

# New Impulses in the Forming of Magnesium Sheet Metals\*

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## **Abstract**

*Owing to growing demands by customers for comfort and safety in cars, the weight of the respective individual automobile increases constantly. Hence, the role of construction materials, such as aluminium and magnesium alloys in car body production becomes ever more important. Especially magnesium is highly attractive because of its small density, its positive mechanic-technological properties, and the ready availability as raw material.*

*It is known that magnesium has a reduced formability at room temperature and needs to be heated up to temperatures at around 300°C to be deformable with technologically useful forming rates. So therefore to form sheets made of magnesium alloys, the workpiece has to be heated previously. The idea of combining the processes “inductive heating” and “pulsed magnetic forming” led to the following research work. The aim was to develop a tool that combines both processes to be able to heat up the forming zone at the workpiece to a significant temperature and to form it afterwards without changing the tool.*

*However, in order to manufacture sheet metal components from magnesium innovative manufacturing technologies are necessary. The Institute for Machine Tools and Factory Management (IWF) carries out research and develops solutions in the field of pulsed magnetic forming.*

## **Keywords:**

Forming, Magnesium, Electrical Discharge Machining (EDM)

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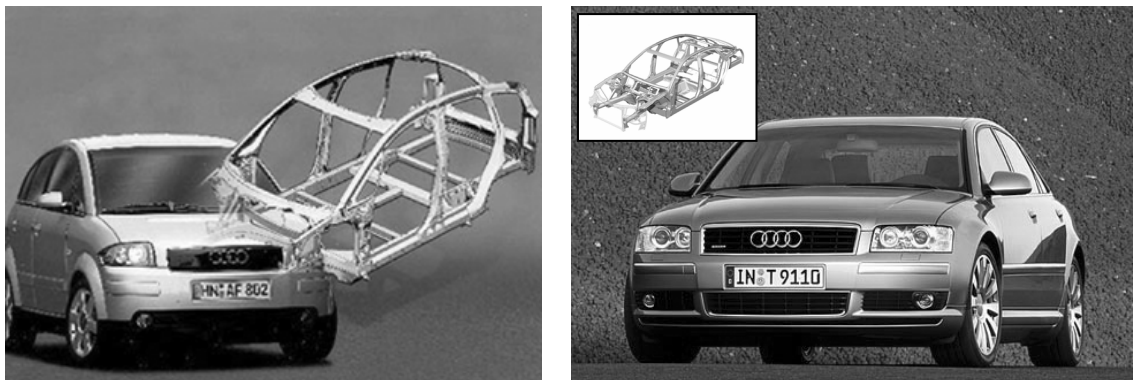
*\*This work is based on the results of the research project “Pulsed Magnetic Flat Forming of Magnesium Sheets by Increased Forming Temperatures”; the authors would like to thank the DFG for their financial support*

## 1 Introduction

The objective to reduce moved masses has led to the reinforced development of light metal alloys. Considering the limited amount of natural resources, growing environmental pollution, the necessity of energy saving, and the resulting ever stricter legal regulations, recyclable lightweight design materials are gaining increasing importance. Additionally, technology-oriented companies place ever more focus on the technological and economic potential of innovative materials. Therefore, it is especially in the vehicle industry that the tendency to novel concepts and solutions for weight reduction continues to be very significant despite the existing innovations in terms of constructive design and the increasing use of lightweight design materials.

As far as the fuel consumption of automobiles is concerned, the factors power, train, and vehicle mass play the most important role alongside the influencing parameters rolling and air drag. Since these values are very difficult to realise and have only a light effect on the consumption value in the case of the first three factors, the main focus is placed on further development work in reducing the vehicle mass. In the field of the drive train, the chassis, and a number of other functional components, the idea of lightweight design has consistently been realised using cast products on aluminum and magnesium basis. Therefore, a further potential of weight economy might be the car body shell [1].

At present, aluminum of a density of approx.  $2,7 \text{ g/cm}^3$  is the most frequently used functional metal in the production industry after steel with a density of approx.  $7,8 \text{ g/cm}^3$ . Recent developments, such as car bodies made completely of aluminum, show that the ratio of lightweight design materials is clearly increasing in the automotive industry. Hereby, the basis is either a tubular grid frame, the so-called space frame, Figure 1, or an aluminum car body in the conventional self-supporting design, Figure 2.



