

# Thixoforming of magnesium alloys and application to automotive industry

Antonio Fuganti, Marta Cordoni, Centro Ricerche Fiat, Materials and Processes

## Abstract

*The use of magnesium alloys in the automotive field is increasing due to their lightness. At present most widespread applications regard non structural components manufactured by high pressure die casting.*

*New forming technologies are now growing aimed at producing structural components which have to meet more severe targets: thixoforming seems to be the most attractive. In this near-net shape process the metal in the semi solid state fills the die with a laminar flow, preventing any gas entrapment in the final component. Besides the high quality reachable in the as cast part, it is possible to improve the mechanical properties by heat treatments. Other advantages of this technology are: energy saving, tighter part tolerances, less machining operations, no dangerous molten metal handling.*

*Till now Thixoforming has been used for the production of aluminium automotive components, even of big dimensions, whereas only some prototypes of small parts were made of Mg-alloys.*

*At present some experiments are on going in order to evaluate the thixoformability of the AZ91 alloy for the manufacturing of structural magnesium components.*

*By means of this innovative process a variety of new application of magnesium alloys in the automotive sector can be envisaged for the next future.*

## Riassunto

L'impiego di leghe di magnesio in campo automobilistico è in sensibile aumento grazie alla loro leggerezza. La gran parte delle odierne applicazioni riguarda componenti non strutturali ottenuti per pressocolata. Al contempo stanno prendendo piede nuove tecnologie per la produzione di componenti strutturali: tra esse la thixoformatura appare come la più promettente. Tale processo near-net-shape consiste nell'iniettare la lega allo stato semisolido all'interno di uno stampo metallico, la cui cavità viene riempita con flusso laminare, evitando inclusioni di gas nel getto. Oltre alla elevata qualità ottenibile allo stato as cast, è possibile incrementare le proprietà meccaniche tramite trattamento termico. Altri notevoli vantaggi del processo sono: il risparmio energetico, le più strette tolleranze, la possibilità di ridurre le lavorazioni meccaniche (rispetto a componenti forgiati), l'eliminazione del trasporto di metallo allo stato fuso; quest'ultimo risulta di particolare importanza per leghe di magnesio.

Attualmente la thixoformatura viene utilizzata per la produzione di componenti autoveicolistici in lega di alluminio, anche di grandi dimensioni, mentre la sua applicazione a leghe di magnesio è limitata alla realizzazione di prototipi e componenti di piccole dimensioni. Sono in corso esperimenti per valutare la thixoformabilità della lega AZ91 e le proprietà che se ne ottengono, in previsione di realizzare componenti strutturali.

L'impiego di questa tecnologia innovativa per le leghe di magnesio lascia intravedere per il prossimo futuro una serie di nuove applicazioni nel settore automobilistico.

## INTRODUCTION

The automotive industry is subjected to continuing market and regulatory pressures to produce low priced, high quality safe and environmentally friendly products. Currently this situation is strongly enforced by legislation (Fig. 1). These demands require the development of vehicles that are less polluting during and after operations (recycling) and

that permit a reduction of fuel consumption. These targets can be achieved by engine efficiency improvement and weight reduction with an appropriate choice of materials. Concerning the weight saving, the automotive industry is looking at innovative process technologies, new design methodologies, development of light alloy applications. Since

## WHY IS THE WEIGHT REDUCTION IMPORTANT?

There is an increasing concern for future fuel availability, environment and safety.



### OBJECTIVES:

- a) Fuel consumption reduction
- b) Noxious emission reduction
- c) Vehicle safety improvement

The weight reduction is the most effective method for meeting these targets.

In some cases also the legislation is pushing it (Ex.: USA C.A.F.E.)

Figure 1

magnesium is one of the lightest metals, it is a very promising material for weight reduction. Low heat content and low reactivity with steel are favourable factors for magnesium; machining is faster, requires less energy and gives well broken chips. At present the most widespread automotive application regards non-structural components as pump housing, steering wheel, engine valve cover, inlet manifold, instruments panels, seat frames.

Two are the obstacles to the introduction of magnesium al-

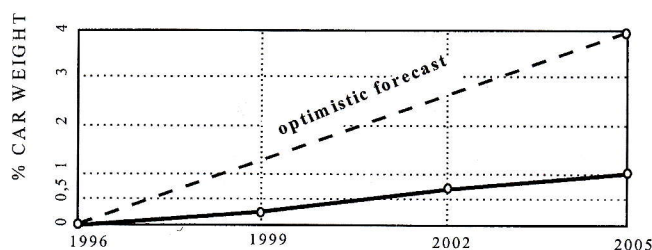
## EMPLOYMENT OF LIGHT ALLOY IN THE AUTOMOTIVE SECTOR

There was a mistake in the European past forecast of light alloys employment in the automotive field where it was foreseen that the application of light alloys should be larger than the present one. The problems which have slowed down the introduction of light alloys are due to cost factors. In fact the material replacement is not an easy objective to meet because the automotive industry does not like to introduce changes able to disturb the organisation of its productive

loys which have always limited their application in automotive sector:

- corrosion
- cost

Nowadays new high purity alloys and coating, innovative mechanical fastenings have been developed, aimed at reducing the atmospheric and galvanic corrosion. New automotive components are now feasible and therefore the trend of magnesium alloys employment in the automotive industry is increasing as reported in the following diagram:



