

Manufacture of Automotive Components by Semi-Liquid Forming Process

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Abstract

Semi-liquid forming process, applied to pressure die-casting, permits to obtain low cost components with high qualitative characteristics and adequate mechanical performances.

The technology is based on the employment of material with globular microstructure (flow-cast alloys) obtained subjecting a metal alloy at the time of solidification to an elevated shear rate. Such microstructure permits the accomplishment of conventional forming processes at temperatures in solidification range.

The particular fluid-dynamic properties of the semi-liquid slurry and the lower injection temperature allow to obtain castings with improved soundness, without need of impregnation, and to extend die life.

The present work describes the Weber (Magneti Marelli) activity for the process industrialization and some applications for the manufacture of automotive components.

Riassunto

Il processo di formatura in semi-liquido, applicato alla pressocolata, permette l'ottenimento di componenti a basso costo con alte caratteristiche qualitative ed adeguate prestazioni meccaniche.

La tecnologia è basata sull'impiego di materiale a microstruttura globulare (leghe recolate) ottenuto sottoponendo una lega metallica in fase di solidificazione ad un elevato gradiente di scorrimento. Tale microstruttura permette l'utilizzo di processi di formatura convenzionali a temperature comprese nell'intervallo di solidificazione.

Le particolari proprietà fluidodinamiche del semiliquido metallico e le basse temperature di iniezione permettono l'ottenimento di getti ad elevata sanità, senza necessità di impregnazione, allungando nel contempo la vita degli stampi.

Il presente lavoro descrive l'attività Weber (Magneti Marelli) per l'industrializzazione del processo ed alcune applicazioni per la fabbricazione di componenti autoveicolistici.

Introduction

At temperatures in solidification range, metal alloys are not industrially used in forming processes as their structure, derived from traditional solidification, is made up of an interlacing network of dendrites in a liquid matrix, that cause it to stiffen, with low percentages of solid phase. It therefore appears impossible to use them in casting. Also, attempts to deform such a structure lead to the formation of hot cracks and zones of elevated segregation which inhibit the obtaining of a sound part having the desired characteristics.

Today it is well known (1 ÷ 11) that, subjecting a metal alloy at the time of solidification to an elevated shear rate it is possible, upon solidification, to verify a microstructure very different from the conventional ones: the effect of the shear forces induced is to destroy the solid network of dendritic interconnections developed during solidification of the liquid; in absence of such a structure the dendrite fragments remain separate and tend to assume spheroidal shapes by continual mutual mechanical collisions (Fig. 1).

This microstructure (globular, not-dendritic) permits the use of conventional forming technologies at temperatures in solidification range.

The main advantages deriving from the use of a semi-liquid alloy in pressure die-casting can be summarized as follows:

In terms of process:

- lower injection temperature (by 120°C at least for an Al alloy);
- extending die life (less thermal shock);
- power saving;
- cleaner and safer environment;

And, in terms of product:

- sounder castings (less trapping of air, less solidification shrinkage);

- no impregnation;
- increased range of pressure die-cast alloys;
- potential development: metal matrix composites.

After all: high-performance/low-cost products.

These advantages must however to be included in a wide scenery which aims at developing a low-cost technology that allows to manufacture an increasing kind of components with reliable quality characteristics and, moreover, with alloys not usually pressure die-cast, supplying the planner with an efficacious aid when are requested special metallurgical and mechanical performances of components.

The present work describes the Weber activity for the process industrialization: at Weber foundry of Crevalcore (BO) are installed a pilot plant for the production of flow-cast material and a pilot plant to manufacture pressure die-cast components in semi-liquid state.

Moreover, some appliances addressed to components characterized by special interest and critical molding will be showed.

Pilot plant for the production of the flow-cast material

In order to produce a flow-cast alloy (i.e. characterized by a globular form in the solid phase) it is necessary to create a vigorous agitation between the various solid particles at the time of solidification.

In such a mode, the formation of the dendritic interconnections that develop during solidification in the absence of agitation is inhibited.

