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Semi-Solid Forming

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Part 1

Semi-Solid Forming: New Advances in Net Shape Manufacturing

Part 2

Commercialization and Potential Applications

Presented by Dr. G. Hirt, EFU GmbH

Recent Developments in Thixoforming

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1. Introduction

Thixoforming has come to play an increasing role as an alternative to classic manufacturing techniques such as casting and forging. One reason for this is the growing demand for high-strength aluminium components for lightweight automotive designs. A necessary condition for the manufacture of low-cost lightweight aluminium parts is the ability to process this expensive material into near net shape components of complex geometry and high strength. Thixoforming provides the engineer with a vastly broader range of design options than forging - possibly even broader than conventional casting processes, for instance, when it comes to wall thicknesses and wall thickness variations. With manufacturing costs now on a level with high-grade casting applications, high mechanical component qualities can be achieved, and applications in the field of highly- integrated safety critical components have become possible.

2. Process outline and state of the art

The basic principles of the process, which consists of the feedstock production, billet reheating and casting operations, are described in detail in /1-3/ and elsewhere in the literature. In the production of the feedstock (usually by continuous casting with electromagnetic stirring) the objective is to achieve a globular structure of maximum grain fineness. In this context EFU has gathered positive results with a variety of casting alloys, wrought alloys and MMCs in the 76 to 200 mm diameter range /4,5/. The pilot-scale experimental continuous caster is able to cast not only aluminium alloys, but also up to 900 kg copper alloys using electromagnetic stirring.

For reheating the billet (previously cut to a precise length) to a temperature in the solidus-liquidus interval, inductive heating has evolved into the method of choice since it is best suited to achieve quick, uniform and accurate heating results. In addition to traditional revolving type furnaces, this is achieved increasingly with modular-type units in which the billet remains in one coil during the entire heating cycle /6/.

Most specimen parts and authentic application components produced in the world to date are still made from AlSi7Mg alloy. This material can be thixoformed into components weighing from under 10 g to more than 10 kg (e.g., /7,8/); products in the medium size range have already been manufactured in high-volume applications exceeding 2 million units, especially in the US. Apart from a reliable process technology, which should provide real-time control of the injection curve, it will become necessary in future applications to include simulation tools for optimizing the injection parameters and die design.

3. Heating technology

In the modular furnace type preferred by EFU, the billet is not transferred from one coil to the next but remains in the same individually controlled coil for the entire heating cycle. Depending on the required cycle time, it is possible to install between 1 and 16 coils. Since this design requires each heating module to have its own frequency converter, the recent availability of low-cost converters with "intelligent" control functions and large control ranges was a prerequisite for an economically feasible implementation of this concept /9/, which provides maximum precision and flexibility.

