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Semi-Solid Processing of Aluminum Alloys

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This article describes the state-of-the-art in developing commercial induction heating systems for semi-solid metal forming. Some subtle aspects of induction slug heating, including end and edge effects will be discussed. Understanding the nature of these effects (such as non-uniform temperature distribution, "slug tilting" and "elephant foot" phenomena) is imperative for induction heating practitioners and engineers in order to produce quality semi-solid formed products.

Semi-solid metal (SSM) casting, originally developed at MIT in the 1970's, is now being practiced commercially on the three continents of North America, Europe and Asia. SSM casting has several advantages compared to casting in the fully liquid stage. This includes a lower level of product porosity and higher flow viscosity during casting.[1,7] The latter provides laminar flow during casting. This results in higher quality of cast products by prevention of entrapment of gas. The semi-solid metal casting process consists of casting metal alloys when they are partially liquid and partially solid (Fig. 1). Several metal alloys have been used for SSM casting, including copper, magnesium, nickel, and ductile iron. However, most of the commercial success in SSM forming has been with aluminum alloys. In aluminum alloys, a typical liquid fraction of about 0.5 is optimum.

Fig. 1 *Sliced aluminum slug in the semi-solid stage.*

During the SSM casting process, it is very important to obtain a uniform temperature. The temperature distribution affects the uniformity of liquid fraction throughout the slug. The need for a uniform liquid fraction distribution is demonstrated by the rheology curve shown in Fig. 2.[1] At a liquid fraction of about 0.5, the rheology of the semi-solid alloy changes rapidly with only a small change in liquid fraction. Thus, if the semi-solid slug has a top-to-bottom or surface-to-core variation in the liquid fraction, this will have a negative impact on the casting behavior, and thus, the quality of the castings produced.

Consequently, a heating method that can provide a suitable temperature profile throughout the slug must be chosen. Other parameters that must be considered include heating time, the level of control, the floor space occupied and total cost.

Induction heating has been identified as the process that best meets these criteria and is used by many commercial SSM casters. IHS built the first induction heater for semi-solid metal forming in the early 1980's. Later, IHS combined its efforts with Inductoheat, Inc. and Buhler to make further improvements on induction systems for SSM forming. Since that time, more than 20 different commercial induction heating machines for semi-solid metal forming have been sold world-wide.

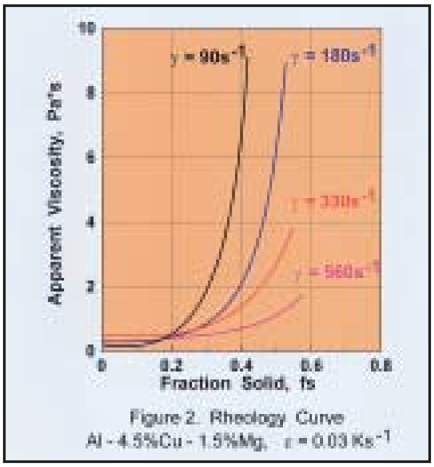

Fig. 2 *Rheology curve for Al-4.5%Cu-1.5%Mg.*

There are two different types of induction coil arrangements used to prepare semi-solid slugs for SSM processing: vertical and horizontal. In a vertical coil arrangement (Fig. 3), slugs are placed on ceramic pedestals and heated to the semi-solid casting temperature. Once semi-solid, the slugs are then transferred to the shot sleeve of a real-time controlled horizontal die casting machine and are cast in re-usable steel dies.

Nature of End Effects

In order to provide a successful design for modern induction heating systems, it is necessary to have a full understanding of the features of the process. The basic idea of induction heating is quite simple. Magnetic field of the coil induces eddy currents in a

Fig. 3 *Compact induction heating machine for semi-solid forming.*

slug located within the induction coil. These eddy currents produce heat by the Joule effect (I^2R).

Induced eddy currents are not uniformly distributed within the slug. The maximum value of the current density is located on the surface. Current density then decreases from the surface of the slug towards its center. This phenomenon of non-uniform current distribution within the slug cross-section is called the *skin effect*. Because of the skin effect, 86% of the power will be concentrated in a slug surface layer. This layer is called the *reference (or current penetration) depth,* δ, and is a function of frequency and electrical resistivity. During the heating cycle of an aluminum slug, the resistivity of the aluminum will increase more than three times. This results in growth of the penetration depth during the heating cycle.

