Weight Savings by Aluminum Metal Foams: Production, Properties and Applications in Automotive

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Abstract

Aluminum metal foams are a newly developed ultra-light weight material with the ability to count for tremendous weight savings, especially in automotive applications. The P/M foaming process allows the production of two different types of components: complex shaped parts and metal foam sandwich panels. Foaming inside a mold can produce complex net-shaped parts. Examples are inserts for bumpers, pillars, or others. The metal foam sandwich process has the main advantage of enabling not only flat panels, but also true 3-dimensional shapes by e.g. deep drawing or other forming processes prior to the foaming. Valuable properties of metal foams for automotive applications are the crush energy absorption behavior and the high stiffness. The presentation reviews the properties of metal foams with respect to automotive applications.

Introduction

Applications of cellulare materials range from lightweight construction and packaging, to thermal insulation, vibration damping, and chemical filtration. Metal foams enlarge the application range of cellular materials because of their excellent physical and mechanical properties, as well as their relative amenability to recycling compared to polymeric foams. Although metal foams can be fabricated in different ways [1], considerable efforts have been made to obtain good foam structure.

A powder method for fabricating metal foams was invented at the Fraunhofer Institute for Applied Materials Research in Bremen, Germany [2]. This method allows for low cost and direct net-shaped fabrication of foamed parts with a relatively homogeneous pore structure. Using the powder metallurgical production method, it is now possible to obtain metallic foams of various metals and alloys with complex geometry. Sandwich structures composed of a porous metallic foam core and metallic face sheets can also be produced. Metallic foams fabricated by this approach exhibit a closed-cell microstructure with higher mechanical strength than open-cell foams. This type of microstructure is particularly attractive for applications requiring reduced weight and energy absorption capabilities.

Manufacturing of Metal Foams with the P/M Method

The process starts with mixing metal powders (either pre-alloyed metal powders or blends of elementary powders) with a small amount of foaming agent (if metal hydrides are used, a content of less than 1% is sufficient in most cases). After the foaming agent is uniformly distributed within the matrix powders, the mixture is compacted to yield a dense, semi-finished product without any residual open porosity (Figure 1). Typical examples of such compaction methods include uniaxial pressing, extrusion and powder rolling. Further shaping of the foamable material can be achieved through subsequent metalworking processes such as rolling, swaging or extrusion. Examples of the semi-finished products include billets, plates, and rods.

Following the metalworking steps, the foamable material is heated to temperatures near the melting point of the matrix material. During heating, the foaming agent decomposes, and the released gas forces the densified material to expand into a highly porous structure. The density of the metal foams can be controlled by adjusting the content of the foaming agent and several other foaming parameters, such as temperature and heating rate.