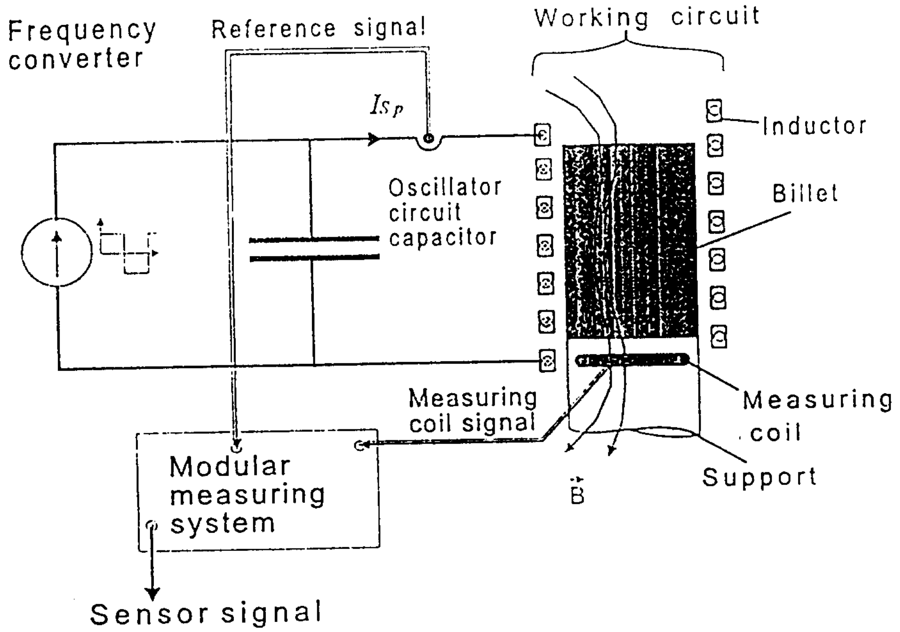


Fig.1: Inductive measuring system to determine the billet condition

The useful thixoforming temperature window may become extremely narrow for a given component /6/. However, due to the large portion of heat of fusion, this narrow temperature range represents a fairly high enthalpy differential, so that it makes sense, in the most simple case, to use the energy introduced into the billet (i.e., the product of heating power input and efficiency integrated over time) as the power control criterion. It should be noted, however, that any change in efficiency, baseline temperature or heat loss during the heating cycle may produce spurious control results in this case. In order to avoid such errors and to permit a flexible response to potential exterior interferences, EFU has developed the measuring system shown in Fig. 1, in which the measurement signal may serve as a direct indicator of the billet condition over large portions of the heating cycle /10/. This system relies on the fact that the electrical conductivity of aluminium changes dramatically as the material undergoes the transition from its solid to a liquid state. This effect produces characteristic amplitude and phase angle changes in the measurement voltage induced in the measuring coil when compared to the reference signal picked up on the heating coil. Through an appropriate electrical evaluation of both signals it is possible to derive a measurement signal which is independent of the current heating power input /6/ and correlates well with the percentage of liquid phase material, at least under certain conditions (Fig. 2) /9/. Although this good correlation is lost under in shopfloor production environments due to geometrical effects, the resolution of the measurement signal in the solidus/liquidus interval is still very high when compared with a mere temperature measurement.

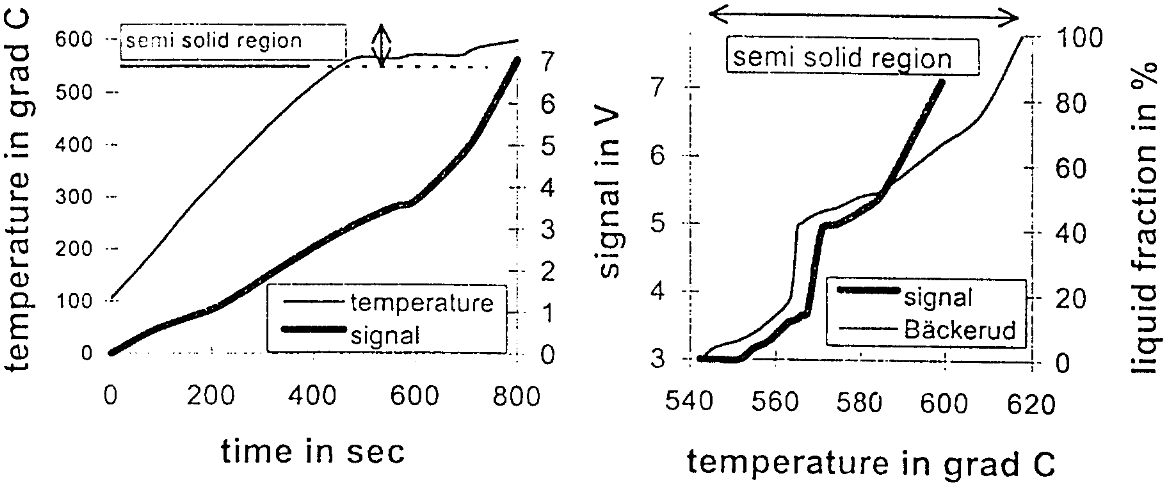


Fig. 2: Sensor signal in comparison to temperature measurement and liquid fraction according to literature

Accordingly, this signal can be used as the basis for a "material-specific" control of the billet condition throughout the reheating process /6/. It is evident from Fig. 3 that the control circuit thus devised will reliably produce the target condition through controlled power adjustments, without operator intervention, even in the case of a greatly deviating initial billet temperature.

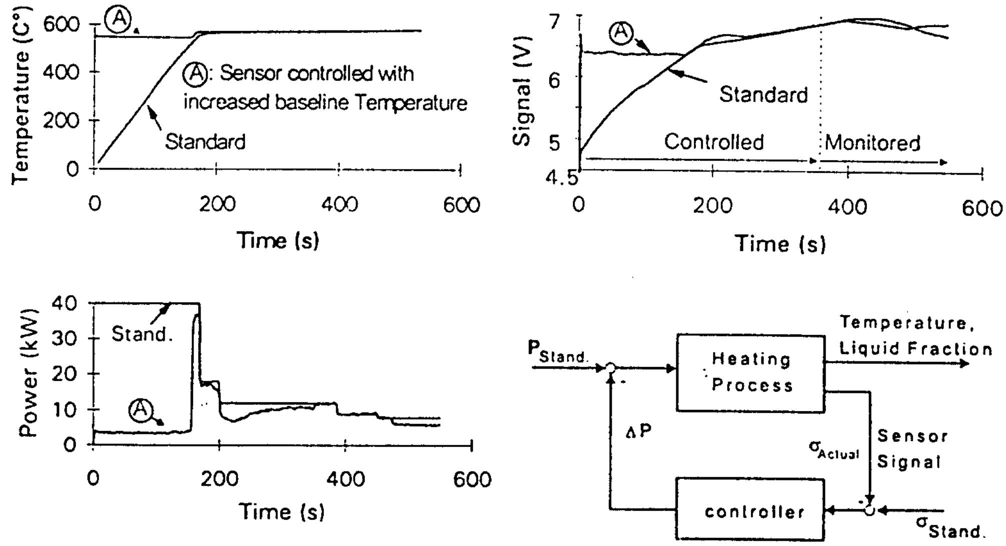


Fig 3: Sensor controlled reheating process: standard curves and values recorded when starting with a reheated billet

By the same token it is possible to maintain each billet in its current state in the case of an exterior interference (e.g., one affecting the die) and to continue the re-heating cycle after the problem has been remedied.