Concerning the costs, new design philosophies are applied to component development. Design for assembling is focused on integrating more part in a single one in order to reduce the cost of manufacturing (welding, dies, work, manpower, etc.). For such a reason the casting processes have more and more a fundamental role. The most diffused one, for a high production volume, is the high pressure die casting in either cold or hot chamber machines. Automotive components already in production with this process are typically non-structural parts like instrument panel, valve cover, etc. In fact the turbulence of the melt flow during the die filling creates a lot of porosity in the cast part; it reduces the achievable elongation and it does not permit the heat treatment. Therefore high pressure die casting is not suitable for the production of structural components.

equipment. These changes have a strong influence on costs in terms of investment, initial low efficiency, materials, training, etc. In the USA the legislation contributed in a large way to push the innovation in new materials; according to the C.A.F.E. Standard (Corporate Average Fuel Economy) the fuel consumption has to be maintained under defined values, which are becoming more and more severe (Fig. 2). For example, in Fig.3 the increase of aluminium alloys in



## C.A.F.E. STANDARD (Corporate Average Fuel Economy)

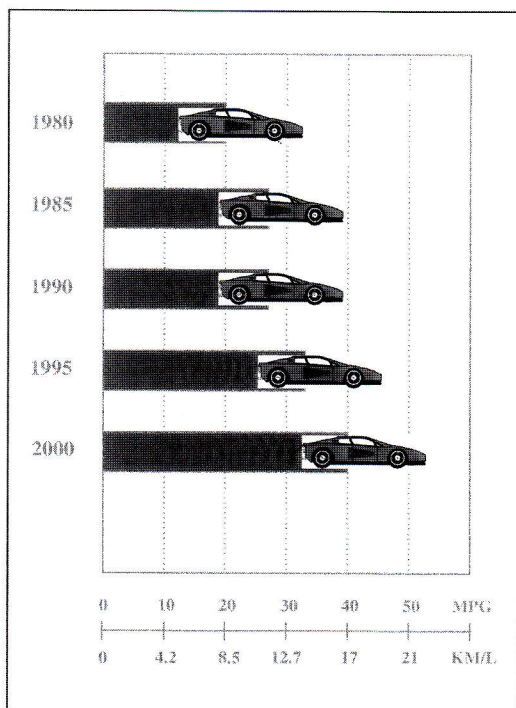
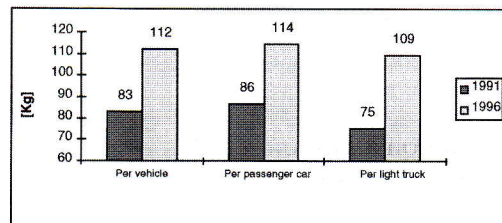


Figure 2

the USA from 1991 to 1996 is reported.

The weight saving has a strong influence on the reduction of fuel consumption, on a fleet economy point of view. It has been calculated that 100 Kg of weight saving permit a fuel consumption reduction of about 5 litres every 1000 Km covered. Considering the European market, the replacement of traditional materials is important in components where the weight saving can introduce other add values as comfort and safety, like suspension parts and more in general "unsprung masses". If such parts or other structural components are considered it is clear that higher material mechanical properties (strength and toughness) are required. For such a reason, in order to reduce the manufacturing cost, a lot of effort was spent for improving the casting processes of light alloys in terms of maximum mechanical properties achievable and Near Net Shape capabilities. Casting processes have the important feature which permit to integrate more part in a casting, reducing at minimum the cost for assembling. For instance Fiat Auto has in production an instrument panel made of HPDC (High Pressure Die Cast) magnesium alloy where one casting replaced 24 welded steel parts with a weight saving of about 50% and an improved stiffness, maintaining the same cost. Other aspects taken into consideration in the R&D of automotive industry are the develop-

## AVERAGE INCREASE OF ALUMINUM CONTENT IN CARS AND LIGHT TRUCKS IN U.S.A. FROM 1991 TO 1996



The U.S.A. trend was stronger than in Europe even because it was supported by legislation



Partnership for the Next Generation of Vehicles (PNGV)  
(consortium of automotive manufactures and suppliers)



objective

80 mpg car (weight saving of 40%)

Developed cars:

- EV1 (GM)
- Plymouth Prowler (Crysler)
- Taurus, Sable (Ford)

Figure 3

ment of advanced forming and joining methods, the development of codes for process numerical simulation, the improvement of material strength and corrosion resistance and the improvement of recyclability. The last two items are really important if magnesium alloys are considered, because the overcoming of the present limit could open their market dramatically. Fig. 4 reports the world-wide prediction in magnesium alloys employment in the automotive field. At present High Pressure Die Casting (HPDC) is the most reliable process for mass production of magnesium alloy components, but it has the limitation that no thermal treatment is feasible after casting due to the blistering phenomena. The problem is related with the gas entrapment during casting. As previously reported, new transformation processes of magnesium alloys are in a development phase for achieving a better trade off between strength and toughness. In particular thixoforming represents a good solution because it permits to obtain NNS parts with very low porosity whose mechanical properties can be improved by heat treatment.