**Figure 1:** Audi Space Frame® (ASF) in Audi A2 and Audi A8 [2]



**Figure 2:** Self-supporting aluminum car body in Jaguar XJ [3]

## 2 Potentials of Magnesium Alloys

### 2.1 Technological and Economic Significance of Magnesium Alloys

With its specific mass of  $1,8 \text{ g/cm}^3$ , magnesium is lighter by approx. 30 percent than aluminum, thus being the lightest metallic design material. Due to the high mass-specific solidity and rigidity characteristics, especially under bending and buckling stress, it has some weight advantages in the component of up to 60 and 25 percent, respectively, if compared to steel and aluminum [4]. Alongside their small density, the main advantages of magnesium alloys are good availability and good mechanical properties. Moreover, the excellent recycling potential of magnesium alloys entails an economical energy balance using comprehensive recycling systems. In comparison to the primary winning of aluminum requiring approx.  $67,5 \text{ kWh/dm}^3$  energy, magnesium shows a favorable energy demand of  $63,0 \text{ kWh/dm}^3$ . If magnesium is recycled in the secondary way from magnesium scrap of the quality class 1 the balance can be further improved. Hereby, only five percent of the energy, used for the primary winning, are required [5].

Despite these advantages, magnesium alloys stay far behind other lightweight design materials in terms of their dissemination. The reasons are the unsatisfactory corrosion resistance of magnesium alloys, reservations in terms of the hazard potential, and the lack of suitable process technologies for the forming of magnesium sheets. It was not until the manufacture of “high purity” (hp) magnesium alloys with small percentages of iron, copper, and nickel, that the corrosion resistance was considerably improved, enabling magnesium alloys to keep up with aluminum materials in this aspect, too [6].

Recent market analyses assume a growing European market for magnesium alloys of two-digit growth rates [7]. Within the period of 1990 to 1998, the consumption of magnesium in the automotive industry thus grew from 23.000 to more than 90.000 tons per year with an average growth rate of 20 percent. Today, cars usually contain around 3 kg of magnesium. Single cars of leading European producers, however, contain 5 to 7 times more. According to a US study, some automobile producers will use as much as 100 kg magnesium in their cars adhering to the objective to reduce the total weight of cars by 10 percent. This may suggest the growth potential to be expected for this material considering a world-wide production of 55 million cars per year [8].

Today, components from magnesium alloys are mainly produced by die casting, Figure 3.



**Figure 3:** Inner door made from AM50 die cast (the newest VW Polo) [9]

The production of components with large surfaces and, at the same time, thin walls is, however, limited by the required locking pressures and by the fluctuation of the material properties [10]. In order to avoid the disadvantages of die casting, sheet metal components of magnesium forgeable alloy should be produced by forming processes in the future. In contrast to primary forming, forming enables a homogeneous, fine-crystal material structure which has very few faults. In contrast to magnesium sheet components manufactured by die casting, the resulting advantages of those manufactured by forming are the higher elongation at fracture making them more suitable for the security field, small wall thicknesses to be realised in large car body components, and their higher potential of application for visible areas of the car body shell due to their smooth surface structure.

## **2.2 The Basis of the Forming of Magnesium forgeable Alloys**

There are only a few recent investigations known on the machining of magnesium forgeable alloys by sheet forming processes. A crucial influencing parameter of the forming of magnesium forgeable alloys is the forming temperature.

Due to its hexagonal grid structure, magnesium is highly formable at ambient temperature. Investigations on the influence of temperature on the forming capacity, however, show that the form changing capacity of magnesium alloys jumps up at temperatures of  $T = 225^{\circ}\text{C}$  [11], as further gliding planes are activated in this way.

For the above-mentioned reasons, nearly only tempered deep drawing tools are used for magnesium sheet forming. Through the variation of alloys, recent research projects are searching for possibilities to reduce the considerable cost factor. It is, however, rather questionable if the heating up of at least one of the tools (die or matrix) can be completely avoided for alloy systems ready for serial production [12].