Various techniques can be employed for keeping the bath in vigorous agitation during solidification, provided that they allow, at the same time, cooling of the alloy so as to withdraw the latent heat of solidification.

A method, patented by Centro Ricerche Fiat [2] for generating elevated shear rates, is making the alloy in the solidification phase pass through a static mixer device.

The geometrical configuration of the mixer is arranged so as to generate high shear forces in the metallic alloy.

In this way it is possible to keep the viscosity of the semi-liquid relatively low, also with very high solid fractions, hard to attain in practice with other mixer systems.

The pilot plant who permits the use of such a mixing device in industrial conditions has been planned and patented by Weber [4] and also built and installed at Weber foundry of Crevalcore.

The system is based on the use of a pressurized smelting furnace (CIVARDI) by wich, by the mechanical action of an inert gas or compressed air, is allowed the outlet of the metal alloy who, at the time of solidification, is forced to pass through the static mixer device.

Fig. 2 shows a side view of pilot plant, Fig. 3 shows a block diagram of the system.

The pilot plant permits the production of flow-cast material at a rate of 20 Kg/min.

The capacity of the furnace is of 400 Kg of Al alloy, but it exist a version of the plant to charge the pressurized furnace in continuous or semi-continuous way to extend the duration of the pouring indefinitely.

The collecting system has been planned in such a way to obtain flow-cast ingots having diameters varying from 4.5 cm to 7.3 cm; the ingots are then cut in slugs having lengths according to the weight of the components to manufacture.

The process is controlled by a PLC by which it is possible to schedule different fluid-thermodynamic conditions for the production of the semi-liquid, flow-cast material.

Operational parameters of every pouring are remarked and recorded for a total parametrization of the process.

Metallographic analyses and preheating tests document the quality of flow-cast ingots.

Pilot plant for the manufacture of die-cast components

Semi-liquid die-casting process is particularly critical in that, in addition to the variables of the traditional pressure die-casting process, it requests a perfect temperature control of preheated slugs and a microstructural quality decidedly high and at any rate higher than that requested for semi-liquid die-forging process: it's therefore necessary to possess choice flow-cast material and suitable equipments ables to assure an accurate temperature control and a fast feeding of die-casting machine.

Weber semi-liquid die-casting pilot plant consists mainly of:

- Plant for preheating and handling of the slugs;
- Die casting machine;
- Analyser for injection parameters survey and recording.

Fig. 4 shows a view of pilot plant.

The preheating and handling plant (FORN/O/MATIC) comprises one resistance furnace with automatic feed of pieces in 3 parallel lines on motorized straight rollers, one unloading manipulator to feed the die-casting machine, one switchboard comprising Siemens 115V programmer, video terminal, alphanumeric keyboard, printer, service package.

The press is a 320-ton IDRA cold-chamber horizontal die-casting machine suitably modified to make easier the semi-liquid material feeding and injection; the machine is interfaced with the preheating plant and equipped with transducers and a DGM analyser to permit measurement and recording of injection parameters (Fig. 5).

The dies are equipped with suitably placed electrical plugs ables to insure a proper warm-up and to allow a localized thermoregulation; detailed studies have been addressed to gates (in terms of location, cross-sectional area, wetted perimeter).

Manufacture of automotive components

Aim of the experiments

The main aims of die-casting in semi-liquid state are:

- to manufacture components *actually die-cast* allowing a reduction of scraps;
- to manufacture components *actually not die-cast* and manufactured with other more expensive technologies or with other materials.

With these motivations, the experimentation has been focussed on components ables to emphasize these expectations, particularly on «fuel rail» and other components for fuel injection systems.

Fuel rail is a component *actually not die-cast* since the quality resulting from the traditional process can't pursue the severe conditions envisaged in the design stage, particularly the metallurgical characteristics in terms of soundness and corrosion resistance.