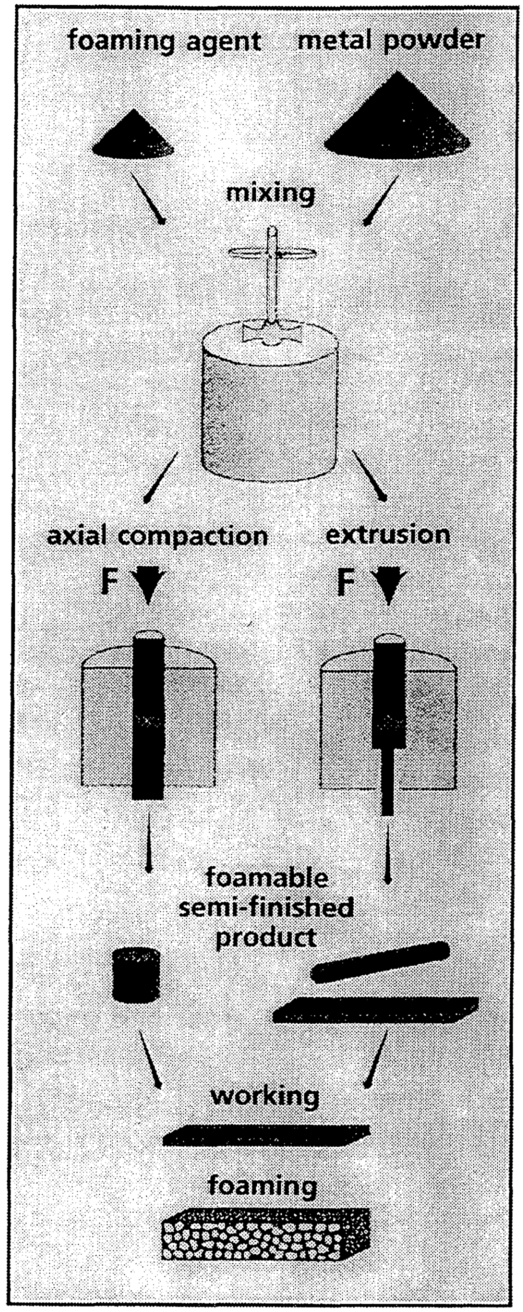

Figure 1: Powder metallurgical production method of metal foams

The most commonly used aluminum alloys for foaming are pure aluminum, 2xxx alloys, and 6xxx alloys. The P/M approach as developed by Fraunhofer, however, can also be used for other metals including tin, zinc, brass, bronze and steel. Different alloys can be foamed by selecting appropriate foaming agents and process parameters. For example, metallic carbonates and nitrides were proven effective foaming agents for some steel alloys [3]. Figure 2 shows the optical micrograph of typical aluminum foam. This type of cell structure is responsible for the high specific stiffness-to-weight ratio (SWR) of the foam. During deformation, localized cell collapse and rapid compaction energy dissipation provide the energy absorption capability in the material.

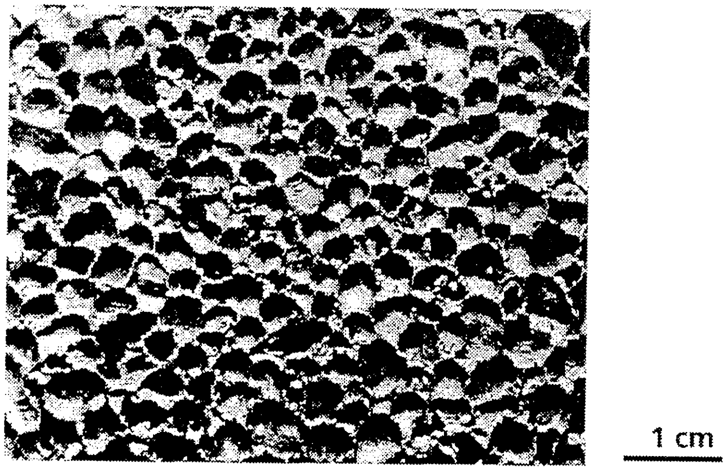

Figure 2: Typical aluminum foam microstructure.

Near-net-shaped foaming

Inserting the foamable material into a hollow mold and expanding it with heating can be used to manufacture complex-shaped metal foam parts. Figure 3 shows a near-net-shaped part prepared this way.

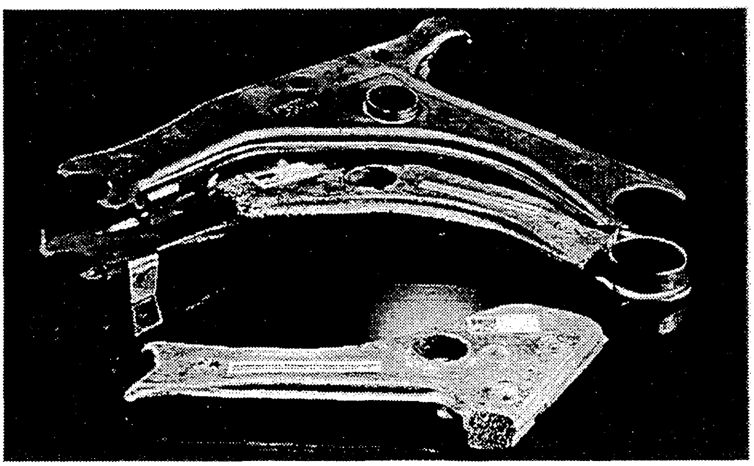

Figure 3: A shaped part made by filling a hollow steel mold with aluminum foam.

Sandwich panels consisting of a foamed metal core and face sheets can also be fabricated by gluing the face sheets onto a foam core. If pure metallic bonding is required, face sheets and foamable material can be roll-clad to make a sandwich structure before foaming. Figure 4 shows a pre-cursor sandwich panel before foaming and a metal foam sandwich panel after being deep drawed and foamed.