## WORLD-WIDE FORECAST OF Mg-ALLOYS EMPLOYMENT AUTOMOTIVE APPLICATION

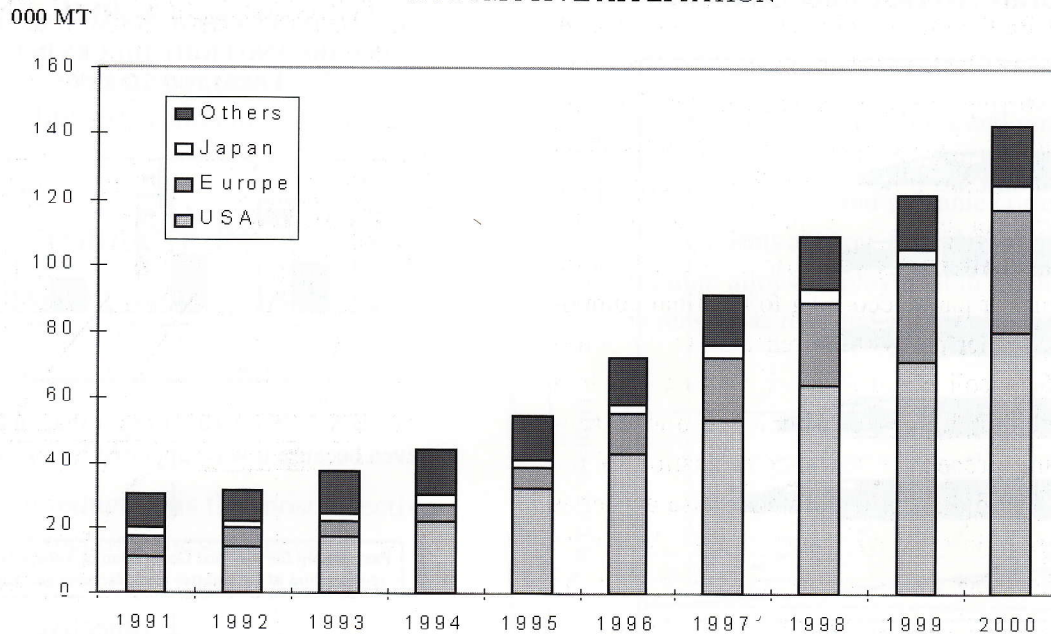
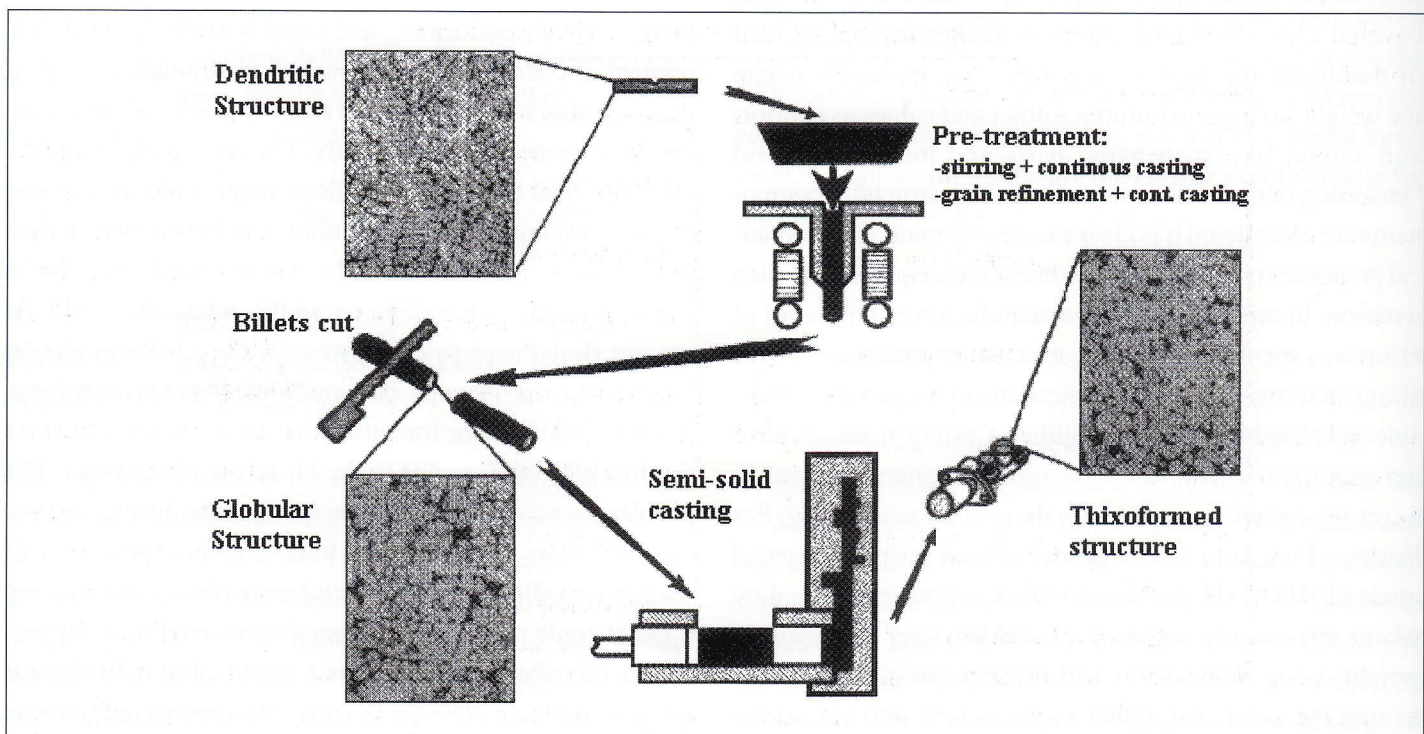