The possible manufacture of the component by die-casting in semi-liquid state should allow to realise savings >50% compared with conventional productions (steel or aluminium die-forged). The saving is attainable by high productive rate (typical of die-casting) and by the possibility of reducing machining and tooling: see Fig. 6 where a sectioned specimen of fuel rail shows a dead hole obtained using a steel core 0.8 cm dia. by 32 cm long (draft angle 0.04°); Fig. 7 shows the moving die half with a steel core (1.3 ÷ 0.8) cm dia. by 32 cm long, draft angle 0.44°.

Experimental procedure

Flow-cast slugs, held in individual sample holders, are introduced in the preheating furnace and heated to a temperature in solidification range to melt the eutectic matrix around the solid Al-Si solution globules (Fig. 8 shows the solidification curve of the UNI 3599 alloy, 93% Al, 7% Si).

The desired temperature is obtained regulating the passage time inside the furnace according to temperature set points scheduled in single areas.

Each holder is then transferred to die-casting machine by a manipulator who discharges the slugs into the shot sleeve; under the shearing action of the plunger the thixotropic slugs flow as a fluid slurry and fill the die in laminar motion.

Slugs used for these experiments measured approximately 7.3 cm dia. by 9.0 cm long and weighed 1000 grams.

The plunger speed was varied from 0.5 to 1.0 m/s and the mean die temperature was held at about 200°C.

Low injection speeds, added to high viscosity values ($\mu \approx 1 \div 100$ P), caused low Reynolds numbers, making it possible to fill the die with laminar flow (Fig. 9).

To avoid effects from contact cooling of the slugs by the shot sleeve, this one was equipped with electrical plugs.

A direct measurement of slugs temperature during the transfer from preheating furnace to die-casting machine was carried out by a rapid-reading thermocouple hooked up the manipulator.

Results

Several hundreds of components have been manufactured as above mentioned using different kinds of Al alloys (UNI 3600, UNI 5077, UNI 3059, UNI 5075, UNI 3599) in order to consider all aspects relating to machinability, corrosion resistance, mechanical tests, and so on.

Particular attention has been addressed to fuel rail for which is provided a series of validity tests (see Table 1).

TABLE 1 - Validity plan

As cast pieces	
A) Dimensional test	
B) Metallographic and chemical analysis	
Tooled pieces	
C) Dimensional test	

(continue)

-
- D) Structural analysis and burr analysis
 - E) Assembling and pressing
 - F) Strength of threads
 - G) Strength of clamps
 - I) Resilience
 - L) Vibrations ($50 \div 1000$ Hz)
 - M) Fast thermal cycles ($-40 \div +130^{\circ}\text{C}$)
 - N) Dimensional test
 - O) Inner surface corrosion (sour-gas: peroxide + fuel C)
 - P) Inner surface corrosion (water-gas: 84.5% fuel C, 15% methanol, 0.5% H_2O)
 - Q) Outer surface corrosion (96 h in saline mist according to ASTM B117)
 - R) Humid-statical test (96 h at 40°C , relative humidity 95%)
-

Preliminary examinations pointed out what follows:

– **Metallographic inspection:**

Specimens were taken for metallographic analysis from metallurgically significant areas of components to check soundness and whether segregation of the eutectic and globular phases had occurred.

The examinations showed that the structural uniformity of the components had been attained.

Apart from a few exceptions related with the alloy UNI 3059 (Al, 3% Mg), neither solidification shrinkage nor gas porosity were observed. (In relation to injection parameters it was possible, in any case, to point out that a plunger speed >1.2 m/s cause a slight appearance of porosity and a plunger speed <0.5 m/s cause a deterioration of surface quality).

– **Corrosion tests:**

– Outer surface corrosion (test Q. Table 1).

After 96 h of exposure to the saline mist (and after HNO_3 pickling) on components are not present corrosion traces (alloys UNI 3599, UNI 3059); unfavourable test for the alloy UNI 5075 (containing Cu);

– Inner surface corrosion (sour-gas) (test O, Table 1)

After 720 h of immersion are not present corrosion traces (UNI 3599, UNI 3059); unfavourable test for UNI 5075 (corrosion traces after 240 h).

