Visco - Elastic Behavior of Mold Flux for Continuous Casting of Steel

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ABSTRACT

Two kind of experiments were performed to clarify the mechanism of lubrication and friction between the mold and the solidified shell in the continuous casting of steel. The research of transition phenomena of mold flux with viscometer and the hot model friction simulator under the actual casting oscillation have been carried out. As the result, the mold flux behaves as the Maxwell type visco-elastic fluid. The coefficient of elasticity is 5～10Pa at the viscosity of 0.28～0.39Pa·s.

1. INTRODUCTION

In the increase of the demand of high quality products such as sheet for the outer panel of automobile body, the requirements for slab caster may be high speed casting for high productivity, prevention of casting defects and achievement of the direct connection between the continuous casting process and the rolling process. One of the problems for the high speed casting is the sticker breakout which is considered to be caused by the excessive friction force working on the solidified shell[1-3].
Developments of mold flux with higher lubrication[4,5] and investigations of the operational conditions[6] have been reported to prevent the sticker breakout. As the result it has been reported that the use of the mold flux with low viscosity and low melting point and the mold oscillation with extended positive-strip time[7] were effective to maintain the good lubrication.

On the contrary, the subject for the high quality slab is the reduction of the inclusion in surface layer and the surface crack. For example to reduce the mold flux entrainment in casting of low carbon steel and ultra-low carbon steel, mold flux with higher viscosity is preferable[8]. To prevent the surface crack of middle carbon steel, soft cooling by high basicity mold flux with high melting point is favorable[9]. To reduce the inclusions at the surface of the slab, high oscillation frequency minimizing the oscillation mark depth is effective[10]. However, sticker breakout is concerned in the application of these techniques[11]. Therefore in the future developments of the continuous casting technologies, it is vital to meet the requirements mentioned above with maintaining the lubrication by making clear the mechanism of the lubrication and friction between the mold and the slab.
Previously, many studies have been made on the lubrication and friction in the mold[12-14]. However the mechanisms of the lubrication of mold flux and the sticker breakout phenomena have not been clarified enough. Because the analysis of the friction on the solidified shell near the meniscus which is the origin of the sticker breakout may be difficult.

In this study to clarify the mechanism of the lubrication and the friction in the mold, unsteady-state flow analysis and direct measurement of the friction on the slab which is impossible in the actual caster are attempted by a viscometer for mold flux and a hot model simulator under the actual casting condition respectively. Furthermore these results are analyzed from the tribology aspect and viscoelastic behavior is discussed.

2. PREVIOUS WORK AND PROBLEM

In the previous analysis of the friction occurring between the mold and the slab, it is assumed that mold flux is a Newtonian fluid in steady state condition[7]. Figure 1 shows a schematic view of meniscus periphery in the mold. In this figure the slab surface is parallel to the mold wall and mold flux is in the constant gap. According to this model, the friction (shear stress) τ due to mold flux working on the slab can be expressed by equation(1).

$$\tau = \eta \ (\partial u / \partial y)_{y=h} \qquad (1)$$

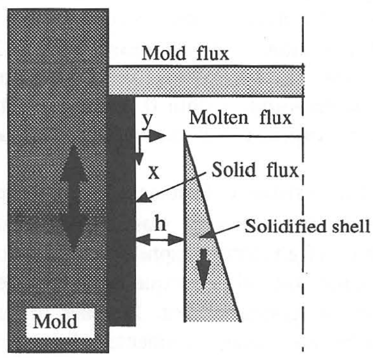

Fig.1 Scematic view of meniscus periphery in mold.

where η is the viscosity of the mold flux and u is the relative velocity of the mold flux with considering the motion of the mold. Equation(1) shows that the friction is determined only by the viscosity of the mold flux and the difference of the speed between the slab and the mold. In general, mold oscillation is a function of time such as sine wave, therefore equation(1) shows a time dependent function. However in the case of high speed reciprocating motion with a period of 0.5sec, it must be confirmed that the viscosity measured in steady state can be applied as a typical value of mold flux.