Non-uniformity of the heating profile at the coil and slug ends is related to the distortion of the electromagnetic field in those areas.[4-7] This distortion is called the *electromagnetic end effect.* Generally speaking, end effect is considered one of the most complicated problems in induction heating. This effect can result in either overheating or underheating of the slug ends. The required temperature distribution along the end of the slug depends on the frequency, the coil and slug geometry (including the slug-to-coil air gap and coil overhang), the material properties of the slug, the refractory, power density and cycle time.

Electromagnetic end effects may be illustrated by the curves in the lower diagram of Fig. 4[4,5,7] and are basically defined by three variables: R_{slug}/δ, σ/R_{slug}, and R_{coil}/R_{slug}, where σ is the coil overhang, R_{slug} is the radius of the slug, and R_{coil} is the inside radius of the coil.

There are two extreme cases of electromagnetic end effect. First, consider what happens with power density distribution in the area located at the left end of slug in Fig. 4 (Zone "a"). An inappropriate combination of the above mentioned factors can lead to underheating or overheating of the slug end. The electromagnetic end effect area extends toward the central region of the slug, no further than 1.5 times the slug diameter. When induction heating aluminum alloys, the end effect area does not, typically, exceed 0.2 to 0.5 of its diameter. Higher frequency and large coil overhang lead to a power surplus in the left end area of the slug. As a result, significant overheating may take place in that area. A low frequency and small coil overhang will cause a power deficit at the left end of slug, causing the end to be underheated in comparison to its central area.

In addition, a uniform power distribution along the end of the slug will not correspond to uniform temperature profile. This is due to additional heat losses (radiation and convection losses) at the slug end area compared to its central part. By properly choosing the design parameters, it is possible to obtain a situation where the additional heat losses at the left end of the slug are compensated for by the additional power (power surplus) due to the electromagnetic end effect. This allows one to obtain a reasonably uniform temperature distribution along the length or height of the slug.

In order to make a complete introduction to the electromagnetic end effect, let's evaluate an opposite case, i.e., the magnetic field distribution in the slug near the right end of the coil in Fig. 4 (Zone "b"). The magnetic field here primarily depends on the radii ratio (R_{coil}/R_{slug}) and the skin effect (R_{slug}/δ), with the later being most prominent. Due to the physics of the electromagnetic end effect in the right end of the slug, there is always a power deficit under the tail end of the coil at

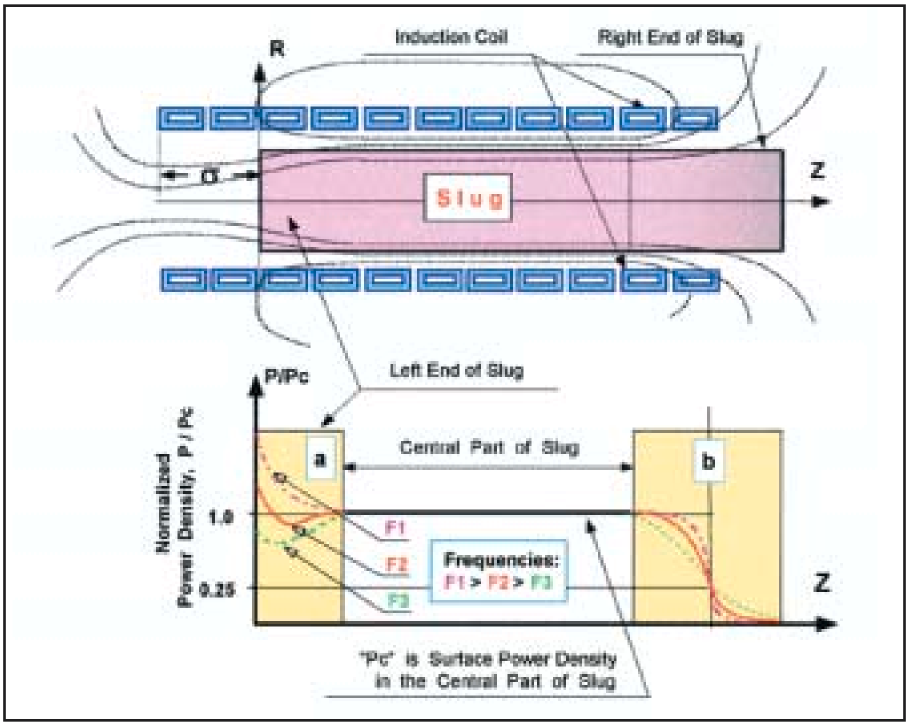

Fig. 4 *Schematic of induction heater and power distribution along the slug length.*