At the present time other experimental data are not available (tensile tests are available and positive (tests F, G) but for the sake of brevity are not reported).

Conclusions

Industrialization of «pressure die-casting in semi-liquid state process» undertaken by Weber is yielding positive results.

By pilot plants installed at its foundry, Weber is able to produce flow-cast material and to use it to manufacture automotive components.

Prototypes of a fuel rail were die-cast in semi-liquid state from flow-cast aluminium alloys.

Metallographic analyses demonstrated the soundness of the castings and the uniformity of their

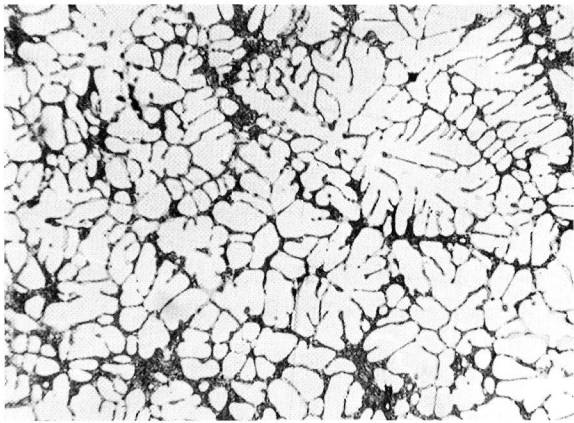
structure; tensile tests and corrosion tests (solely for the alloys UNI 3059 and UNI 3599) showed requested characteristics.

Acknowledgement

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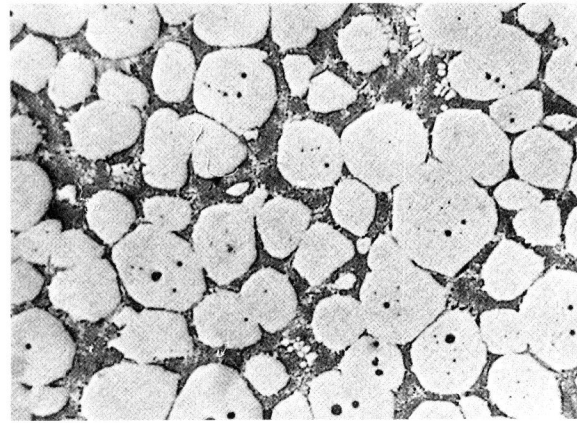
References

- [1] Flemings, M.C., Mehrabian, R., and Riek, R.G. *Continuous process for forming an alloy containing non-dendritic primary solids*, U.S. Patents No. 3,902,544 - Sept. 2, 1972.
- [2] Manfré, G., Moschini, R., and Mironi, J. - Centro Ricerche FIAT, *Process for the preparation of a mixture comprising a solid phase of a metal alloy, and device for its performance*, U.S. Patent No. 4,310,352 - Jan. 12, 1982.
- [3] Dantzig, J.A., and Tyler, D.E., *Process and apparatus having improved efficiency for producing a semi-solid slurry*, European Patent Application No. 82105446.7; June 22, 1982.
- [4] Moschini, R. - Weber, *A continuous semi-liquid casting process and a furnace for performing the process*, European Patent application No. 90112546.8, Aug. 17, 1990.
- [5] Moschini, R. - Weber, *Procedimento per l'ottenimento di pressocolati ad alte prestazioni meccaniche mediante iniezioni di una lega metallica allo stato semiliquido*. Patent No. TO 91A 000299, Apr. 19, 1991.
- [6] Flemings, M.C., Adams, C.M., Hucke, E.E., and Taylor, H.F., *Metal solidification in a flowing stream*, Transaction American Foundrymen's Society, Vol. LXIV, 1956.
- [7] Joly, P.A., and Mehrabian, R., *The rheology of a partially solid alloy*, Journal of Material Science, 11 (1976), 1393-1418.
- [8] Flemings, M.C., *A history of the development of rheocasting*, in Frenc, R.D., and Hodi, F.S. (Eds.) Rheocasting. Proceed, of the Workshop on Rheocasting held at Army Materials and Mechanics Research Centre 3-4 Feb. 1977. MCIC - 78-35. Metals and Ceramics information Center, Columbus Ohio 1978.
- [9] Bercovici, S., *Controle des structures de solidification et des propriétés des alliages Al-Si*, Revue de l'Alluminium, Fevrier 1979.
- [10] Millière, C., Secondé, J.F., Sécordel, P., and Suéry M., *Structure, propriétés et mise en forme des alliages brassés à l'état sémi-solide*, Memories et Etudes Scientifiques Revue de Métallurgie. Juillet-Aout 1983.
- [11] Antona, P.L., and Moschini, R., *New foundry process for the production of light metals in the semi-liquid, doughy state*; Metallurgical Science and Technology - Vol. 4, No. 2, August 1986; Foundry Trade Journal International - December 1987.