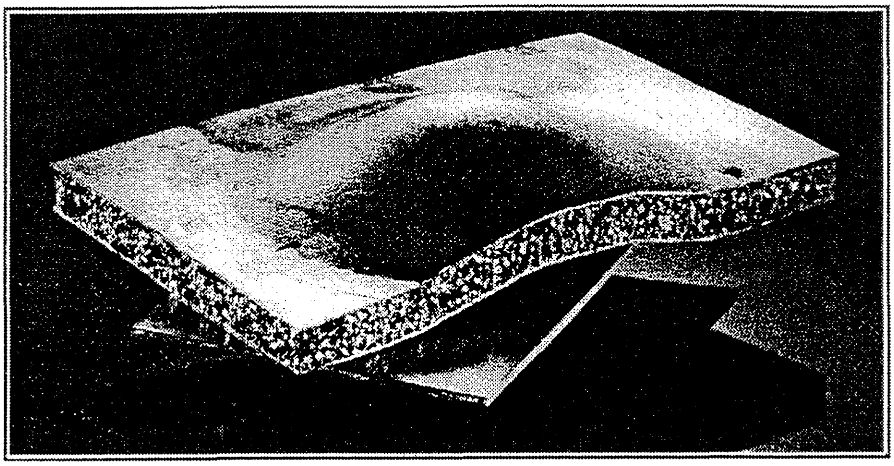

Figure 4: Metal foam sandwich before and after foaming

Deformation energy absorption

A typical loading curve of metal foams can be exemplified in several stages as shown in Figure 5: initial, almost linear deformation, plastic collapse and final densification. It can be seen from the comparison between the stress-strain curve of aluminum (AlCu4) foam (initial fractional porosity 83%) and the corresponding curve of a polyethylene (PE) foam (initial fractional porosity 87%), that the two loading curves are similar. However, the stress amplitude of the AlCu4 foam was approximately 30 times higher than that of the PE foam.

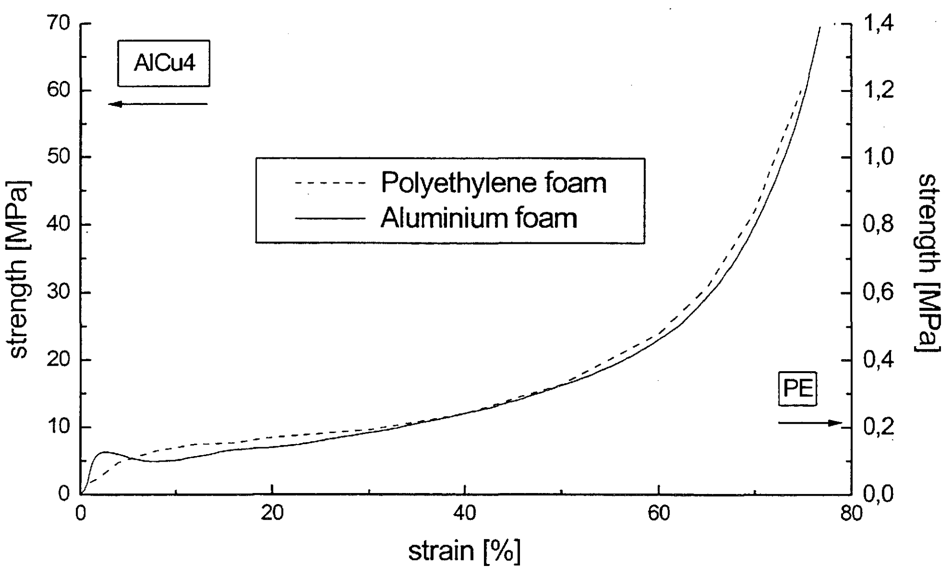

Figure 5: Loading curves of aluminum and polyethylene foams.

Because of the special form of the compressive stress-strain curve, foamed materials are capable of absorbing large amounts of energy at a relatively low stress level. Metal foams undergo plastic deformation with a typical yielding. A plastic yielding follows an initial elastic deformation.
Figure 6 shows the compression strength as a function of aluminum foam density. In the log-log plot a relatively linear relationship (with a slope of approximately 1.7) was observed. It is noted that the elastic portion of the stress-strain curve is only partially reversible. During loading, small scale localized plastic deformation has already taken place within the sample. This is also the reason that the mechanical testing of the elastic moduli can be difficult to analyze. Furthermore, these small-scale plastic deformations also contribute to the mechanical damping of metal foams.