Figure 4

## THIXOFORMING PROCESS

There are a lot of different processes based on the behaviour of an alloy in a thixotropic semi-solid state: solid globular dendrites dispersed in a liquid eutectic phase. In this state the material looks like a solid but shows a pseudoplastic (viscosity decreases with the increasing shear rate) and thixotropic behaviour (viscosity decreases with the shear stress

application time). So that it is possible to handle and move mechanically a billet of such a semi-solid material, placing it in a die (like a solid), and then inject it by a piston (like a liquid) thanks to the reduced viscosity due to the shear forces during the forming operations. The following schema shows the different steps of thixoforming process.





As shown in the schema, the material has to be subjected to a preliminary procedure for obtaining billets having the right structure suitable for the injection in the semi-solid state. A lot of methods are available in order to reach this structure: electromagnetic stirring, mechanical stirring, passive stirring, grain refinement. Electromagnetic stirring is the most diffused one for aluminium alloys whereas grain refinement seems to be suitable for magnesium alloys and in particular for the AZ91 alloy. After the pre-treatment the long solid billet is cut in smaller parts according to the final component mass; each smaller part is then reheated to the semi-solid state (40÷60% solid) and injected into the die. It is interesting to note that whereas in aluminium alloys, subjected to a stirring procedure, the spheroidisation of the dendrites begins during the pre-treatment phase and ends during the reheating, in the magnesium alloys added with grain refiners, the spheroidization occurs only during the re-heating before injection. The possibility for magnesium alloys to obtain a good globular structure only with grain refinement is due to their facility to spheroidize with the increasing of the temperature; this is important because it permits to limit the extra costs of the stirring, reducing the gap between the cost of raw material for conventional die casting and thixoforming, in comparison with aluminium alloys. There is a similar process suitable for magnesium alloys, called Thixomolding®, where the material is first introduced in the machine as chips and then injected directly