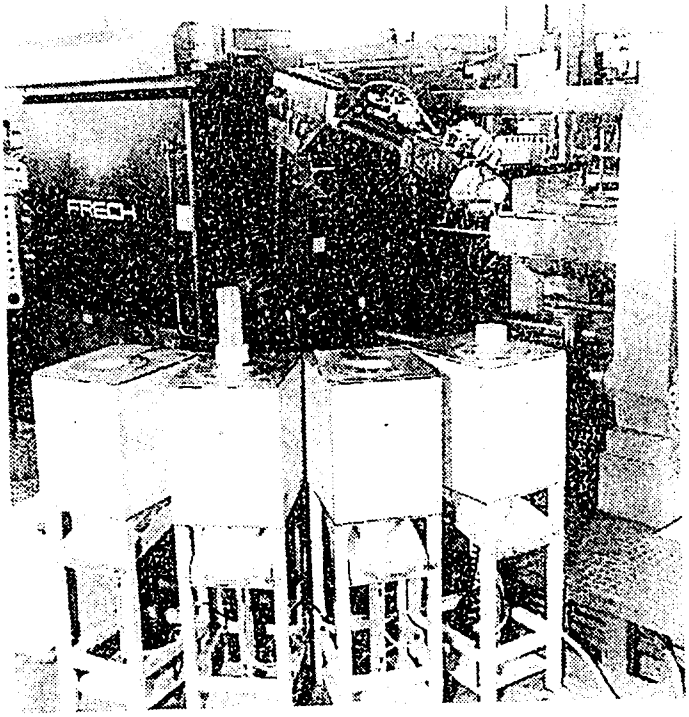


Fig. 4:
4 coil pilot system for billet reheating (foreground) with ABB robot and Frech DAK 500 DCRC real time controlled high pressure die casting machine (background)

A pilot plant operating on this principle was installed at EFU in the spring of 1996 (Fig. 4). This is a four-coil system capable of reheating billets measuring up to 100 mm in diameter and 250 mm in length.

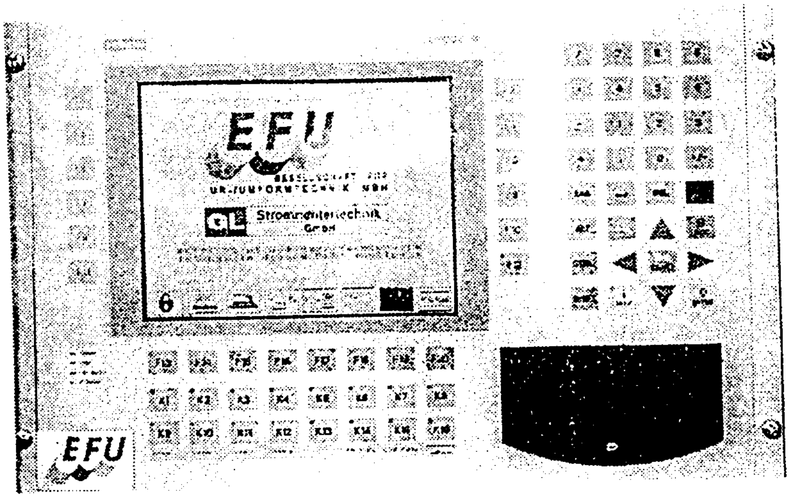
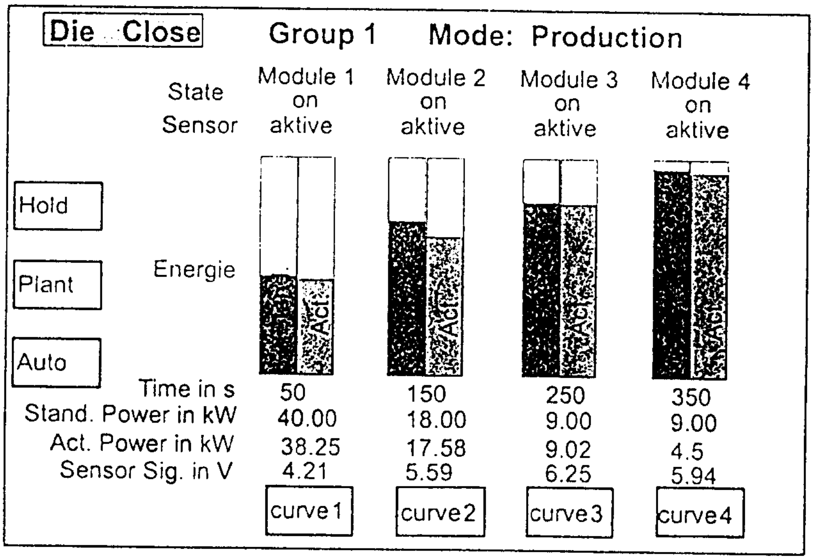