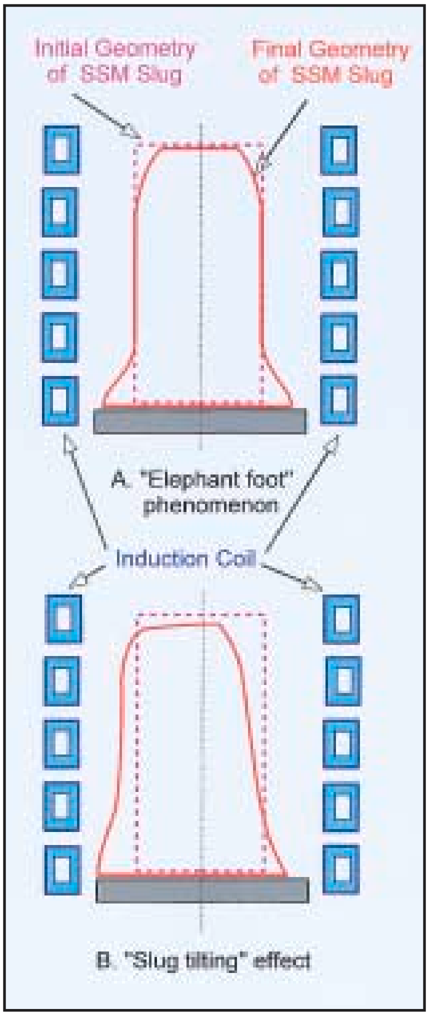

Fig. 5 *(a) "Elephant foot"phenomenon and (b) "slug tilting" effect.*

any frequency. It is possible to show that in the case of a long multi-turn coil with a long homogeneous slug (Zone "b"), the density of the induced eddy current in the slug area under the coil tail end is only half that in the central part. Therefore, the power density in that area is only one-fourth of the power in its central part. Typically, the length of Zone "b" is equal of 0.5 to 3.5 times the coil radius.

The choice of frequency is defined not only by the required temperature profile in the slug, but also by the requirement for providing high electrical efficiency in the induction system and minimum electromagnetic (EM) forces. During induction heating, aluminum slugs experience EM forces which are directed out of the coil. Under normal process conditions, slugs consist of a significant amount of liquid fraction. Essential EM forces may result in uncontrollable removal of liquid metal from inductor. Therefore, special attention should be paid to their minimization.

It is important to understand that temperature profile in the slug is formed not only by the skin effect and electromagnetic end effect, but by the thermal edge effect as well. Thermal edge effect takes place due to Lambert's cosine law.

One should also note that the end effect is more pronounced at different stages during the cycle. For example, at the beginning of heating and at the end of heating, the rate of the end effect is different. This is due not only to the change in electrical resistivity of the aluminum, but also to several unique features of SSM induction heating, including the "elephant foot" effect.

Computational Shortcomings

Mathematical modeling is one of the major factors of successful induction heating design. During the last decade, a considerable amount of experience has been accumulated on the computation of induction heating by using numerical techniques. Unfortunately, the features of SSM generate several limitations for using any existing commercially available software. This may be illustrated by the following example. In a vertical type coil arrangement, the existence of the "elephant foot" phenomenon is an indication that the slug has obtained a semi-solid condition. As a result of that phenomenon, the coil-to-slug air gap will not be the same along the coil height (Fig. 5a). The variation of the air gap changes the electromagnetic coupling between the coil and different areas of the slug. Thus, the power density distribution along the slug height will vary as compared to a perfect cylindrical body.

In addition to the "elephant foot" phenomenon, a "slug tilting" effect and "surface erosion" at the top of a slug makes the situation even more complex (Fig. 5b). Due to tilting, certain areas of the slug will have better coupling with the inductor than areas located on the opposite side of the slug. The areas with better coupling will receive more intensive heating which will result in more intense tilting.

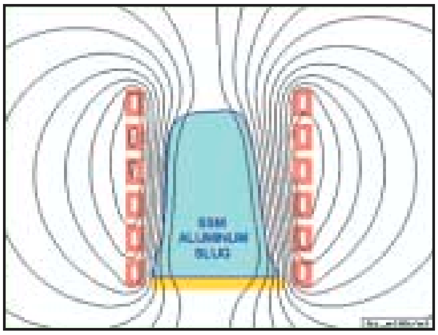

Fig. 6 *Computer graphics of magnetic vector potential.*

Due to "surface erosion" at the top of a slug and the "elephant foot" phenomenon at the bottom, the length of the eddy current paths at slug's top, bottom and central areas will be different. This will result in distinct resistances to eddy current flow in different surface areas of the slug and, therefore, in different Joule losses. In other words, from electromagnetic point of view, slug will be seen by the magnetic field as a number of disks made from metals with different electrical conductivity.