As an attempt of the direct measurement of the friction in the actual plant, it has been proposed that the friction could be obtained as a difference between the measured force working on the mold and inertia force of the mold[12,13]. However there is a problem in this method indicated as follows. The measured value is the friction exited by the whole area of the mold wall. Therefore the result does not reflect the friction near the meniscus which causes the sticker breakout. Also measured value is the force acting to the mold and is not the force acting to the solidified shell. From the above aspects, in order to evaluate the lubrication in the casting mold, it is significant to measure the friction working on the slab at just below the meniscus in unsteady state condition. However such measurement is impossible in the actual casting mold. Therefore experiments by the simulator must be carried out. In the present work two investigations are performed as follows.

1) The viscosity of the mold flux in unsteady flow is evaluated with using the high temperature viscometer.
2) The friction on the slab is evaluated from the experiment at high oscillation frequency using a hot model simulator (friction simulator).

3. EXPERIMENTAL APPARATUS AND PROCEDURES

3.1 Experiment of unsteady flow of melted flux

Figure 2 shows a schematic sketch of the apparatus of the viscosity measurement. In order to investigate the step response in short period, higher sensitivity must be needed in the measuring system. In commercial viscometers time lag ranging from 1 to 2 seconds occurs as a whole system (including torque meters, output voltage converters and pen recorders). Therefore a new more sensitive torque meter was used and output data was recorded in a 32-bit personal computer via an A/D converter to measure the rapid variation of the torque within 0.2 seconds. This measuring system was responsive to the variation of the torque in 2 msec.

An electric resistance furnace was used as an external heater and measurement was carried out under Ar atmosphere. High purity graphite was used for the crucible and the immersion rod. A torque meter was set between the motor and the graphite rotor. Number of revolution was measured by an encoder connected directly to the motor. The inner diameter of the crucible was 42 mm and the maximum diameter of the immersion rod was 35 mm. Chemical composition and physical properties of the mold flux used in the measurement are shown in Table 1 and 2 respectively. The viscosity of the mold flux was 0.28Pa·s at 1220℃ and 2.3 Pa·s at 1120℃.

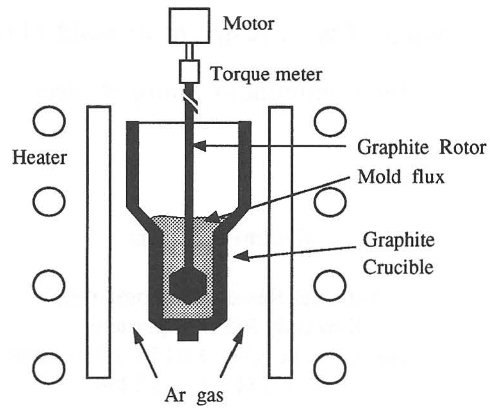

Fig.2 Apparatus for the viscosity measurement of mold flux at unsteady state.

Table 1 Physical properties of mold flux.

softening temperature	1070℃
solidification temperature	1110℃
viscosity	η =0.28 Pa · s at 1220℃ = 2.3 Pa · s at 1120℃

Table 2 Chemical composition of mold flux (mass%)

T.C	SiO2	CaO	Al2O3	Fe2O3	Na2O	F	CaO/SiO2
2.9	34.4	33.0	6.1	0.2	13.4	8.1	0.96

3.2 Friction simulation under the operational condition of the actual caster

Figure 3 shows a schematic view of the new friction simulator. The mold flux is inserted between two disks of 100mm in diameter which are set parallel to each other. The top side disk rotates in unidirection with connected motor and plays the role of the slab. The bottom side disk can oscillate with the sinusoidal reciprocating motion by the motor and the crank mechanism and plays the role of the mold. A torque on each side can be measured separately by setting a torque meter on each side. The disks were made of high purity graphite. The mold flux was melted uniformly by electric resistance furnace under Ar atmosphere. The diameter of the bearing for centering of the top side disk was designed as small as possible (15mm) to minimize the disturbing torque.