Fig 5:
Display and keybord of the control system

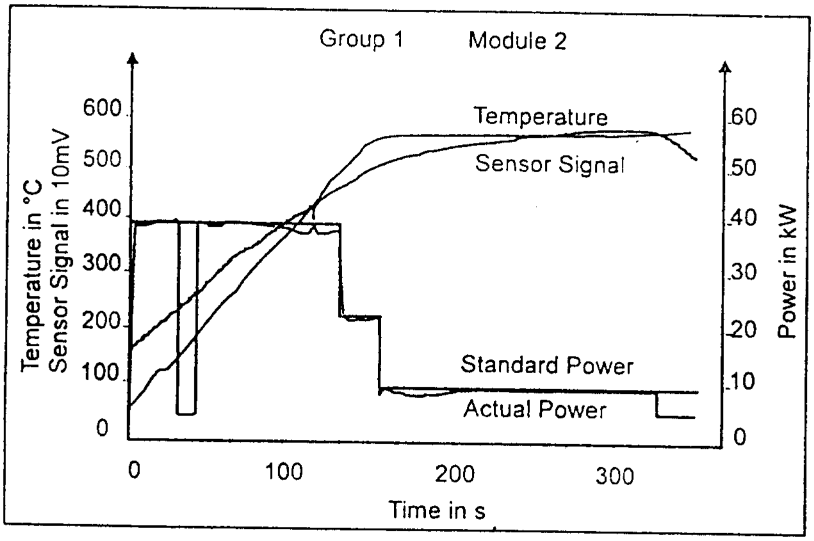
A master control sytem coordinates the operation of the individual heating modules, the robot, and the die-casting machine. The re-heating furnace is operated on a menu-controlled basis using COROS (Siemens) with colour monitor and keyboard (Fig. 5).



	Module 1	Module 2	Module 3	Module 4
State	on	on	on	on
Sensor	aktive	aktive	aktive	aktive
Time in s	50	150	250	350
Stand. Power in kW	40.00	18.00	9.00	9.00
Act. Power in kW	38.25	17.58	9.02	4.5
Sensor Sig. in V	4.21	5.59	6.25	5.94

Fig 6:
Control system for reheating units:

a) general status and energy overview



b) time history of module Nr. 2

The various menu levels can be used to select different operating modes (set-up, manual, production), to load and store the parameter sets for various billet dimensions and alloys, and to visualize the plant status and heating curves for each billet. Fig. 6 a illustrates a current "energy status" display for modules 1 through 4. Differences between the specified and actual energy input may be the result of individual controller action or, as in the case of module 2, an intermediate soaking phase inserted shortly after the start of the heating cycle. Fig. 6 b shows an example of a heating curve over time (specified/actual power levels, sensor signal), which can be produced for each individual billet and may be used for documentation purposes.

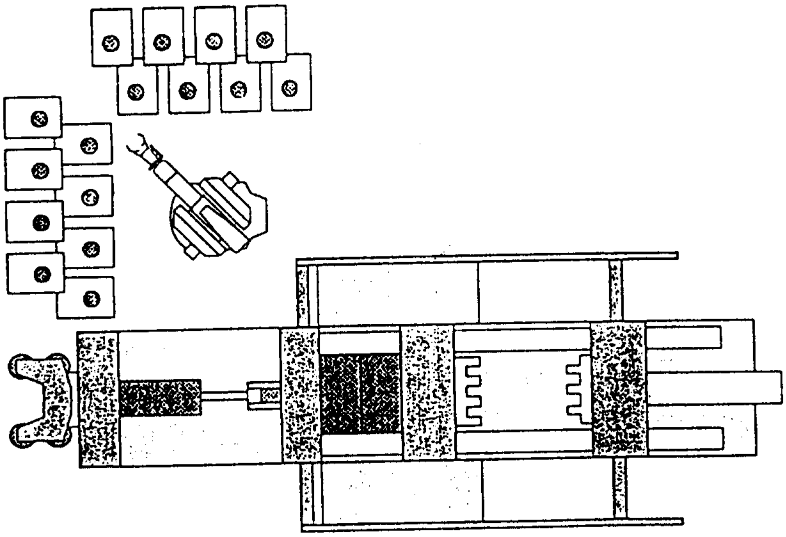


Fig 7: Layout of a thixoforming cell

This plant design provides a versatile system with modular features which allow a flexible equipment layout near the pressure die-caster, depending on the number of coils and floorspace availability (Fig. 7). Interlinking with product handling systems or pressure die casters can be implemented via the interface signals provided by the master control system.

4. Forming process

4.1 Process potential and demonstration components

Aluminium thixoforming can be used to produce highly resistant components of complex geometry. It is possible to distinguish roughly between four categories of components for which the thixoforming process may be of particular interest:

- components subject to high pressures (e.g., brake cylinders);
- thick-walled components subject to high loads (e.g., suspension parts);
- thin-walled structural components;
- components made of special materials such as metal matrix composites, which are expensive, difficult to machine and known for their poor casting properties.