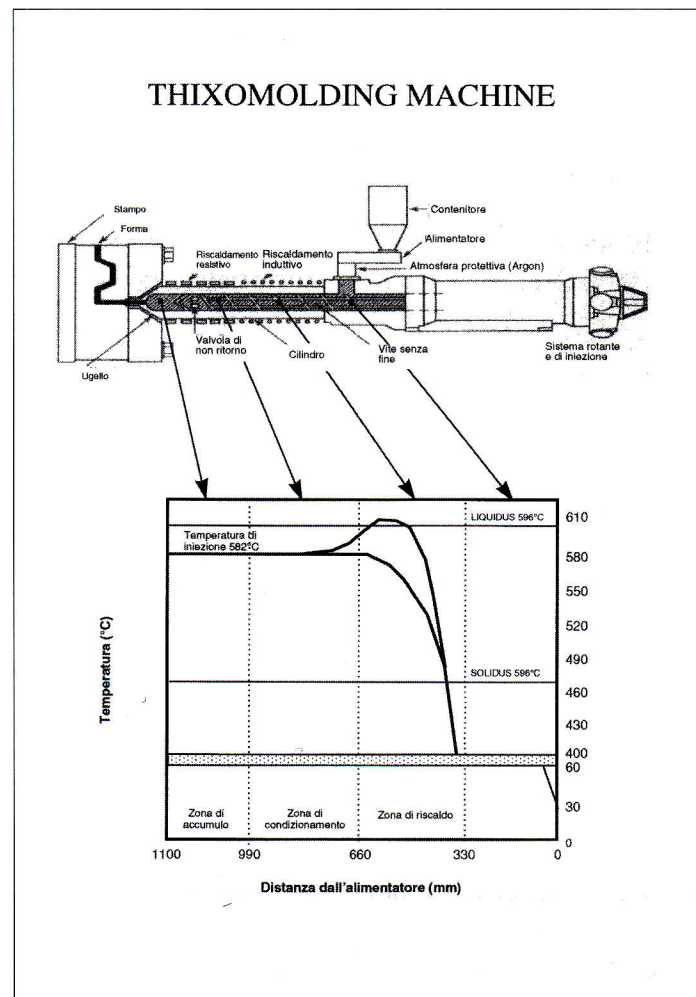


Figure 5

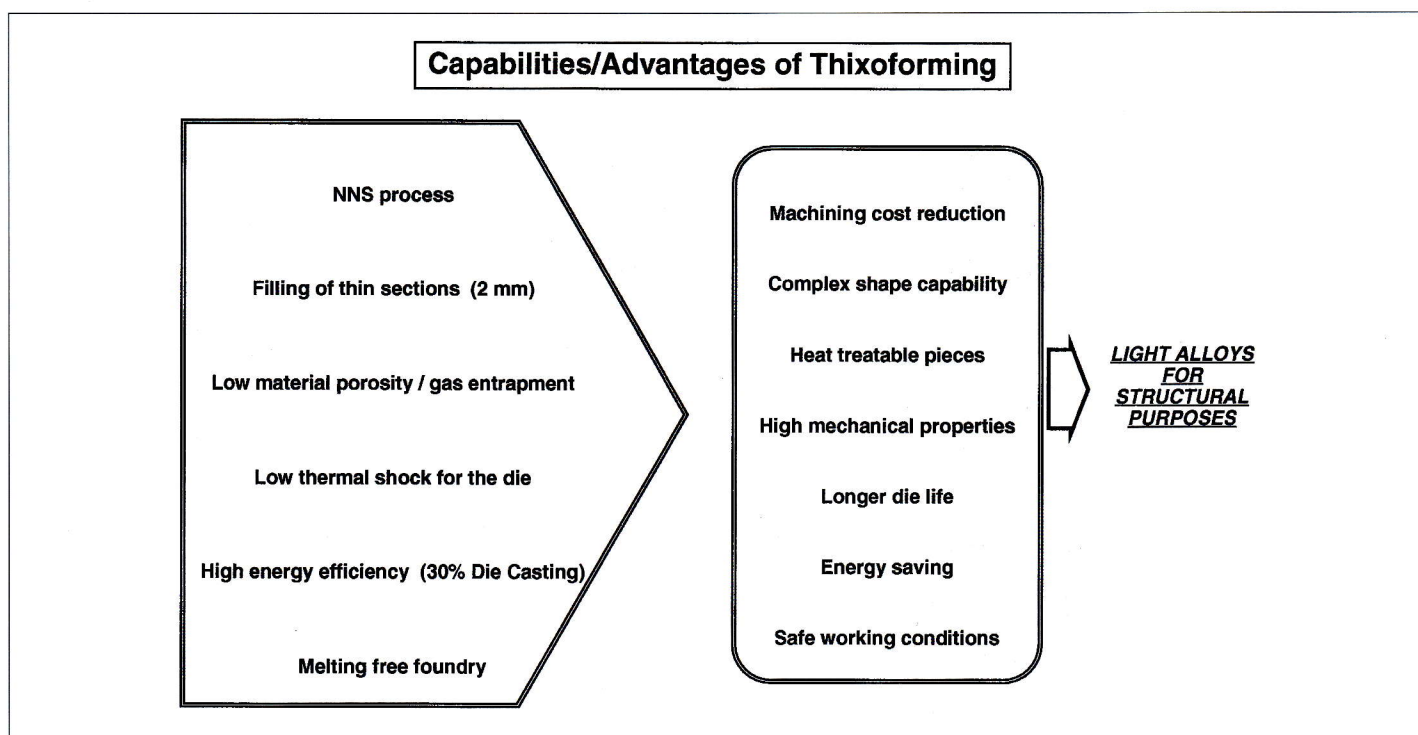


Figure 6

into the die after the stirring carried out on-line, without the steps of solidification and re-heating of the billets (Fig. 5). In this case the solid fraction of the material before the injection is less than 40%, anyway the process could be really cost effective particularly if the thixomolding machine is located close to a machining workshop. The semi-solid metal is able to fill the die with a laminar flow, preventing any gas entrapment (porosity) in the final component. Therefore, besides the high quality reachable in the as cast part, it is possible to improve the mechanical properties by heat treatment. Other big advantages are achievable by thixoforming, due also to the fact that the material is heated and injected at a temperature of about 100°C below the conventional casting temperature: energy saving, tighter part tolerances (less shrinkage in the die, less residual stress, less component distortion), less machining operations (near-net shape process), no dangerous molten metal handling etc. In Fig. 6 the process capabilities and advantages are reported. At present, thixoforming is employed in the production of aluminium alloys automotive components, even of big dimensions, whereas only some prototypes of small parts were made in magnesium alloys.

## COMPONENT DEVELOPMENT

The Fig. 7 reports the step of the methodology which has to be considered for the development of a component, starting from initial ideas and objectives. Engineering takes care of both design and industrial requirements through this methodology. The main steps are:

- Original design verification
- Process and material choice
- Design optimisation

Taking into consideration the targets (i.e. weight reduction, performances improvement, cost reduction, etc.), the component requirements are evaluated in terms of performances and costs, necessary for the following analysis. At this point in fact starts the simultaneous analysis for both process/material choice and design optimisation. The mechanical and geometrical characteristics requested by the component, point out the limits for the choice of the material and also a range of available processes. Using databases and results from experimental tests the material and its heat treatment are then definitively chosen. At the same time the capabilities and limits of different processes are evaluated for defining the most suitable one. The geometry of the component is then optimised on the base of the mechanical properties coming from the defined process, by means of FEM structural analysis. Moreover the process parameters are defined with the help of the process numerical simulation. The next step is the prototypes manufacturing and testing, taking a great care of the metallurgical aspects in order to reduce possible defects and to simulate the real production conditions. The same procedure was employed for development of magnesium alloy components like those described in Fig. 8. In this case the chosen process was the High Pressure Die Casting (HPDC), till now the only used for high volume production. In this Figure also the most used alloys are indicated. It is interesting to note that there was a strong increasing of AM alloys employment because of their toughness properties which make them suitable for safety parts even though manufactured by HPDC. Concerning thixoforming, the important aspect for the development of structural components is the evaluation of the process capabilities and obtainable mechanical properties. These aspects are at present time in an evaluation phase.

