁷⁾

$$\text{Flow length } L = \text{Flow velocity } V \times \text{Maximum filling time } T_f \quad (2)$$

$$T_f = \frac{0.5px^2\{qa+c(tm-ts)\}}{k\{tm-(td \times 1.15)\}} \quad (3)$$

K: thermal conductivity of the molten iron,
 qa: molten iron latent heat,
 c: specific heat,
 p: molten iron density,
 tm: molten iron temperature,
 ts: solid phase line temperature,
 td: die temperature,
 x: thickness $\times 1/2$

Compared to aluminum die-casting, Fe-thixo casting has a greater temperature difference between the molten iron temperature and the die temperature, so there were concerns that the maximum filling time would become shorter. However, as shown in Table 3 the molten iron has a high density and low thermal conductivity, so a filling time equal or greater than that for aluminum die-casting was obtained.

Table 3 Calculated maximum filling time

		Fe-thixo	ADC12
K	cal/s · cm · °C	0.099	0.23
qa	cal/g	55	94
c	cal/g · °C	0.166	0.26
p	g/cm ³	7.1	2.4
tm	°C	1200	650
ts	°C	1150	520
td	°C	200	200
x	cm	0.3	0.3
Filling time	sec	0.21	0.14

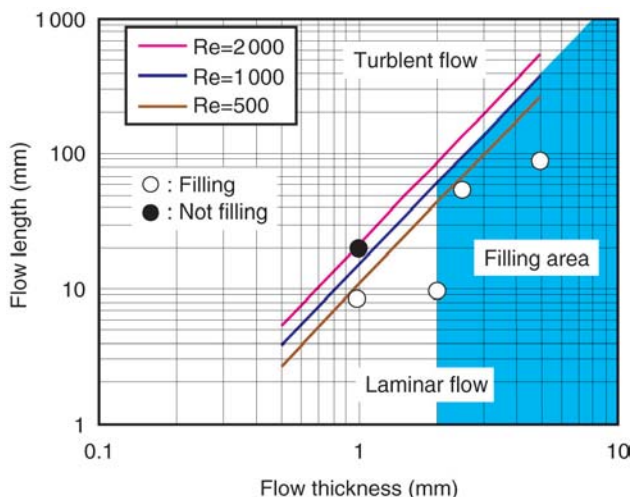


Fig. 12 Filling area of Fe-thixo

Controlling the filling rate to achieve laminar flow filling is essential to prevent the inclusion of air during Fe-thixo casting. The flow rate upper limit is determined for thixo casting which assumes laminar flow filling, so there is a theoretical correlation between the product thickness and the flow length. Therefore, the area below the Reynold's number lines shown in Fig. 12 is presumed to be the range over which sound products can be cast. Filling was verified by casting thin plate step-shaped test pieces, and the results were plotted in Fig. 12. These results confirmed that while 5.0 mm and 2.5 mm thick parts were filled, the flow length for 1 mm thick parts was approximately 10 mm.

5. Continuous Casting of Raw Materials

Low-cost mass production of uniformly shaped materials with stable composition and internal quality is required for the billets used in Fe-thixo casting. Developed materials having a semi solid range at 200 °C were unstable and broke easily inside the mold in places where solidification cores occurred. Thus, manufacturing is not possible with current continuous casting technology, which selects compositions with a narrow semi solid range. Therefore, it was necessary to establish new continuous casting technology. This research optimized the mold materials, drawing conditions, and molten iron temperature control to allow horizontal continuous casting of developed materials using a structure such as that shown in Fig. 13.

Issues for continuous casting raw materials (hereafter "continuous casting materials") are thought to be the black skin on the surface and solidification shrinkage defects in the core areas. However, these issues were resolved by casting rod-shaped test pieces and evaluating the fatigue strength which is susceptible to defects. A black skin approximately 0.5 mm thick is present on the surface (Fig. 14), and when this film mixes to the inside of the product, it can act as a defect and lower the fatigue strength. However, the fatigue strength of test pieces cast using continuous casting materials with this black film was evaluated, and it was confirmed that the black skin had no effect on the fatigue strength.