a) conventional

100 X



b) flow-cast

100 X

Fig. 1:
Microstructure of an Al-Si-Cu alloy.

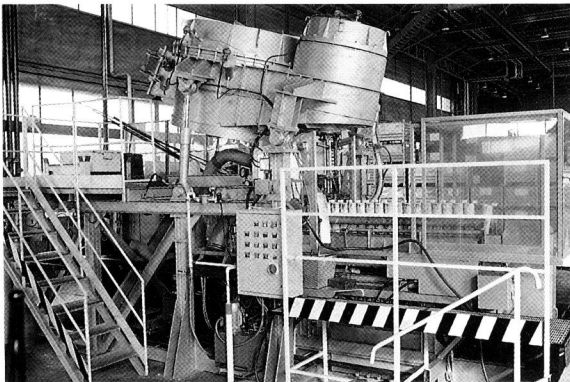


Fig. 2:
Pilot plant for the production of flow-cast ingots.

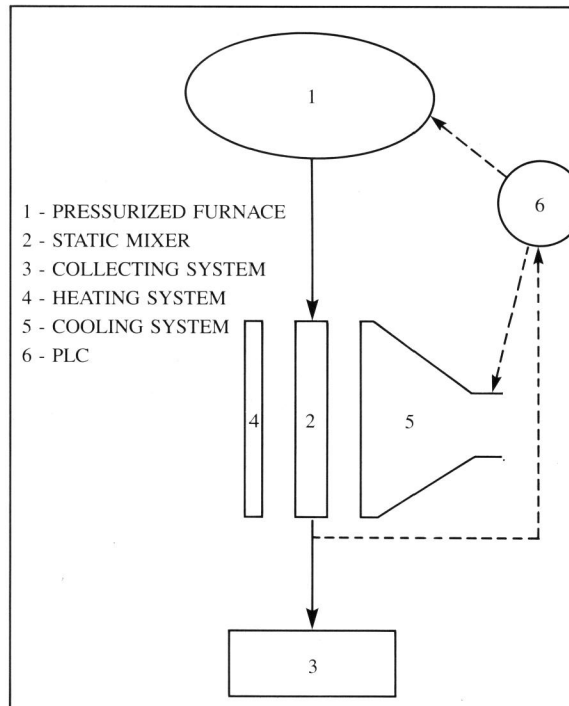


Fig. 3:
Schematic diagram of pilot plant shown in Fig. 2.

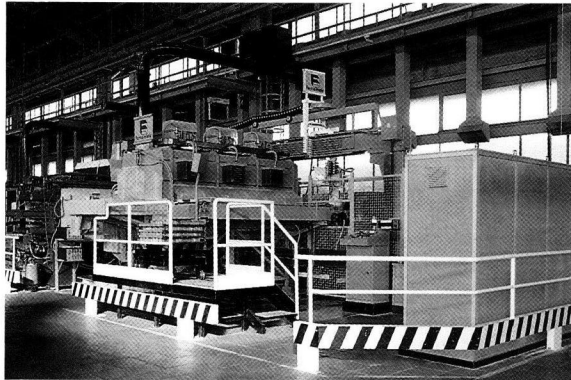


Fig. 4:
Semi-liquid die-casting pilot plant.
In the middle: plant for preheating and handling
of the slugs; Behind: die-casting machine.