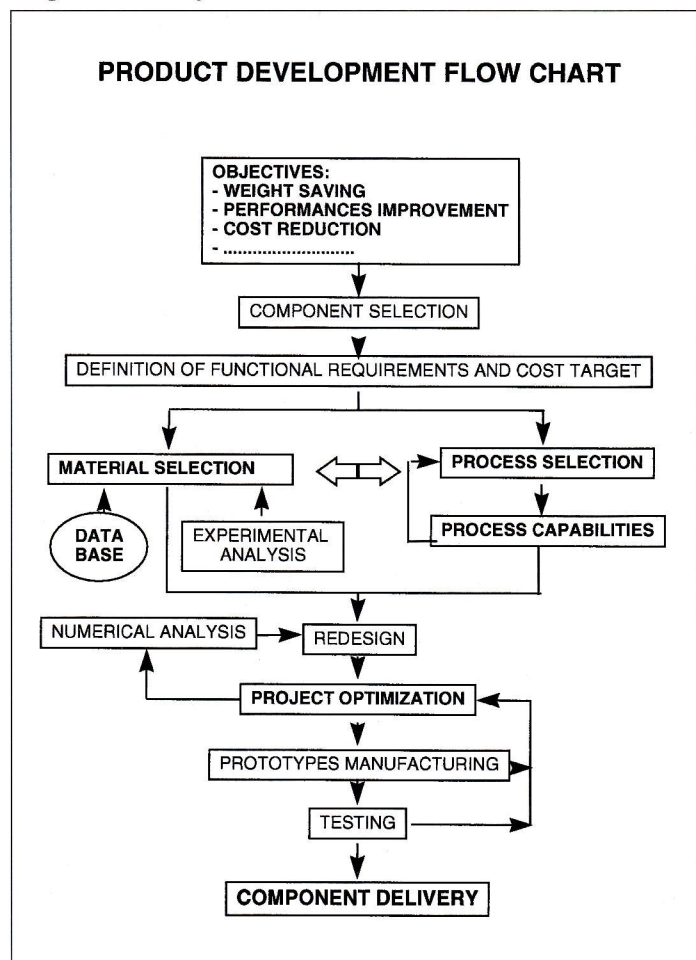
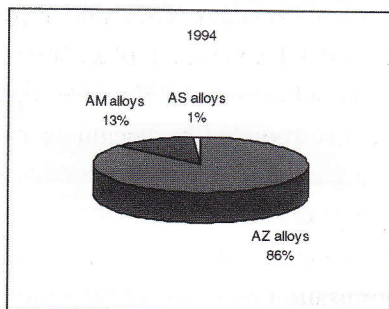


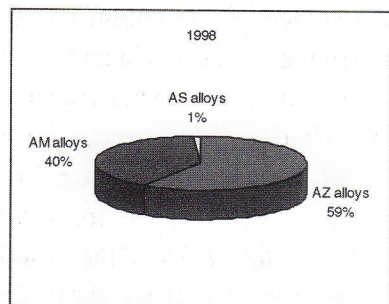
Figure 7



## Mg-ALLOYS FOR AUTOMOTIVE COMPONENTS



Trend of Mg-alloy employment, 1994-1998



Examples of Mg-alloy components

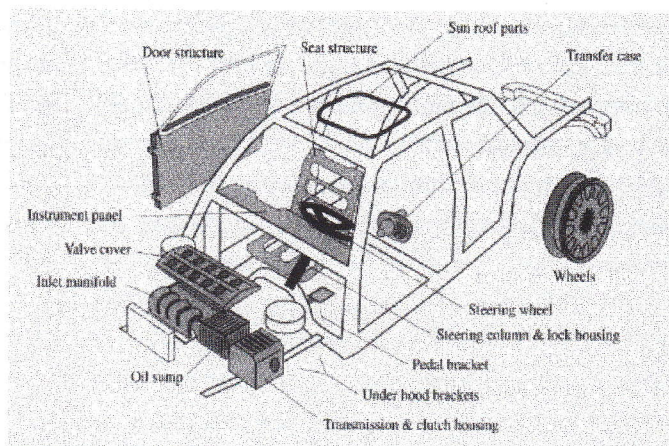


Figure 8

### GOING ON STUDIES

Some experiments were carried out aimed at evaluating the behaviour of thixoformed AZ91 alloy. The alloy was first prepared with a continuous casting machine, adding a grain refiner (carbon base and wax) in order to obtain a thin and uniformly distributed dendritic structure throughout the entire billet. The big billet was then cut in smaller parts. In Fig. 9 is reported the microstructure of the billet along its diameter in a slice cut from the middle: dendritic arms containing  $\alpha$  phase (white) and in between the eutectic containing  $\text{Mg}_{17}\text{Al}_{12}$ - $\beta$  phase (grey). The distribution of  $\alpha$  and  $\beta$  phases appears quite homogeneous, even if the dendrites are a little bigger in the centre. The cut dendritic billet was then re-heated in a 50Hz induction furnace where the micro-