## **2.3 Challenges to the Forming of Magnesium Alloys by Conventional Forming Processes**

Independently of the fact whether the magnesium sheet is heated up externally, i. e. outside the forming tool or within it, the tempering of the forming tool cannot be avoided in any of the forming processes. This, however, implies some difficulties because the uneven heating up of the machine leads to a reduction of the guide clearance of the machine

tappet making it jam [5]. In order to avoid these negative effects, the tool must be completely thermally de-coupled from the machine by insulation layers and cooling elements.

Such a thermal de-coupling proves to be very complicated in practice. Additionally, investigations have shown that the heat transfer as a result of convection must also be considered for thermal de-coupling despite the use of heat insulating plates for the reduction of heat conduction between tool and forming machine [5].

### 3 Potentials of the Pulsed Magnetic Flat Hot Forming for the Lightweight Design

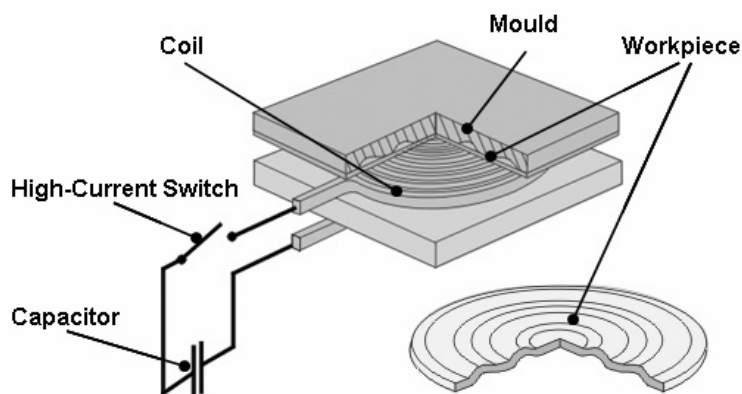
Due to the difficulties in the heating of the forming tools occurring during conventional forming processes, the goal of a topical research project promoted by the Deutsche Forschungsgemeinschaft (DFG) is to realise new possibilities for the forming of magnesium fine sheets. Hereby, impulse magnetic hot flat forming is an interesting possibility to consistently harness the potentials of this ultra light material.

#### 3.1 The Process of Pulsed Magnetic Hot Flat Forming

Pulsed magnetic forming (PMF) is a non-contact technique where large forces can be imparted to a conductive metallic workpiece by a pure electromagnetic interaction. A significant amount of energy is stored in a bank of capacitors by charging to a high voltage. The charge is switched over low inductance conductive buswork through a coil acting as a tool so that large currents run through the coil.

The currents take the form of a damped sine wave and can be understood as a ringing Inductance-Resistance-Capacitance (LRC) circuit. The peak current is typically about 10<sup>4</sup> to 10<sup>6</sup> amperes and the time to peak current is on the orders of tens of microseconds. This creates an extremely strong transient magnetic field in the vicinity of the coil which induces eddy currents in any conductive material nearby.

These currents will generally be opposite in direction to the primary current. So the opposed fields in the coil and workpiece set up an electromagnetic repulsion between the coil and the workpiece. This electromagnetic force can produce stresses in the workpiece that are several times larger than the material flow stress. Ultimately, this can cause the workpiece to deform plastically and to be accelerated at velocities exceeding 100 m/s [13]. The process of pulsed magnetic forming for metal sheets is shown in Figure 4.



*Figure 4: Tool and workpiece by pulsed magnetic flat forming*

The small strain rate achievable on magnesium alloys in cold state is problematical for the application of the process for the pulsed magnetic flat forming. However, it is known from sheet metal forming that magnesium alloys can be deformed at temperatures of approximate 250°C to 300°C to sufficient strain rates [5].

A suitable solution for pre-heating the workpiece is to use inductive heating (IH), because the physical principles of both processes, inductive heating and pulsed magnetic forming, are close to each other. A combination of both processes was described for the first time in a patent from 1962, but it is unknown if it ever has been realised or investigated in a scientific way [14].

### **3.2 Former Investigations in Pulsed Magnetic Hot Forming of Magnesium Alloys**

In the former USSR, basic investigations were done to form sheet metals and profiles with pulsed magnetic forming at high temperatures. The workpieces were previously heated up in an oven. This was tested at alloys of copper, steel, and magnesium. Especially for the investigated magnesium alloys, the results demonstrated a clearly increase of the formability at temperatures of 200°C to 250°C [15,16].