It is very important to remember that any computational analysis can, at best, produce only results that are derived from modeling assumptions. Even a cursory look at a computer simulated magnetic field distribution (Fig. 6) reveals the danger in underestimating the parameters of SSM heating and using overly simplified assumptions (i.e., considering the slug's geometry as a perfect cylinder). Assumptions that are readily used in conventional forging or extrusion applications, can lead to an incorrect mathematical model that will not be able to provide the required accuracy in SSM processing.

In order to adequately simulate induction heating in SSM, the computation model should couple electromagnetic, heat transfer, phase transformation and metal flow phenomena. The development of software which will be able to take all four inter-related phenomena into account is a very complex task even for modern computers. Software of this complexity is not expected to be available in the world market for at least three to four years. Therefore, the recommendations obtained from conventional coupled electromagnetic-heat transfer software should be applied for cases where elephant foot, slug tilting and surface corrosion phenomena are not pronounced (as sometimes is the case for horizontally arranged coils or small slugs).

Another factor that effects an accuracy of computer modeling is availability of reliable property data. There are a number of handbooks available where one can find information regarding thermal conductivity, electrical resistivity and specific heat of most metals. Unfortunately, similar information for SSM is very limited. In some instances, SSM property data exists, but due to measurement complexity and cost, the reliability of that data, especially in the most critical semi-solid stage, is quite poor.

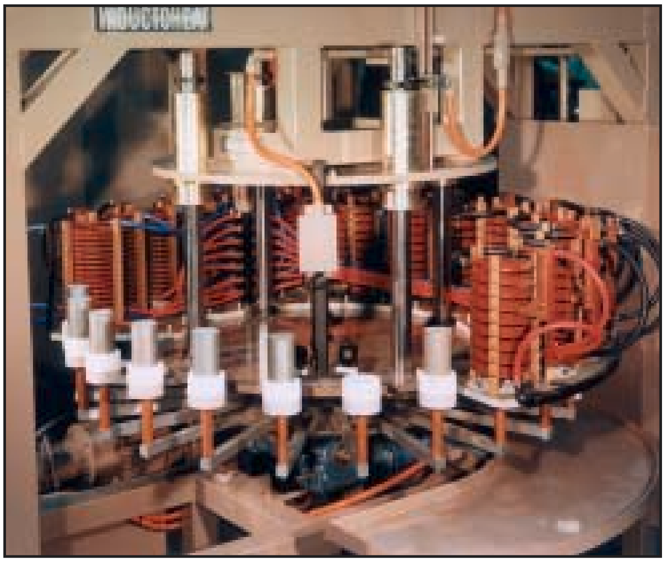

Fig. 7 *The slugs stand on ceramic pedestals with the vertically oriented induction coils.*

Therefore, in opposition to conventional induction heating computation, the results of SSM modeling should be considered as basic guide lines or “ball park” numbers, and should be used only in conjunction with experience and engineering background in SSM.

Advanced Induction Heating System for Semi-Solid Metal Forming

Above described complex features of induction heating for SSM should not discourage users of this unique technology. On the contrary, an understanding of these phenomena allows a designer to build an induction system which provides the required slug conditions for successful SSM forming. Proper handling of end and edge effects, and the correct choice of design parameters, allow one to obtain the required temperature uniformity and optimum semi-solid casting condition while maintaining high system efficiency, small equipment space requirements, and high production rate.

One of the most successful developments of an induction slug heater is shown in Fig. 3. This compact carousel-style induction heater has actually become a de facto standard for use in modern induction heating for semi-solid metal-forming. This heater is powered by a 350 kW, 1 kHz power unit, and uses 24 pedestals and 18 induction coils. The cold slugs are loaded onto ceramic pedestals, and indexed to the first induction coil. The coils are lowered around the slugs and the power is applied. After a preset time, the current is turned off and the coils are raised. The pedestals then index forward by one position, the coils are lowered and the process is repeated (Fig. 7). In this manner, the slugs index from coil to coil, until at the final heating position, the temperature and fraction liquid of the slugs are suitable for SSM casting.