Microstructure of AZ91 billet for thixocasting

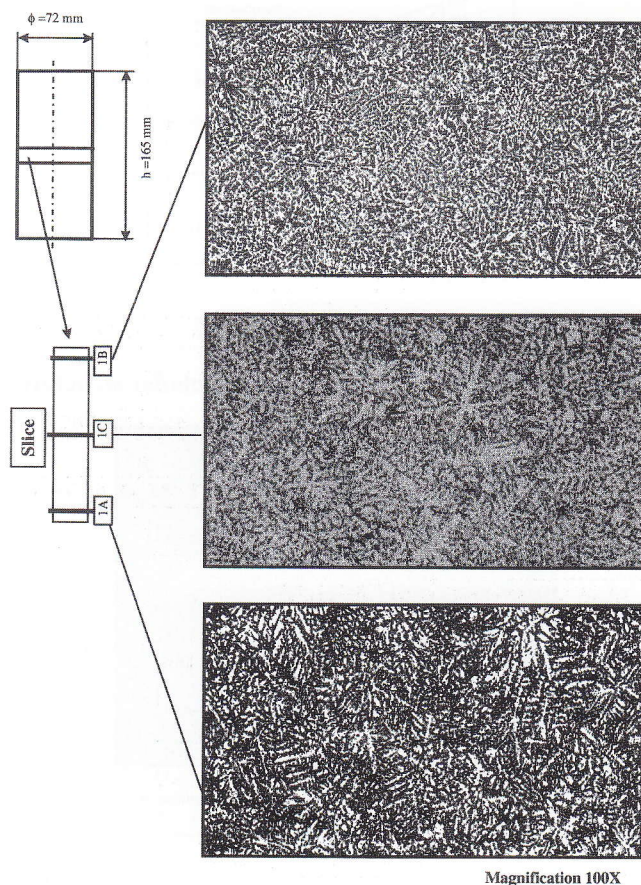


Figure 9



structure transformation occurs. During the re-heating to the semisolid state, at a temperature of 560–580°C, the dendrites spheroidize reaching a globular shape. In Fig. 10 is reported, together with the Mg–Al phase diagram, the microstructure after re-heating:  $\alpha$  globules (white) surrounded by eutectic phase (grey); some eutectic is present also inside the globules. In these conditions the billet looks like a “soften” solid. Re-heating is the critical step of the thixoforming process: the material changes its structure and at the same time reaches the thixotropic state. So that the re-heating process parameters must be very carefully controlled. Moreover, with magnesium alloy, the potential ignition problems were solved using  $\text{SF}_6$  gas and an appropriate diffusion system inside the

furnace. After the re-heating the billet was placed in the injection chamber where the piston injected it into the die. The semisolid metal flowed easily inside the die, filling the cavity. This was possible because of the thixotropic behaviour of the metal in the semisolid state due to the mentioned solid  $\alpha$ -globules surrounded by the liquid eutectic phase. The thixoforming experiments were conducted using different injection parameters; in comparison with aluminium alloy it was seen that for Magnesium alloy a higher piston speed is requested because of the lower solidification time. In Fig. 11 is reported the microstructure of a thixocast bar. The distribution of the globules appear not so regular: near the external part of the bar the  $\alpha$ -globules are finer and sur-