Other systematical experiments were carried out in Germany at the Technical University of Berlin. In this case, a tool which combines the processes of pulsed magnetic forming and inductive heating for thermally-supported-joining of magnesium profiles was developed [17].

The investigations on thermally-supported-joining were carried out at a tube-core-joint. Here, a tube consisting of the technically relevant magnesium alloy AZ31 was compressed to an aluminium-core by using the combined compression-coil. The results of the investigations for pulsed magnetic hot joining showed that there is a distinctive potential for forming of magnesium alloys.

Joining by forming became possible for this material through pulsed magnetic hot forming. Those investigations proved that magnesium can be used in future lightweight designs not only in casted parts, but also in formed components like compressed tube-profiles [17].

## **4 Tool Principle and Developments**

To utilise the potentials of the pulsed magnetic hot flat forming to turn magnesium sheets, it was necessary to develop an adequate tool which integrates the process of pulsed magnetic forming on the one hand and the inductive heating on the other hand.

### **4.1 Basic Reflections**

The main problem was posed by the design layout of such a tool. Usually, coils used for both processes have to live up to completely different requirements in electro-technical, thermal, and mechanical terms. While in the case of a coil for pulsed magnetic forming, the mechanical stability is more important than its thermal stability. However, a coil for inductive heating has to be strongly cooled and is subject to only small mechanical strain [18].

Moreover, the requirements on both coils concerning the number of turns are very different to each other and can be changed only in narrow limits. For that reason it is not possible to use only one coil for the application of the two processes.

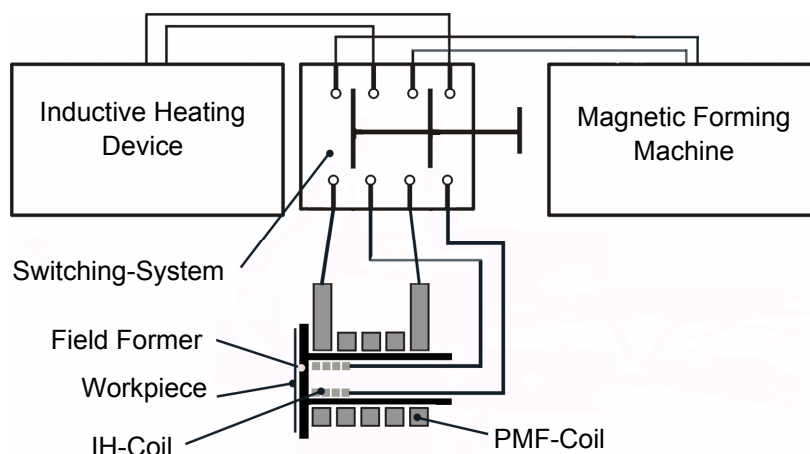
For the combination of both processes, it was necessary to develop a tool in which two separate coils focus on the same area of the workpiece. To realise this demand, it was inevitable to integrate a field former in the tool. Field formers are often used in pulsed magnetic forming, especially for compression. But also simply for the flat forming they have a lot of advantages:

- reduction of the process forces on the PMF-coil,
- possibility to integrate cooling channels in the field former,
- low-cost replacement,
- low-wear tool surface, and
- possibility to adjust the distribution of the magnetic pressure by changing the field former geometry.

Above all, the last reason to use field formers is the most important for the process of pulsed magnetic flat forming. That is why, because in the center of a directly working PMF-coil there is no magnetic pressure at all. A radial vectored force acts on each volume element of the workpiece and the coil if the orientation of the current density in the workpiece and the magnetic field between workpiece and coil are both at the same time, vertical and in parallel levels to each other. There are no conditions like this in the center of the coil.