The induction heater has been designed to match the throughput of the horizontal casting machine, which typically operates at a cycle time of 30 to 90 seconds, depending upon the size of the casting and number of cavities being cast. This style of heater can heat aluminum slugs up to 5 kg (12 lb.) at this rate of throughput.

Since all the coils are connected in series, two different designs of coils are used to provide the optimum heat cycle: fast heating and soaking used during commercial SSM casting. The fast heating coils have a greater number of turns, and are used to rapidly heat the slugs to the solidus temperature. The soaking coils have fewer turns and heat the slugs more slowly. This provides sufficient time for the heat to conduct from the surface to the center of the slug, ensuring a uniform surface-to-core temperature profile. The longer heating time provided by the soaking coils is also used to complete the spheriodization of the alpha-aluminum particles from the equiaxed dendrites found in the electromagnetically stirred SSM feed material. In order to provide sufficient time to obtain a uniform liquid fraction and to complete the spheriodization of the microstructure, minimum heating times are recommended for all slug sizes. The optimum heating times for 3”, 3.5” and 4” diameter slugs are listed in Table I.

The induction heater also utilizes an automated unit for cleaning any debris remaining on the pedestal once the semi-solid slugs have been removed. Debris can include drips or small pieces that were knocked off the semi-solid slug during heating. This ensures that the pedestal is clean once it returns to the slug loading position and the cold slug will sit squarely on the pedestal. Operations such as pedestal cleaning are important to ensure the problem-free operation of the induction heater in a fully automated semi-solid metal casting cell.

Casting Trials

Heating trials were performed using the carousel-style induction heating sys-

Fig. 8 *Induction heaters for SSM forming.*

Table I **Recommended Slug Heating Times**[7]

Slug Diameter, inches	3.0	3.5	4.0
Optimum Heating Times, min.	9.0	12	16

Table II **Longitudinal Temperature Profile**

Temperature, °C (°F)		
Top	Center	Bottom
586 (1087)	583 (1081)	582 (1080)

tem described above. Slugs measuring 140 mm (5.5") in length were cut from 76 mm (3") diameter alloy A356 VELVET flow SSM feed material produced by Ormet Corp. These slugs were heated to the semi-solid temperature using induction coils that were approximately 282 mm (11.125") long. The heating time was 42 seconds per coil with an indexing time of 10 seconds. Slugs were standing on ceramic pedestals with the induction coils oriented with a vertical axis. Once the slugs exited the final soaking coil, a type-K thermocouple was used to measure the temperature of the top, center and bottom of the slug. Table II shows a longitudinal temperature profile at optimal slug position.

These data show that with the slug in an optimal position, its top-to-bottom temperature profile is essentially uniform. For the slugs that are off-optimal position, the end of the slug that has the largest coil overhang has a significantly higher temperature and liquid fraction.

In Ref. [4], one can find the impact of the coil overhang on slug's top-to-bottom temperature uniformity. These results indicate the importance of controlling the electromagnetic end effects to obtain a uniform temperature and the proper liquid fraction, and to minimize tilting in the slug. Different applications call for different design approaches. Some of these are shown in Fig. 8.

SUMMARY

Some people traditionally view induction heating as a "stand alone" process or system. In their view, it is possible to simply adapt conventional design concepts used in forging and rolling applications to build induction heaters for SSM forming. While there are some similarities with traditional design concepts, SSM forming technology has several features which create unique requirements for induction system design and induction process modeling.

REFERENCES

[1] M.C. Flemings, "Behavior of Metal Alloys in the Semi-Solid State," Met. Trans. 22A, 1991, p. 957.

[2] S.P. Midson and K. Brissing, "Semi-Solid Casting of Aluminum Alloys: A Status Report," Modern Casting, February 1997, p. 41.

[3] Young, K.P., "High Integrity High Pressure Casting Processes: Market Demands and Process Development," CIATF Technical Forum, UK, June 1997.

[4] V.I. Rudnev and R.L. Cook, "Bar End Heating," Forging Magazine, Winter 1995, pp. 27-30.

[5] V.S. Nemkov, V.B. Demidovich, V.I. Rudnev and O. Fishman, "The Use of End and Edge Effects for Induction Heater Design," Proc. of Electroheat Congress "ELECTROTECH 92," Montreal 1992, pp. 180-188.

[6] Althix Billets, Aluminum Pechiney, April 1996.

[7] S. Midson, V. Rudnev and R. Gallik, "The Induction Heating of Semi-Solid Aluminum Alloy," Proc. 5th Int. Conference on Semi-Solid Processing, Golden, CO, June 1998, pp. 497-504.