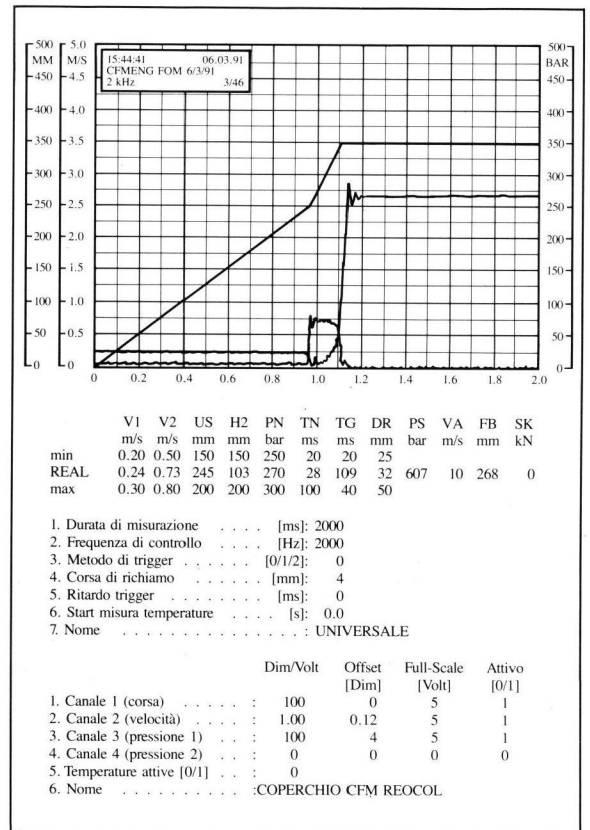


Fig. 5:
Die casting of «upper body» (central fuel injection): injection parameters recorded by DGM analyzer.

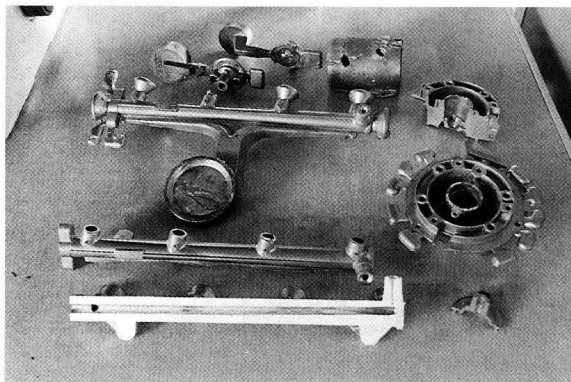


Fig. 6:
Components of fuel injection systems die-cast in semi-liquid state.
Behind: a flow-cast slug; Close up: sectioned specimen of fuel rail.

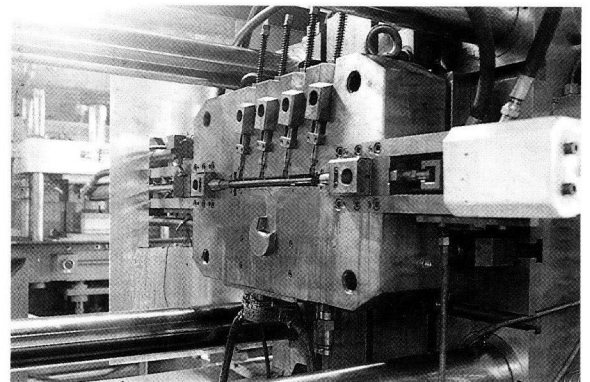


Fig. 7:
Moving die half of fuel rail: notice the steel core (0.8 ÷ 1.3) cm dia. by 32 cm long (draft angle = 0.44°).