In all of these categories EFU has manufactured a number of initial demonstration components which were kept deliberately straightforward in some cases:

- The brake cylinder housing produced in cooperation with the Frech Co. (Fig. 8) is a typical pressure-loaded component. In this application thixoforming avoids the porosity of thick-walled component sections which is almost impossible to avoid with other casting techniques.

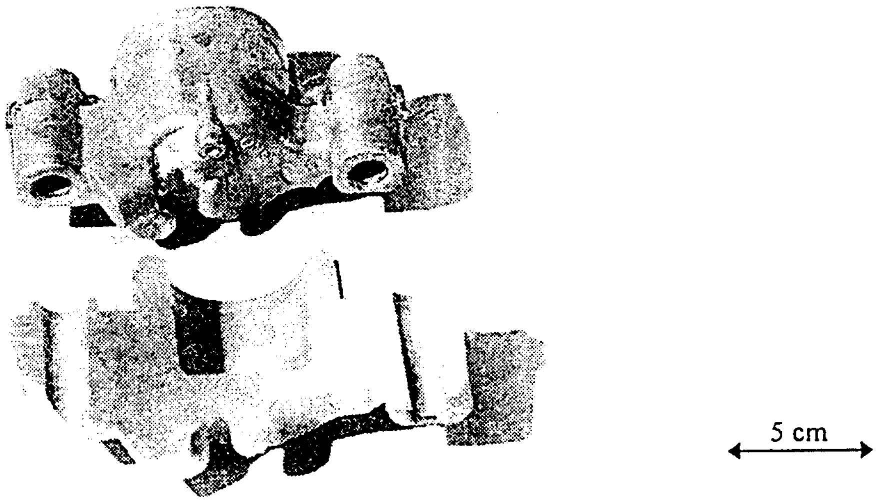


Fig 8: Demonstrator part: brake cylinder housing

- In the case of the suspension link (Fig. 9) it is possible to achieve wall thicknesses between 6 and 25 mm, depending on the mould insert selected.

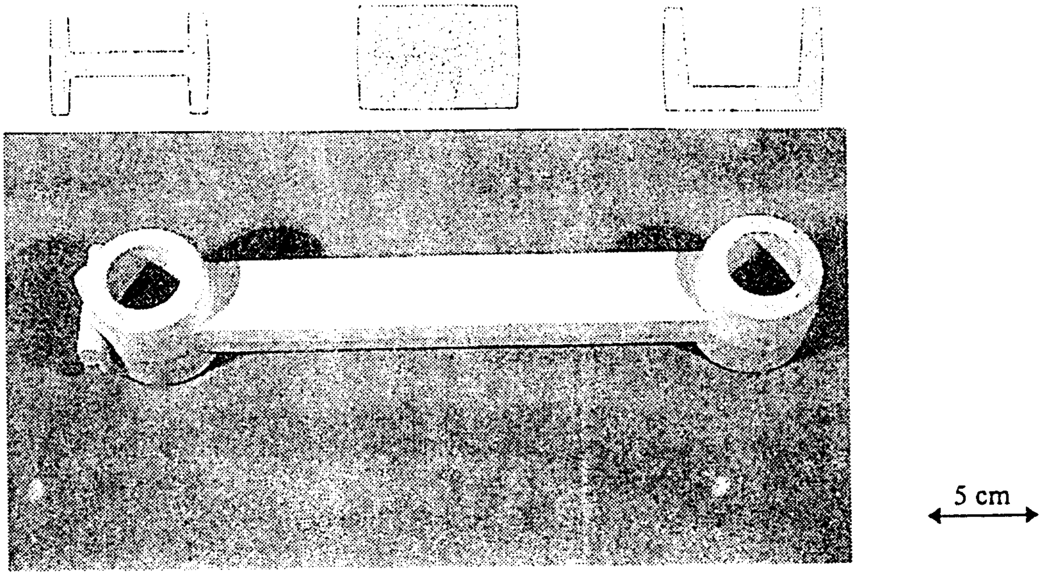


Fig. 9: Demonstratot part: suspension arm

- The ribbed "hat section" shown in Fig. 10 has a wall thickness between 2,5 and 3 mm. This is a typical example of a thin-walled structural component which should ideally achieve high tensile and yield strengths even without heat treatment to avoid distortion.