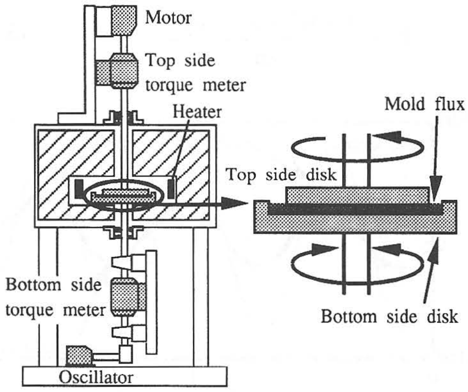

Fig.3 Schematic view of new friction simulator.

The gap between the disks, namely the equivalent value to the thickness of the mold flux film between the mold and the slab was 2mm which is almost the same as the thickness of the flux film in the actual casting. The number of revolution of the top side disk was 10 rpm and the tangential velocity at the middle point of the radius was equal to the casting speed of 1.6m/min. The deflection angle of the oscillation of the bottom side shaft was 6 degree which is equal to the 5.5 mm stroke of the mold oscillation. The mold flux is the same as in previous section, which is the typical mold flux for the casting of low carbon Al killed steel. The experiment was carried out at 1150℃ by considering the accuracy of the measurement. The viscosity of the mold flux is 0.39Pa·s. The friction force of the top side disk, namely the force acting to the solidified shell, was measured and analyzed with changing the frequency of the mold oscillation from 100 to 400 cpm.

4. RESULT AND DISCUSSION

4.1 Unsteady-state flow of the melted flux

A typical time-varying speed of revolution and torque in changing the speed of revolution of the rotor from 0 to 300 rpm rapidly are shown in Figure 4.
Time-varying torque without specimen in the crucible is also shown in the same figure.

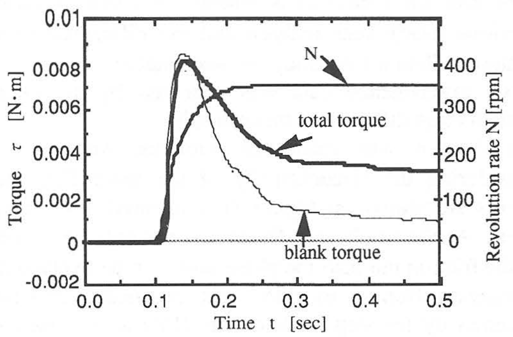

Fig.4 Change in revolution rate of rod, total torque, and blank torque with time.

The torque without specimen is caused by the friction exited by the supported part of the rotor and the inertia force of the rotor. Therefore the net torque due to the mold flux can be obtained as a difference between the total torque with specimen and that without specimen. This net torque is shown in Figure 5 together with the viscous torque due to the mold flux which was calculated from known viscosity and change of the velocity. It can be seen that the response of measured torque is slower than the calculated value.

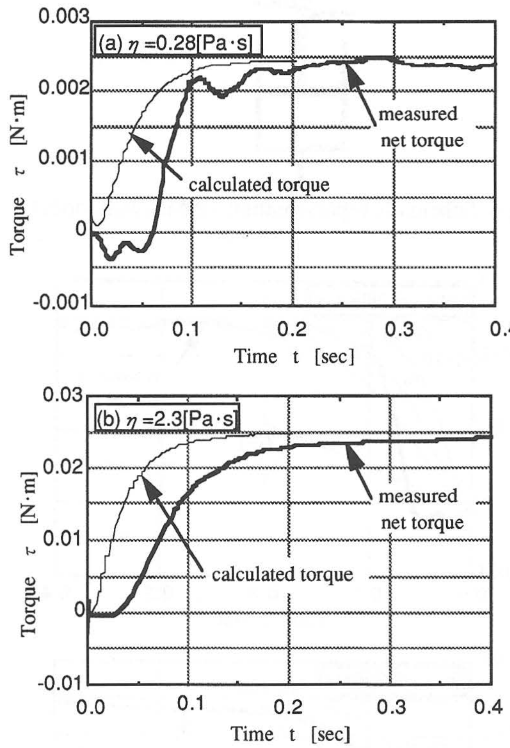

Fig.5 Comparison of measured net torque and calculated torque with unsteady state Newtonian fluid flow analysis.