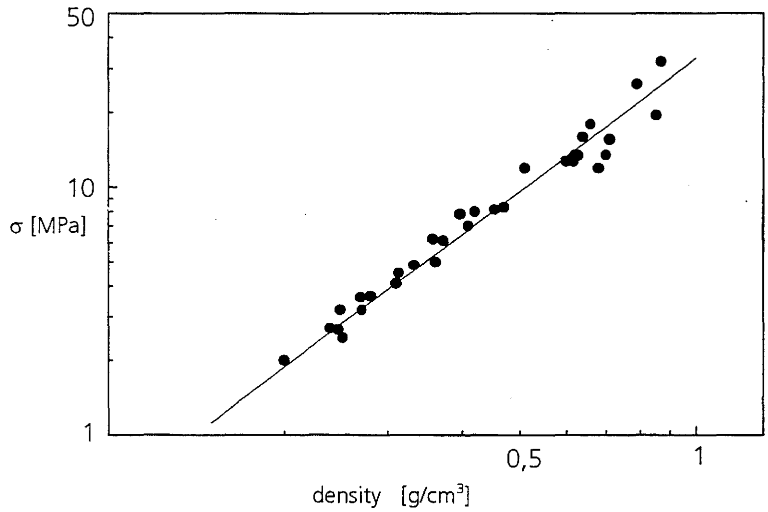

Figure 6: Compression strength of a series of AlSi12 foams.

It can be determined from Figure 7 that a higher foam density presents a higher stress level. Moreover, the addition of an alloying element such as Mg to the Al matrix can improve the strength of the foam significantly. It can also be shown [5] that a heat treatment of the foam improves its strength provided that the matrix alloy is age-hardenable.

Applications in energy absorption systems offer a great potential for the use of metal foams. Obviously, the foam can absorb much more energy at a given peak stress level than the dense solid (at a given strain level the dense solid naturally absorbs more energy but this situation does not represent a realistic condition). The capability for keeping the peak stress down while absorbing kinetic energy makes foams in general an excellent energy absorber. Metal foams in particular exhibit a comparably high strength and therefore absorb a high amount of energy efficiently.

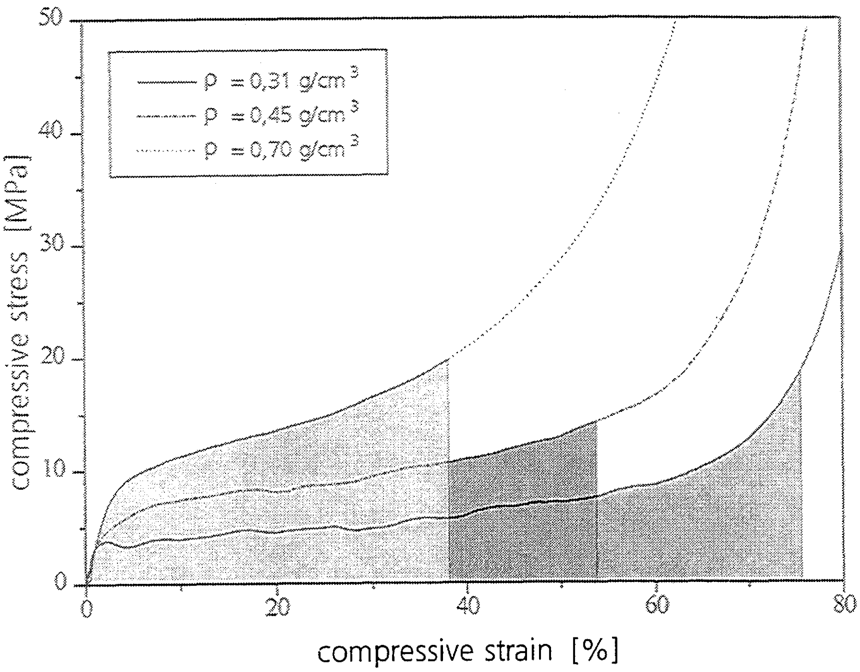

Fig. 7: Loading curves of three Al foams

Figure 7 shows the experimental test data on Al foams with three density levels: 0.31 g/cm3 (12% fractional density), 0.45 g/cm3 (17% fractional density) and 0.70 g/cm3 (26% fractional density). The shaded areas represent the same amount of energy. One sees the foam in the medium density range absorbing the given amount of energy at the lowest stress level. Thus, for a given energy absorption task the proper foam density has to be selected.