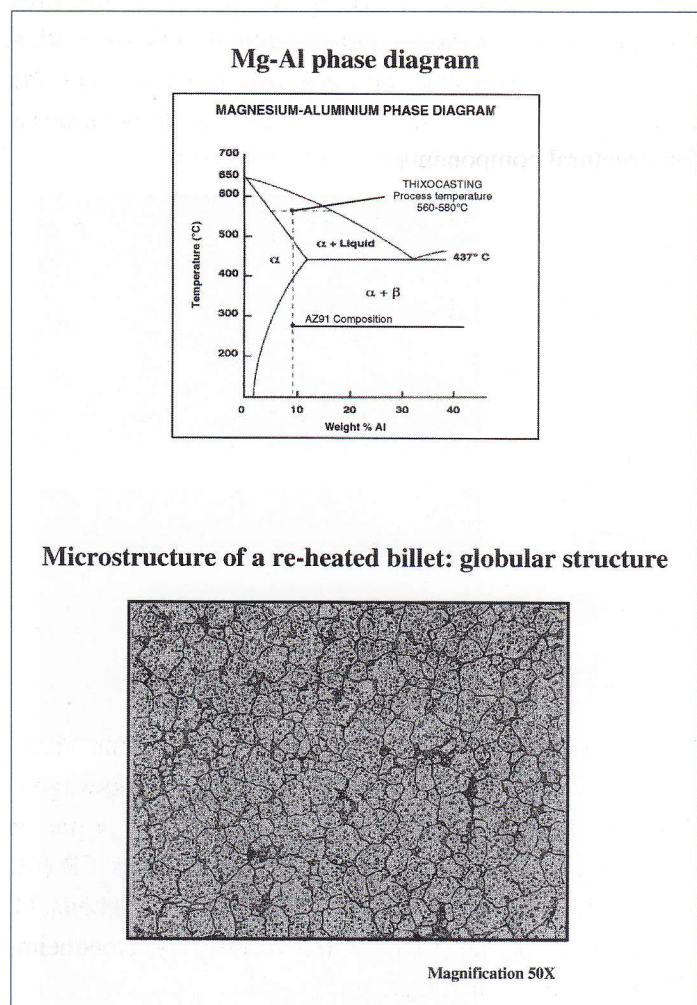


Figure 10

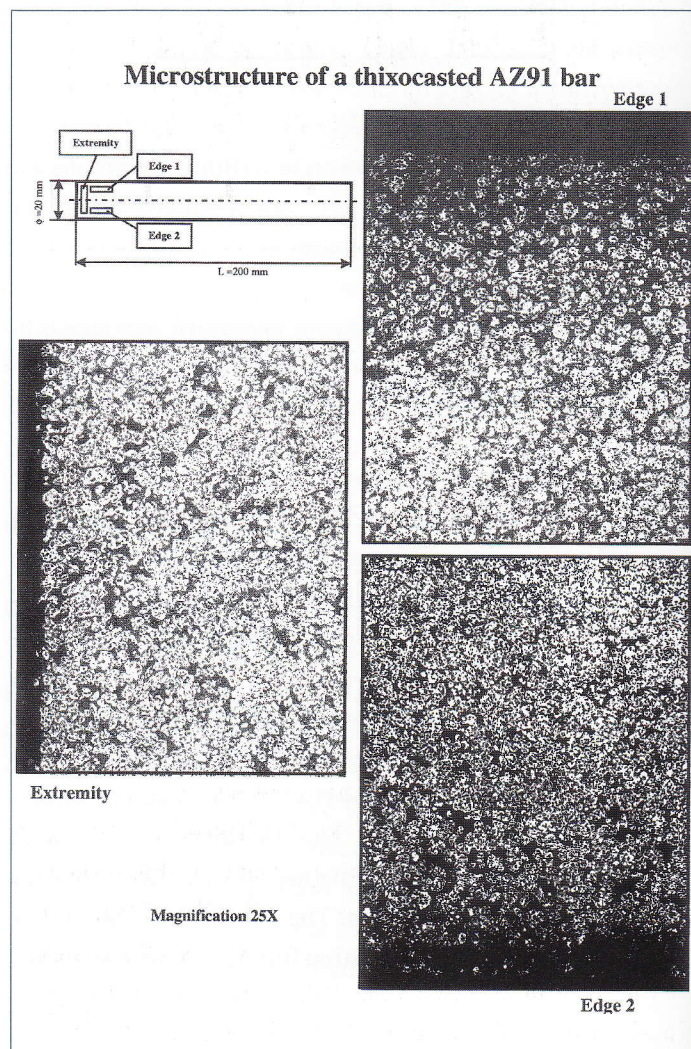


Figure 11



### Mechanical properties of thixocasted AZ91

Alloy	Heat treat.	YS [MPa]	UTS [MPa]	E	Source
AZ91	as cast	120	180	3	EFU
AZ91	as cast	115-125	220-245	5 to 7	Buhler
AZ91	as cast	100	220-250	6 to 10	Hydro Mg
AZ91	as cast	120	250	5	Thixomat
AZ91	T4	85	240	11	Buhler
AZ91	T4	110	265	10	Thixomat
AZ91	T6	160	280	5	Thixomat

### Comparison among different processes

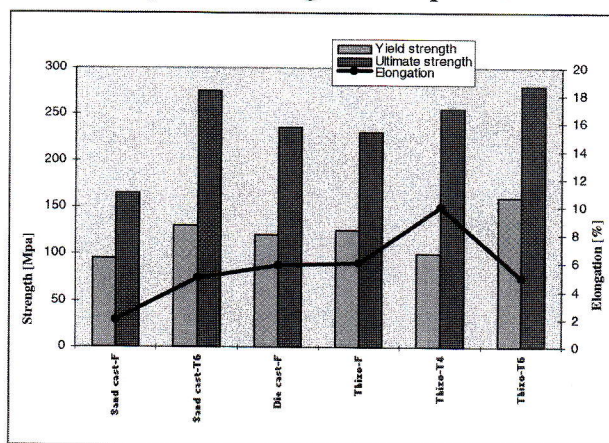


Figure 12

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rounded by an interglobular eutectic phase larger than in the central part. With the described method some bars were manufactured for the successive tests. In Fig. 12 are indicated the mechanical properties reported in the literature for thixocasting components, with and without heat treatment. In the same figure is also represented a comparison among the properties obtainable with different casting processes: the thixocasting properties are similar to the sand casting ones, but this last process does not meet the requirements for industrialization and moreover shows lower elongation values; on the contrary comparing die casting and thixocasting, the mechanical properties obtainable with the second one are clearly better, because of the possibility to heat-treat the thixocasting components. At present some static tests are on going on AZ91 bars thixocast with different process parameters, in order to meet the literature mechanical properties values. In the immediate future other thixoforming experiments changing the frequency of the inductor and the injection parameters (piston speed, final pressure inside the die, ecc.) are planned; moreover other tests (fatigue, corrosion, etc.) will be carried out with the purpose of evaluating the real exploitability of the process for structural components.

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