#### 4.2 Realisation of the tool conception

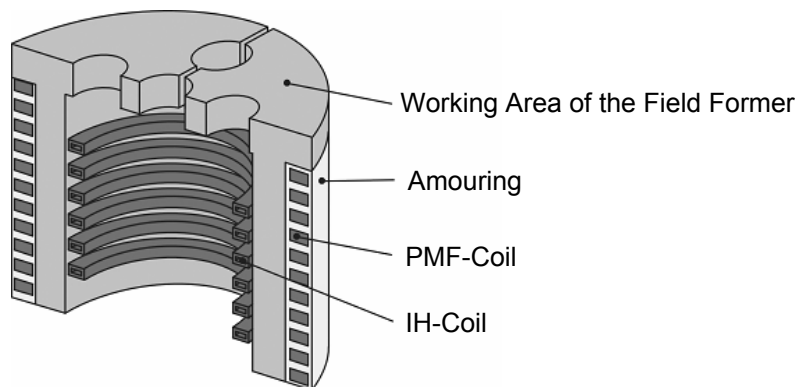
Figure 5 shows the principle of the combination of both processes “inductive heating” and “pulsed magnetic flat forming”.



**Figure 5:** Principle of process combination IH and PMF

In this case, the coil for IH is situated at the inside of the field former, while the PMF-coil is placed at the outer circumference of the field former, Figure 6. Both processes act on the

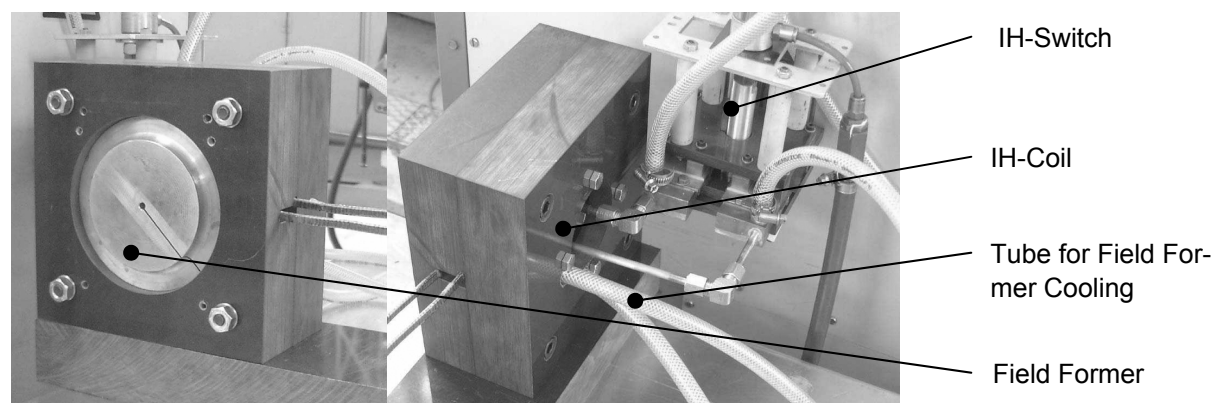
same area of the workpiece without changing the tool or movement. The coil for inductive heating and the field former are water-cooled, thus contributing to the cooling of the PMF-coil. The most important reason for using a cylindrical PMF-coil instead of a spiral one is the enhanced possibility to integrate the armouring to increase the mechanical strength of this coil.



**Figure 6:** Design of the combined tool

This so-called combined coil was manufactured at the IWF and has already been successfully tested. The working area has a diameter of 96 mm. The IH-coil is fitted with five windings and the coil for pulsed magnetic forming has eight windings and an inner diameter of 110 mm.

Both coils are connected to the induction heating device and the magnetic forming machine via appropriate switches, which provide that the coil of the non-active process is electrically separated from its device. Figure 7 shows the experimental setup for the thermally supported pulsed magnetic flat forming.



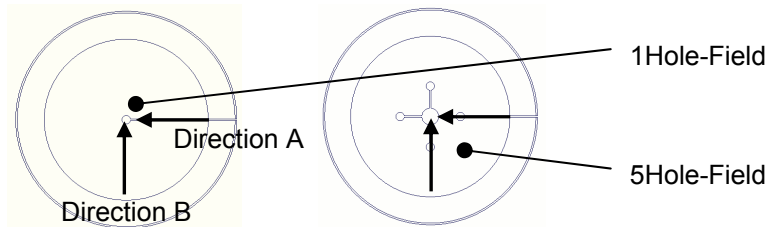
**Figure 7:** Experimental setup with combined coil and peripheral equipment

The investigations were carried out on magnesium sheets AZ31 with the measurements of 100 mm x 100 mm and a thickness of 1,0 mm. The first investigations were focused on the influence of the work area geometry of the field former on the temperature spreading in the workpiece during the heating process. Another object of investigation could be found in the connection of the field former geometry and the absolute and relative magnetic pressure within reach.