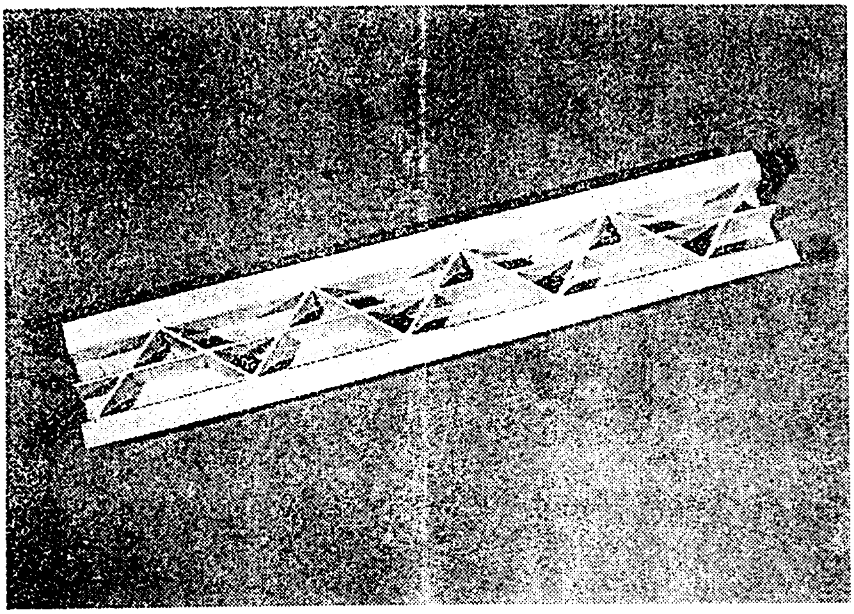


Fig 10: Demonstrator part: thinwalled, ribbed "hat section" (length: 500 mm)

Accessing process benefits through the appropriate use of design options

In order to exploit the full potential of the thixoforming process it is necessary to adopt a component design geared to the specific process and application requirements, while making use of the expanded range of design options offered by this technology. Thixoformed aluminium components are often intended to replace steel or nodular cast iron forgings. Apart from a high yield strength and fracture toughness, the stiffness of the component will be a important boundary condition in this case - especially allowing for the fact that the modulus of elasticity of aluminium is only one-third that of steel. If there is a simultaneous need for weight reduction, the product must be re-designed by exploiting the typical thixoforming design options of combining thick-walled and thin-walled areas with stiffening ribs and undercuts. A decisive step in this direction is the steering knuckle for a compact passenger car which was thixoformed by EFU under a contract with Krupp-Gerlach GmbH (Fig. 11). On the basis of prescribed loading conditions, geometrical restrictions and given functionality the part was designed by Porsche Engineering (under a contract with Krupp-Gerlach GmbH) also considering the process-specific boundary conditions defined by EFU. The component is currently undergoing trials. The weight of the part is approx. 35% below that of a conventional forged steel design, despite identical functional capabilities.

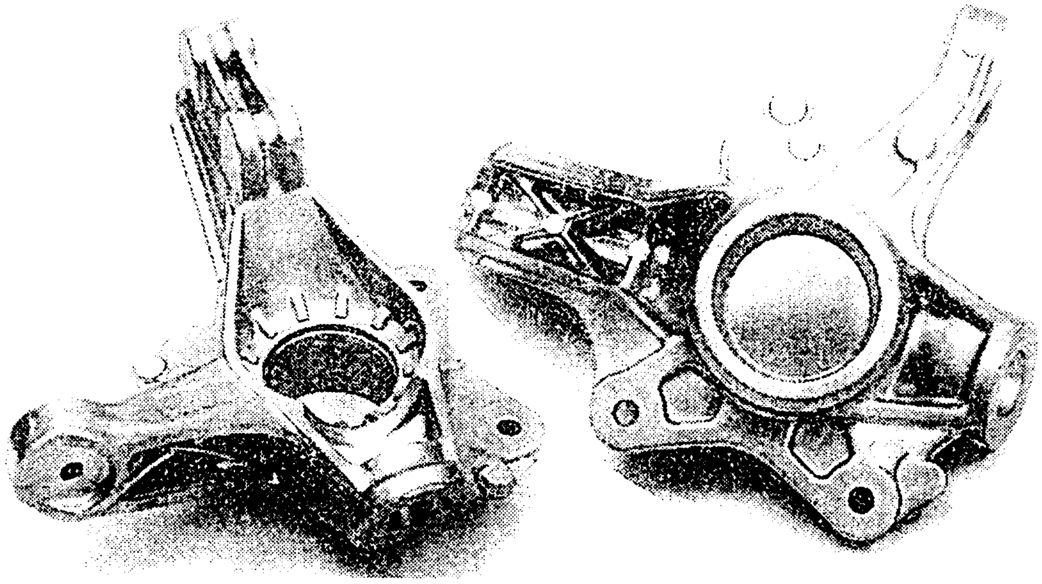


Fig 11: Steering knuckle for compact passenger car

4.2 Suitability of the thixoforming process for other aluminium alloys, magnesium, and higher-melting materials

Apart from the standard thixoforming alloy AlSi7Mg, EFU has conducted trials with various other alloys. Several of the demonstration components mentioned earlier were manufactured from these alloys listed below and the experience gathered in these trials can be summarized as follows:

AlMgSi1: This wrought alloy can be thixoformed into products of very good mechanical properties /11/. However, its susceptibility to hot cracking and poor fusion of confluent melt fronts greatly restrict the application range.