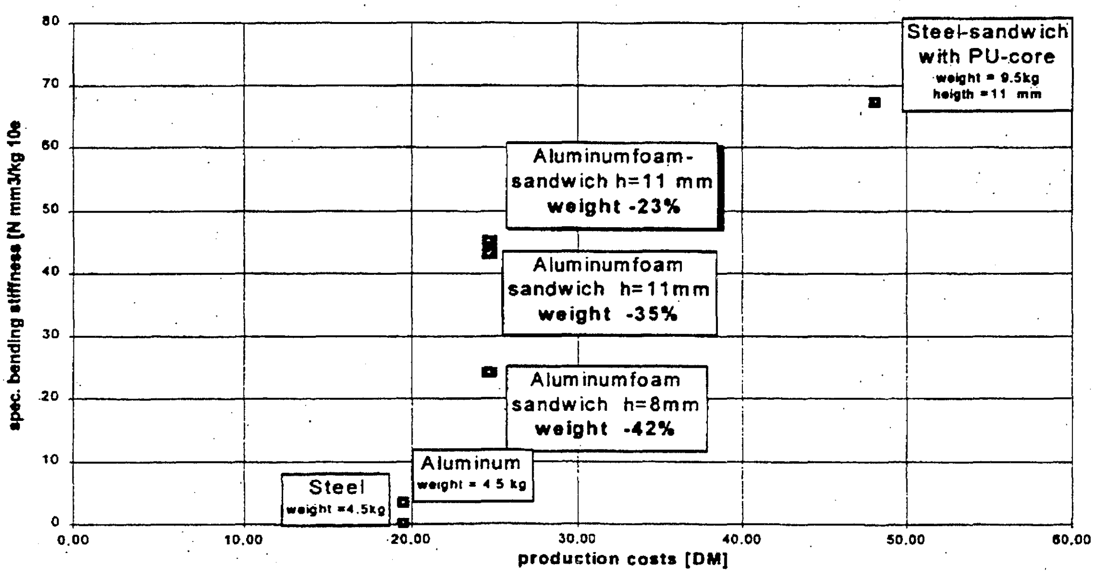

Figure 8: Potential for weight reduction and production costs in automotive applications

Calculations on the static stiffness of aluminum foam sandwiches were done by finite element simulation. As a result, the sandwich part has a significant lower stress level and the maximum displacement is eight times lower than the steel part. In order to compare different metal foam sandwiches with steel parts, the specific bending stiffness is summarized in figure 8. The specific bending stiffness is equivalent to an efficiency rating. The production costs for aluminum foam are just 20% higher than for the aluminum or steel panels, but they are more than ten times stiffer.

Conclusions and applications

A new powder metallurgy process for the production of metallic foams was developed for a range of alloys. This method allows for a direct net-shape fabrication of foamed parts with a relatively homogeneous and isotropic pore structure. Metallic foam made by this approach has a high fraction of porosity and exhibits a closed-cell microstructure. This type of microstructure is particularly attractive for applications requiring high specific stiffness and energy absorption. Light, stiff structures made of aluminum foam and foam sandwich panels could help to reduce vehicular weight and increase stiffness. Examples are hoods, trunk lids and sliding roofs, where weight and stiffness are the primary concern. A concept car was recently developed with three-dimensional aluminum foam sandwich panels, where stiffness needs to be enhanced (Figure 9). The resultant foam sandwich panel is about ten times stiffer than the original steel panel.