## 5 Results

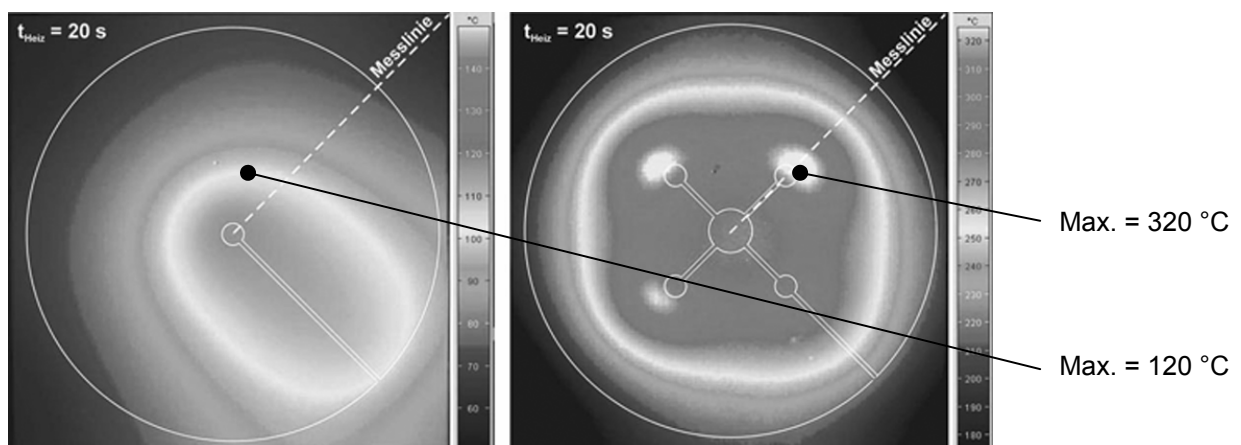
In order to ascertain the possible temperature and the magnetic pressure, the investigations were carried out with two different field former geometries. They are called the 1Hole-Field former and the 5Hole-Field former, Figure 8.



**Figure 8:** Used field former geometries

### 5.1 Results for the process of the inductive heating

For the two different geometries, there are different temperature maximums after a heating time of 20 s, Figure 9. There are differences up to 200°C.



**Figure 9:** Maximum and spreading of the heating temperature after 20 s heating

So it is possible to carry out the process in a more efficient way by varying the geometry of the working area which is close to the workpiece. A first investigation shows that the number and the spot of the holes on the working area have a big influence on the efficiency of the process of inductive heating.