AlSi17CuMg, AlSi25CuMg: Hypereutectic alloys are fairly well suited for the thixoforming process and may be of interest for components subject to wear.

Metal matrix composites: The production of feedstock from modified Duralcan material with subsequent thixoforming has been extensively investigated at EFU /12/. These materials can be processed very well by thixoforming, without the problems encountered with conventional casting methods. A low-cost future alternative might consist of materials with an increased content of TiB particles which are obtained by means of an in-situ process /13/.

Magnesium: AZ 91 alloy feedstock can be produced by a suitable combination of chemical grain refinement and control of the solidification rate /14/. Billets of this type were sourced from North Hydro and could be easily heated and thixoformed.

Cu alloys and steels: Unlike light metals, higher-melting materials pose the key problem of the elevated temperature level which, in the case of steel, may reach 1400°C. The thermal loads acting on the die and the prevention of oxidation effects are major concerns. Initial investigations conducted in cooperation with the Technical University of Aachen (RTWH) confirmed that several Cu alloys and steels are suitable for thixoforming.

4.3 Simulation

The die design (gating system, overflows, cooling, venting) is still very much an empirical matter at this point, and the available experience is naturally limited. The same applies to the selection of optimum casting parameters (piston speed curve, point of changeover from speed to pressure control, die temperature, etc.). The importance of these parameters is clearly evident from the case of the simple suspension link shown in Fig. 9. At a low piston speed, the die fills evenly from the inside out (Fig. 12). If the piston speed becomes too high, an advance jet of molten metal is formed and may cause air inclusions when deflected by back pressure.The determination of optimum casting parameters may involve costly and time-consuming trial runs, especially with sophisticated component geometries.

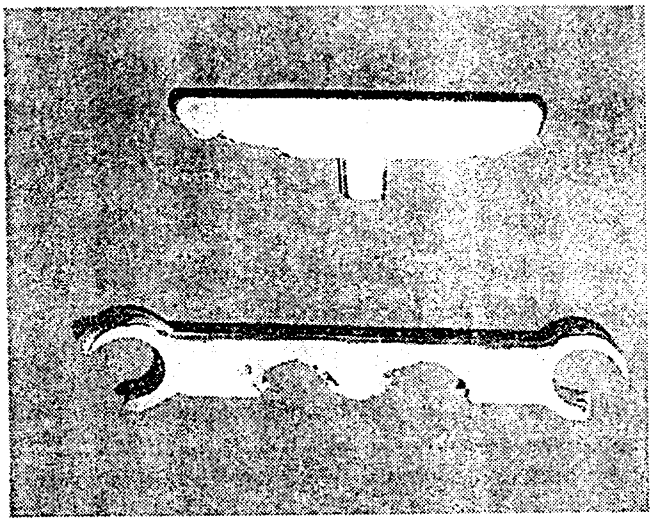


Fig. 12: Die filling pattern at different casting injection velocities

In the meantime EFU has gathered some initial experience with the numeric simulation of the die filling process, which is expected to accelerate the development process and provide advance evidence of the feasibility of the die design. EFU performs these simulations using the Magmasoft FDM package. In the first simulations conducted at Magma Co., the material behaviour was described using the Oswald - deWaele model in which the viscosity is a function of temperature and shear-rate:

$$\nu = \nu(T;\dot{\gamma}) = m \cdot \dot{\gamma}^{n-1} \qquad (1)$$

ν = kinematic viscosity, $\dot{\gamma}$ = shear rate, T = temperature,
m and n are temperature-related parameters

The calculations performed with material characteristics taken from the literature /15/ showed a surprisingly good qualitative coincidence with the actual form filling process (cf. Fig. 13). However, other comparison parameters such as the injection pressure and slurry temperature could not be correctly determined with these material characteristics.