Generally it is known that the deformation of colloid and high polymer are rheological[15]. The mold flux in which silicate makes the network structure could behave as a viscoelastic fluid.
J. H. Simmons et al.[16] reported that viscoelasticity appeared in soda-lime-silicate glass at 560℃. Maxwell model for the viscoelastic theory was used to analyze the variation of the stress under such a fixed condition of the strain as in the present experiment. Figure 6 shows the schematic sketch of the Maxwell model. Fundamental equation is given in equation(2).

$$\frac{d\zeta}{dt} = \frac{1}{G}\frac{d\tau}{dt} + \frac{\tau}{\eta} \qquad (2)$$

where ζ is the strain and G is the coefficient of elasticity. After evaluating the viscosity η of the flux from τ in steady state, torque as a function of G was calculated numerically by considering the measured variation of the speed of revolution of the rotor in unsteady state. The calculated results are shown in Figure 7. The measured value shows the good agreement with the calculated results which include the effect of the viscoelasticity. It has been shown that the coefficient of elasticity G is 10Pa at the viscosity of 0.28Pa·s and 50Pa at 2.3Pa·s.

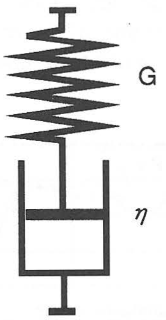

Fig.6 Schematic representation of Maxwell model.

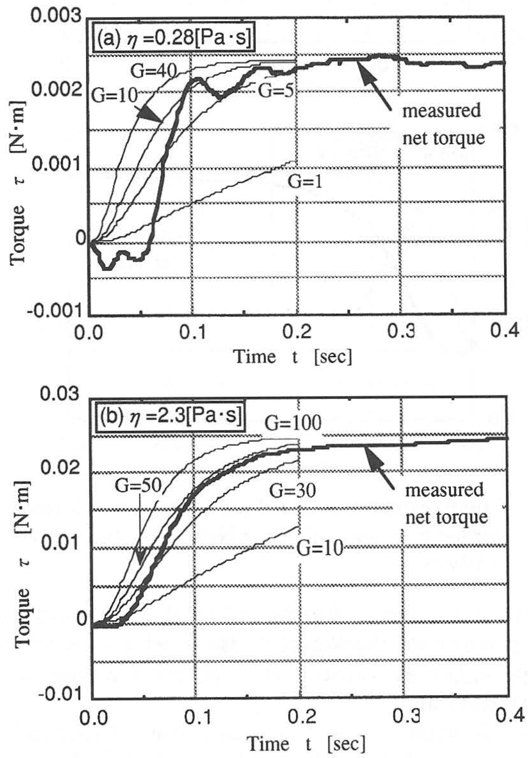

Fig.7 Comparison of measured net torque and calculated torque with visco-elastic flow analysis (G:elastic modulus,Pa).

4.2 The friction of the solidified shell obtained from the hot model simulator

The time-varying friction on the top side disk, namely on the slab, at the oscillation frequency of 100 cpm and 300 cpm is shown in Figure 8 and Figure 9.

According to the theory of Newtonian fluid, the torque working on the shaft can be obtained by integrating the shear stress expressed by the equation(1) to the whole surface of the disk. This torque T is given by equation(3).

$$T = \frac{\pi \eta R^4 (\omega_1 - \omega_2)}{2h} \quad (3)$$

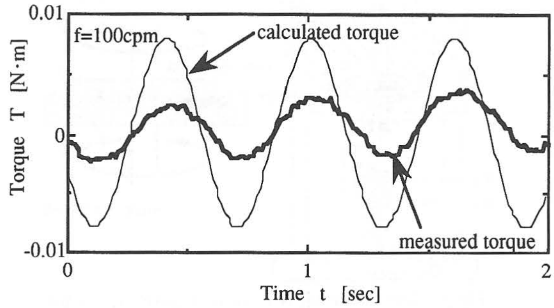

Fig.8 Comparison of measured torque and calculated torque with Newtonian fluid flow analysis at hot oscillation simulator.