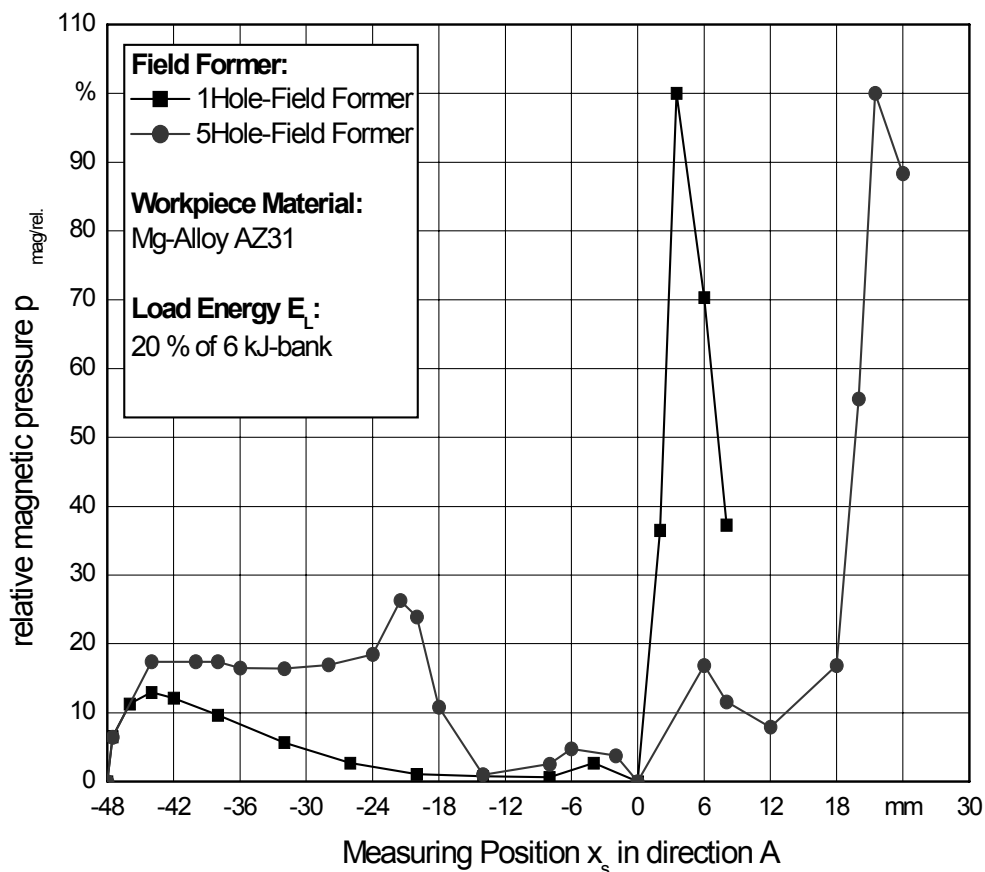
### 5.2 Results for the magnetic pressure within reach

For the magnetic pressure within reach, and thus for the maximum forming force, there also exists a connection between the number and the spot of the holes on the working area and the magnetic pressure. In the margin of the holes there are always the maximums of the magnetic pressure, Figure 10 and 11.

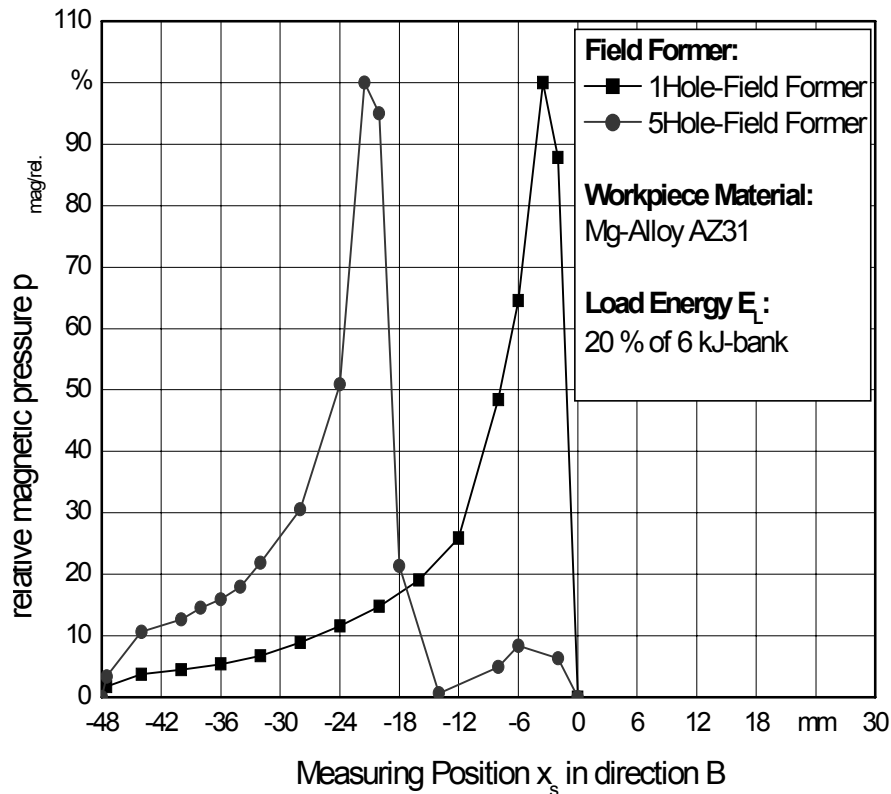
The measurements were done in two directions on the field former working area. The first measuring direction, the so-called “direction A”, was from the outer margin of the working area (-48 mm) along the field former slit to the center of the field former (0 mm) and be-

yond. Vertical to this orientation, the relative magnetic pressure in “direction B” was measured. Because of the symmetry of the working area in this direction it was only necessary to measure the pressure from the margin of the field former to the center of it, Figure 11.