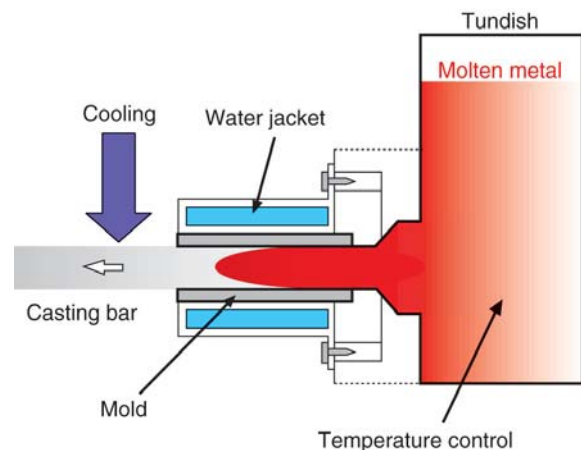


Fig. 13 Horizontal continuous casting

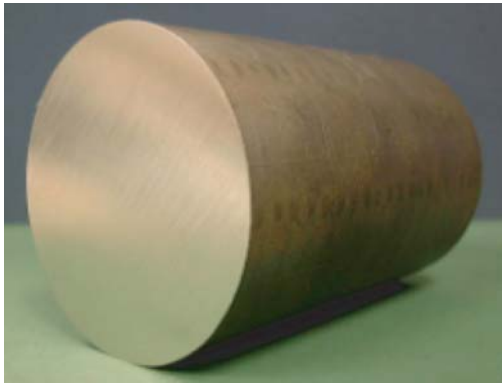


Fig. 14 Continuous casting bar

In addition, the effect of internal defects was evaluated using a billet having a cavity with a diameter of approximately 5 mm intentionally created in the center. This defect was crushed during the heating and casting process so that the defect did not remain in the cast product, and there was found to be no effect on the fatigue strength.

6. An Example of an Automotive Parts Study

A prototype engine oil pump cover directly driven by the crankshaft was manufactured using the Fe-thixo casting method. Fig. 15 shows the cast product, and Fig. 16 shows the pump structure. This part is currently manufactured by conventional aluminum die-casting, but Fe-thixo casting increases the stiffness and makes it possible to reduce the clearance with the iron rotor while heated, thus improving the pump volume efficiency. In addition, if the cover stiffness can be maintained at the same level as the aluminum die-cast part, the cover thickness can be reduced and the pump rotor thickness can be increased by the same amount, making it possible to increase the pump capacity without changing the crank shaft length. Some other companies manufacture the oil pump cover using the steel plate fine blanking method. However, in this case most surfaces require machining such as the convex portions after press molding the ports or the flat countersunk screw joining surface, and this machining increases the cost. Therefore, this oil pump cover is a part



Fig. 15 As-cast oil pump cover

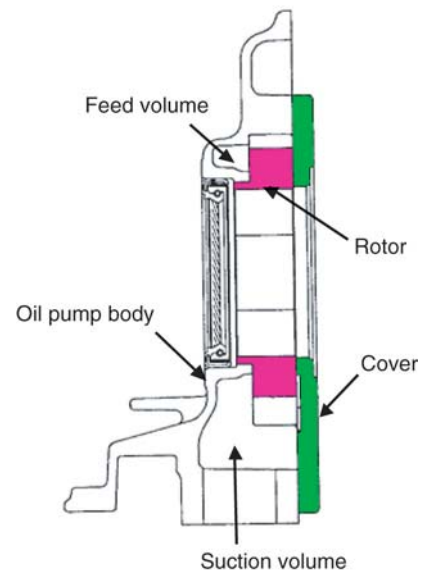


Fig. 16 Structure of engine oil pump directly driven by crank shaft

that can benefit from the material characteristics of steel and the degree of shape freedom of aluminum die-casting which are features of the Fe-thixo casting method.