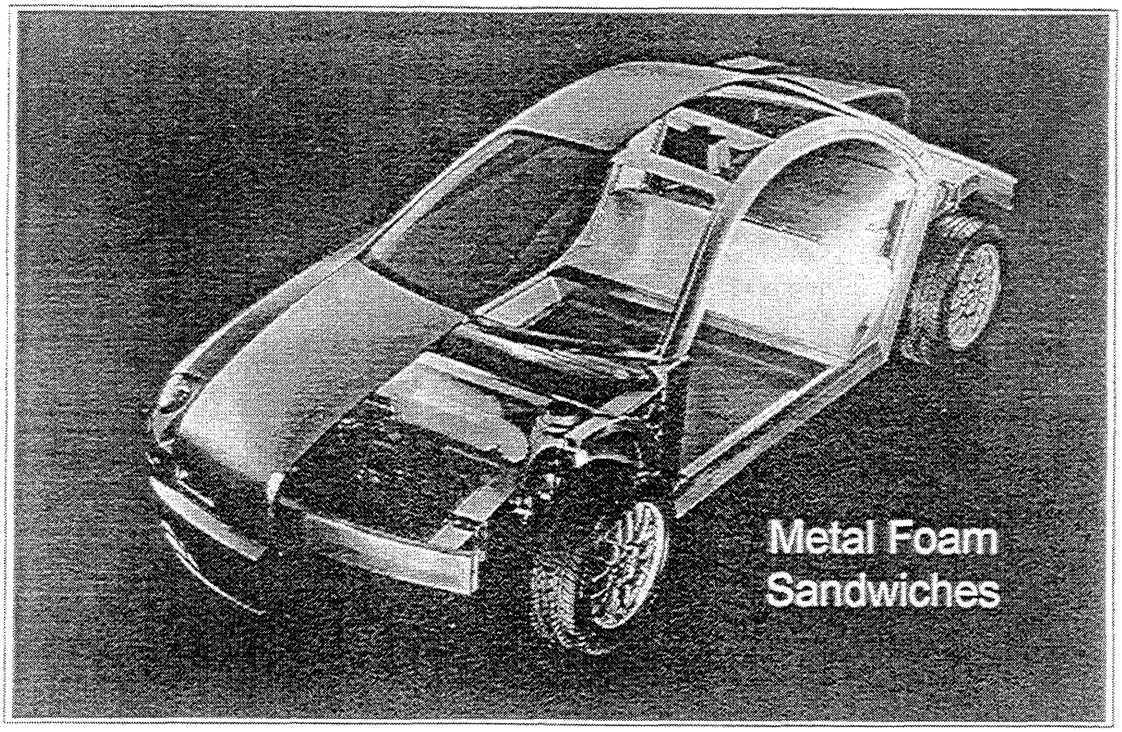

Figure 9: Karmann concept car with aluminum foam sandwich panels.

With regard to energy absorption, it is possible to engineer a controlled deformation into the crash zone of cars and trains with maximum impact energy dissipation. Possible applications include elements for side and front impact protection. Metal foam-filled hollow profiles present interesting deformation behavior and failure mode during buckling. In general, foam filling leads to higher deformation forces when profiles are bent and to higher energy absorption when profiles are axially crushed. Potential applications can be in bumpers, underside protection of trucks, A- and B- pillars, or other elements subjected to buckling or large deformation.

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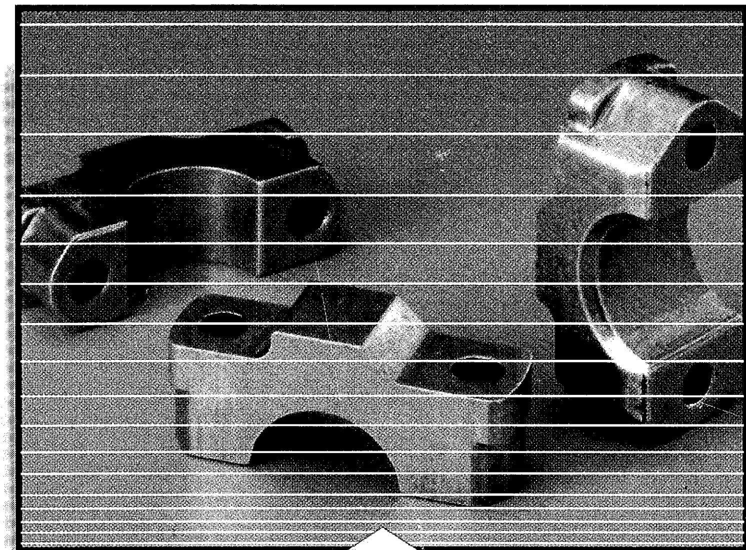

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