It is evident that the maximums of the magnetic pressure are situated in both cases at the margin of the holes which are turned away from the slit. The reason for this can be found in high magnetic flow density at this point. At this point, the magnetic field is especially high, because the lines of electric flux get out of the small holes in the working area of the field former. There, they have to change their directions in a rectangular way, because the magnesium sheet acts like a shield. So a very high magnetic field between the workpiece and the field former working area gets a vertical orientation to the current density in the workpiece within a short way. This causes a maximum radial vectored force in this point.

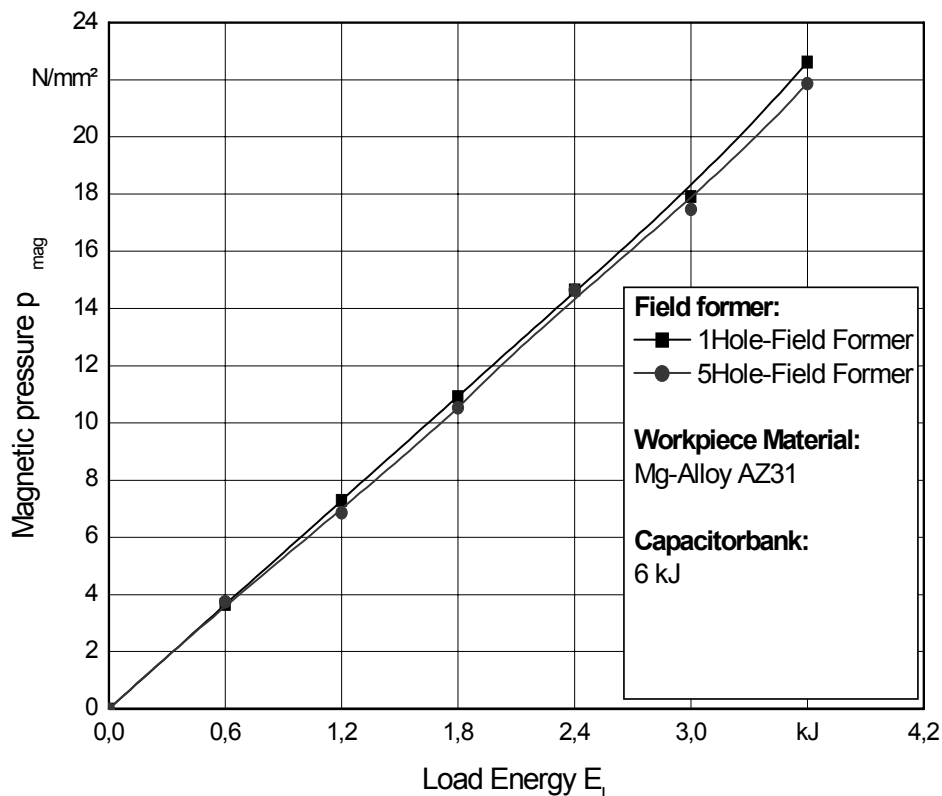


**Figure 10:** Relative magnetic pressure in dependence on the working area geometry, Measuring direction A



**Figure 11:** Relative magnetic pressure in dependence on the working area geometry, Measuring direction B

Further object of investigation was the finding of the absolute magnetic pressure in dependence on the load energy at one point on the working area of the field former. This point could be found during the measuring of the relative magnetic pressure. To compare the values of the 1Hole-Field former and the 5Hole-Field former, it was necessary to measure the absolute magnetic pressure at the point of the relative maximum. Figure 12 shows that the absolute magnetic pressure increases almost linear to the increase of the used load energy.



**Figure 12:** Absolute magnetic pressure in dependence on the load energy, measuring point is the point of the maximum pressure within reach

For both field formers the absolute magnetic pressure is almost identical by using the same load energy. This is important for future investigations. So it will be possible to generate an even spreading of magnetic pressure all over the working area of the field former by arranging the holes in the working area in a certain kind of way.

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