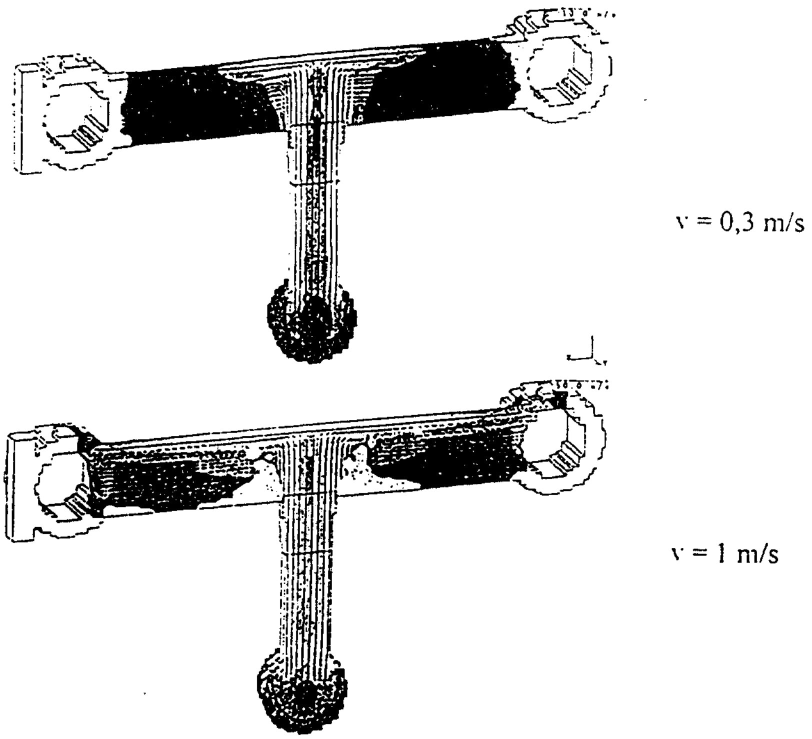


Fig. 13: Die filling simulation results for the parameters used in Fig. 12

These considerations have prompted EFU to embark on a selective expansion of its database through experiments based on the use of a capillary-type viscosimeter. Initial experience with such a measuring configuration had been gathered by EFU some time ago on a customer project for the Raufoss Hydro Automotive Research Centre AS with the alloy 7108.

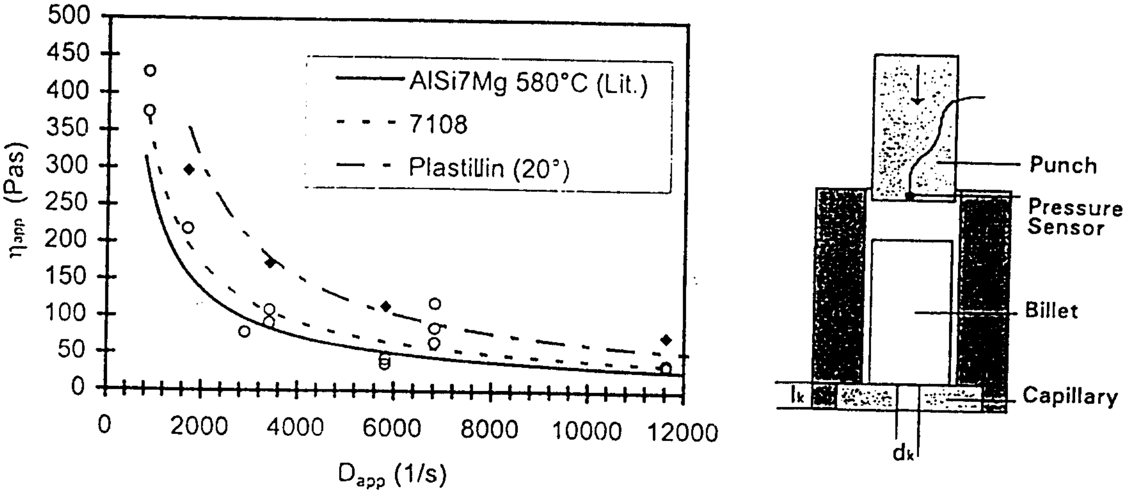


Fig 14: Viscosity determination with a capillary-type viscosimeter

These data (cf. Fig. 14) were obtained by precision measurements of the metal pressure under constant injection pressure conditions. A first approximation of the apparent viscosity can then be derived with the following formula

$$\eta_{ap} = \frac{\pi \cdot R^4 p}{8 \cdot L \cdot A \cdot v} \qquad (2)$$

where η_{ap} = apparent dynamic viscosity
R, L = radius, length of the capillary tubes
A, v, p = surface area, velocity, pressure of the piston

4.4 Casting plant technology

As with other forming methods, plant technology plays a crucial role in the thixoforming process. When using standard machines a reproducible injection curve adapted to individual component needs can best be achieved with a pressure die-caster with real time control. The DAK 500 DC RC machine used by EFU in cooperation with Oskar Frech Co. has a closing force of 580 metric tons (Fig. 4); its piston rod movement is controlled by a quick-acting control valve arranged on the secondary flow side of the casting piston. At a typical Vmax of 2,5 m/s, the high dynamic response of this valve allows an acceleration from 20 to 80% Vmax (and conversely, a deceleration from 80 to 20% Vmax) at a rate of 4 ms /16/. This is sufficient in any case for meeting the requirements of a form-specific injection curve for thixocasting. Of the comprehensive range of menu-guided data monitoring and control options offered by this machine, the following are particularly useful for the thixoforming application:

- definition of the piston speed as a function of travel (10 interpolation nodes);
- changeover from speed control to pressure control as a function of travel or casting pressure.

5. Summary and outlook

In recent years we have seen a continuous evolution in thixoforming equipment technology (billet heaters and casting machines) and accumulated experience through the manufacture of numerous specimen components. From the volume production applications realized to date it is evident that large production runs can be realistically implemented. In order to exploit the full potential of the process it will be necessary to demonstrate its reliability under volume production conditions (also with regard to safety-related components) and to consistently adopt component design principles accommodating the specific process and loading characteristics. Numeric simulations of the die filling process, although still flawed, will soon help to reduce development times and minimize die adapting costs.

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