Improvements in volume efficiency and pump efficiency were confirmed in specific characteristics tests on the oil pump as shown in Fig. 17. In addition, specific durability tests also showed that the flow degradation rate, flat countersunk screw tightening torque degradation, and wear all cleared the standard values, and confirmed sufficient performance as an operational part.

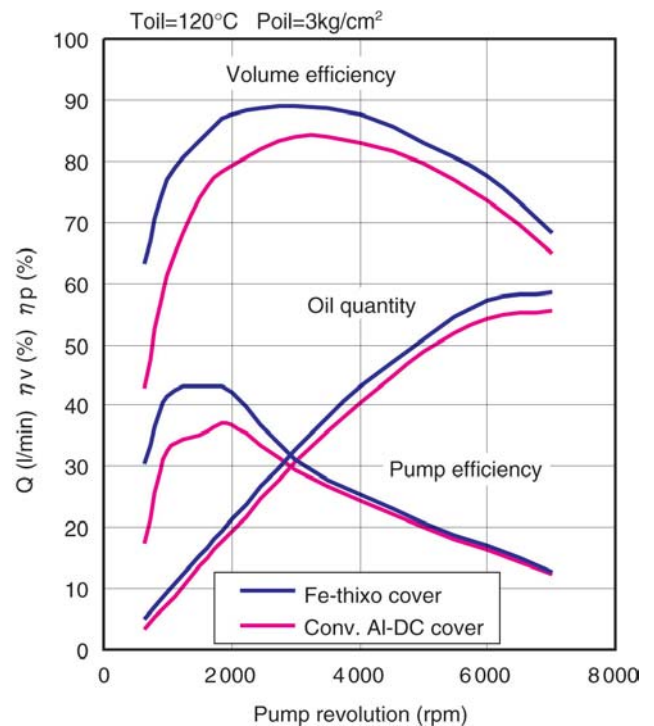


Fig. 17 Difference in oil pump efficiency between Fe-thixo and Al-DC cover

Table 4 Accuracy of Fe-thixo cover (mm)

	Size range	~30 (mm)	50-80(mm)
Fe-thixo cover	Deviation 3σ	0.16	0.31
General tolerance 1st class of JIS	Al die-cast	± 0.25	± 0.35
	Steel forging	± 0.4	± 0.6

Table 4 shows the dimensional accuracy evaluated by the dimension between the pump cover screw holes. The dimensional variance for a deviation of 3σ was within ± 0.25 and ± 0.35 for the dimension setting values of 30 mm or less and 50 to 80 mm, respectively, which satisfies the general tolerance 1st class of JIS for aluminum die-casting. In addition, a surface roughness of 25S or less was confirmed to be possible by performing heat treatment in a nitrogen atmosphere.

7. Conclusion

Fe-thixo casting technology was established which offers excellent casting performance and allows manufacture of parts combining the material characteristics of iron with a degree of shape freedom and dimensional accuracy equivalent to aluminum die-casting. The following knowledge was obtained.

- (1) Fe-thixo casting exhibits excellent casting performance with a composition having a eutectic quantity of 30 to 50%. Materials having a wide strength range from $\sigma_B = 400$ MPa to 1,000 MPa could be obtained by selecting the heat treatment for the cast product.
- (2) Fe-thixo casting allows rapid heating of the billet in the austenite region by using copper die materials and lowering the injection system speed. Also, a maximum filling time equal or greater than that for aluminum was obtained, and casting with a partial thickness of 1 mm was possible.
- (3) A continuous casting method for Fe-thixo compositions was established by optimizing the die materials, drawing conditions and molten iron temperature.
- (4) A prototype oil pump cover was manufactured, and the Fe-thixo casting method was confirmed to have a degree of shape freedom and dimensional accuracy equivalent to aluminum die-casting. Applying Fe-thixo casting to the cover of an engine oil pump directly driven by the crankshaft made it possible to both increase the pump volume efficiency and reduce the size.

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