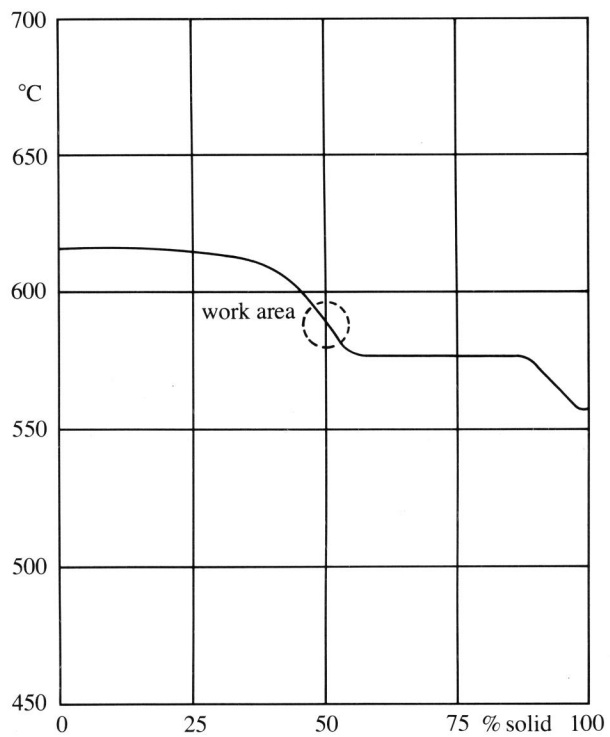


Fig. 8:
Solidification curve of the alloy UNI 3599 (Al,
7% Si).
Solid fraction versus temperature.

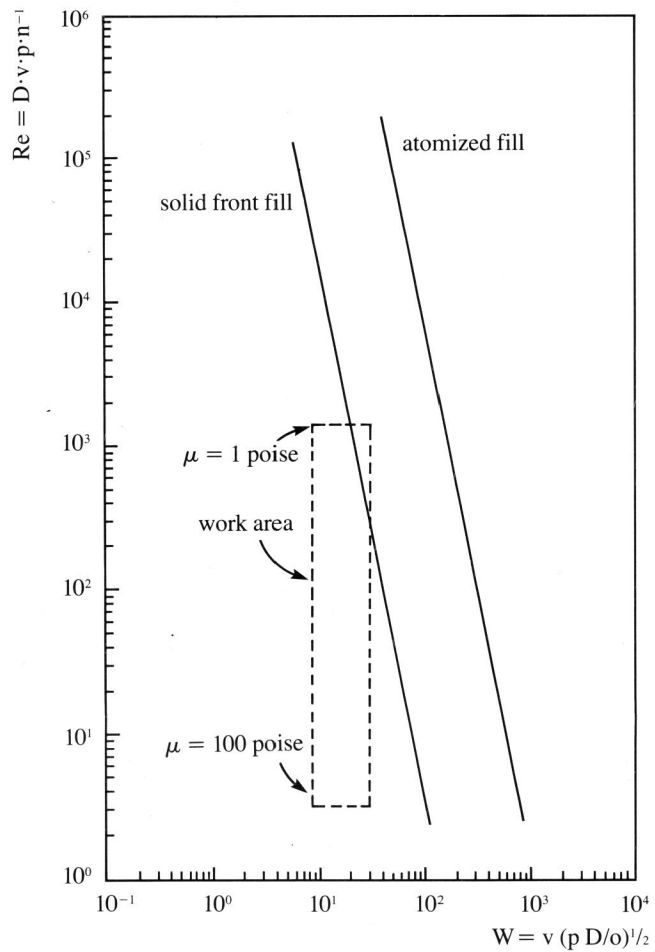


Fig. 9:
Reynolds number versus W number (prediction
of the mode of die filling according to «Hong,
Backman, Mehrabian - Univ. of Illinois). Work
area of the experimentation in semi-liquid state.