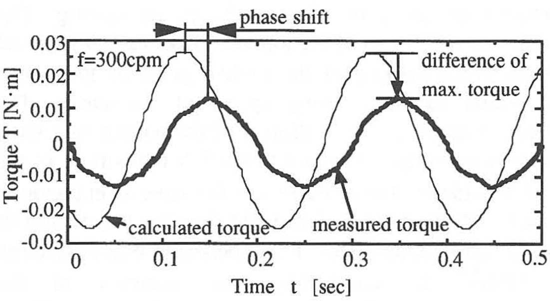

Fig.9 Comparison of measured torque and calculated torque with Newtonian fluid flow at hot oscillation simulator.

where R is the radius of the disk, ω_1 is the angler speed of the top side disk, ω_2 is the angler speed of the bottom side disk and h is the gap between the disks.

The calculated torque T is superimposed on the same figures.

The following significant disagreements can be pointed out.

1)The measured torque is smaller than that calculated from the theory of Newtonian fluid in both cases of 100 cpm and 300 cpm.

2)There is a phase shift between the measured torque and that calculated from the theory of Newtonian fluid. This trend becomes remarkable in the case of 300 cpm.

These facts show that the friction working on the solidified shell near the meniscus is smaller than that predicted by previous steady-state analysis and this difference increases as the oscillation frequency becomes higher.

Next, experimental data was analyzed by the model to explain these differences theoretically.

The friction was calculated with the Maxwell model considering the viscoelasticity of the mold flux and the results are shown in Figure 10 compared with measured value. As the result, it is found that not only the difference of the friction but also the phase shift can be explained with G ranging from 5 to 10Pa. The coefficient of elasticity obtained by the step method was 10Pa at the viscosity of 0.28Pa·s and that by the rotational oscillation method was from 5 to 10 Pa at 0.39Pa·s. It is notable that results show a good agreement with each other regardless of the difference of the facility and the method .

From above results, it is found that the mold flux shows the viscoelastic character which is specified by viscosity η and elasticity G.

The reduction of not only viscosity η but also elasticity G can be effective to decrease the friction force acting to the solidified shell. Since reducing the viscosity of the mold flux may results in the trouble such as the flux entrainment[17], the study on the practical application of the idea mentioned above is anticipated.

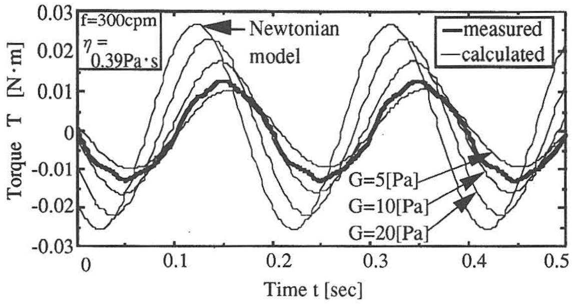

Fig.10 Comparison of measured torque and calculated torque with visco-elastic flow analysis of hot oscillation simulator (G:elastic modulus, Pa)

5. CONCLUSIONS

Unsteady-state friction analysis was performed to clarify the mechanism of lubrication and friction in the continuous casting mold with using the viscometer of mold flux . Furthermore considering the unsteady-state flow of the mold flux due to the mold oscillation, the hot model experiment with the friction simulator was carried out for the purpose of direct measurement of the friction working on the solidified shell. The following conclusions were obtained.

1) The mold flux behaves as the Maxwell type viscoelastic fluid. The coefficient of elasticity is 10 Pa at the viscosity of 0.28Pa·s and 50 Pa at 2.3Pa·s.
2) From the experiment with actual casting condition, the friction force working on the solidified shell is smaller than the calculated value based on the mold flux as a Newtonian fluid. This difference becomes remarkable as the frequency of oscillation becomes higher.
3) At the frequency of 300cpm, there is a phase shift between the measured torque and that calculated from the theory of Newtonian fluid. This phase shift can be explained quantitatively by the elasticity of the mold flux.

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