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Magnesium sheet production – state and perspectives

Produkcja blach magnezowych – stan obecny i perspektywy

Abstract
Magnesium and its alloys are becoming more and more interesting for the metal working industry. These materials combine density with mechanical and physical properties in a way that gives them excellent suitability for light-weight applications. Therefore, they offer a high innovation potential. The advantages of magnesium are already being used intensively in cast products. So far, wrought magnesium alloys have been used only on a small scale. The major reasons for this are the low availability of semi-finished products made of wrought alloys and the high price.
This paper will discuss the production of sheet and strip products, looking into the current state of development and the motives for the intensive development.
At the end, material properties will be considered using the magnesium alloys AZ31 as an example. Thereby the influence of temperature on the change of properties is of special interest. In addition, for better assessment of the forming behaviour as well as of the limit of forming at different stress- and forming states, forming limit diagrams are used.

Streszczenie
Magnez i jego stopy cieszą się coraz większym zainteresowaniem przemysłu metalowego. Materiały te łączą gęstość z właściwościami mechanicznymi i fizycznymi w sposób, który czyni je doskonale przydatnymi do zastosowań w lekkich konstrukcjach. Mają zatem wysoki potencjał innowacyjny. Zalety magnezu są już intensywnie wykorzystywane w wyrobach odlewanych. Dotychczas przerobione plastycznie stopy magnezu stosowane były na małą skalę. Głównymi powodami tego stanu rzeczy była mała osiągalność półproduktów ze stopów przerobionych plastycznie i wysoka cena. W niniejszej pracy omówiona została produkcja wyrobów z blach i taśm, z przedstawieniem stanu aktualnego i motywów intensywnego rozwoju. W części końcowej, na przykładzie stopów magnezu AZ31, rozważono właściwości materiału. Szczególnie ciekawy jest tu wpływ temperatury na zmianę właściwości. Celem lepszej oceny zachowania się materiału podczas kształtowania oraz granicy plastyczności w różnych stanach naprężenia i kształtowania, stosuje się wykresy odkształceń granicznych.

Key words: magnesium alloys, casting-rolling, mechanical properties, forming limit diagram

Słowa kluczowe: *stopy magnezu, odlewanie-walcowanie, właściwości mechaniczne, wykres odkształceń granicznych*

1. INTRODUCTION

Among construction metals magnesium is the lightest. Due to its low density it is about ¾ lighter than steel and about $^1/_3$ lighter than aluminium. Magnesium cast products in the automotive industry have shown high growth rates for already 10 years and can be controlled with respect to both their technology and eco-nomy. But although the amount of magnesium wrought products, in particular for sheets, has increased; only 9% of the world's produced magnesium is used for that (Fig. 1). One of the main reasons is certainly the unattractive high price for magnesium sheet, which cannot be compensated for by the attractive ratio of mechanical properties and density. Furthermore, lacking experience on the processing of semi-finished products and the unsolved problem of a suitable corrosion protection are extra barriers for a wider application of this very interesting material, whose availability is almost unlimited.

Total 2002: 364.959 t

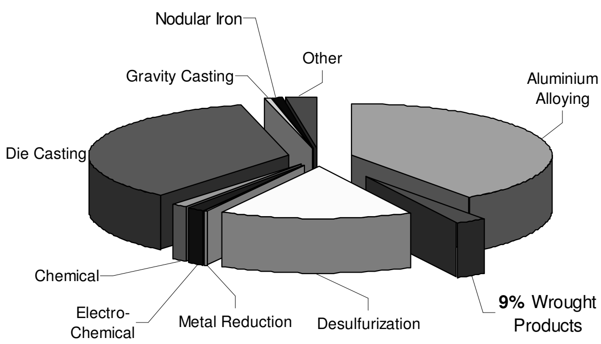


Fig. 1. Markets-overview for magnesium, 2002

Rys. 1. Rynki – przegląd dla magnezu, 2002

Table 1 shows the important characteristic values of magnesium in comparison to steel and aluminium in the area of vehicle construction. Except for the E-modulus, the relations of the properties of magnesium and its alloys lie on a higher level than those of steel and aluminium.

Table 1. Mechanical properties of magnesium in comparison to steel and aluminium

Tablica 1. Właściwości mechaniczne magnezu w porównaniu ze stalą i aluminium

Property	**Algorithm**	**Steel**	**Aluminium** high strength	**Magnesium**
Bending rigidity for panels	$\sqrt[3]{E}/\rho$	1.0	2,0	**2,7**
Dent rigidity	$\sqrt{E}/\rho$	1.0	1.7	**2.1**
Tensile/ /compression	E/ρ	1.0	1.0	1.0
Torsion rigidity	G/ρ 1) $\sqrt[3]{G}/\rho$ 2)	1.0 1.0	1.0 2.0	1.0 **2.7**
Tensile/ /compression	R_p/ρ	1.0	1.1	1.1
Dent strength	$\sqrt{R_p}/\rho$	1.0	1.8	**2.3**
Crash (bending)	R_m/ρ	1.0	1.2	1.1
Crash (buckling)	$\sqrt[5]{E}\,\sqrt[3]{R_p}/\rho$	1.0	1.7	**2.1**

Other material-specific advantages of magnesium in comparison to steel and aluminium are the high heat conductivity, the small thermal elongation, the better electromagnetic shielding ability and the excellent good damping properties. Furthermore, it is easy to recycle. The major disadvantage is the low corrosion resistance, which will require further work in the area of surface treatment and corrosion protection.

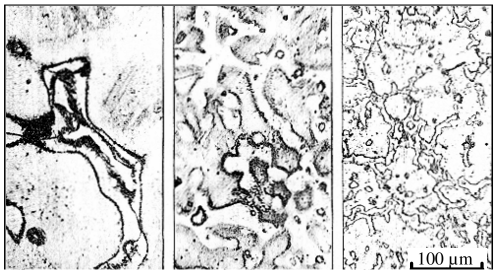
2. STATE OF THE PROCESS TECHNOLOGY FOR SHEETS AND STRIPS AND DEVELOPMENT TENDENCIES

The high price for magnesium sheets has several reasons. On the one hand, the forming of hexagonal metals is complex, so that only high strain rates in a temperature dependent range are possible. On the other hand, there are only a few plants worldwide that have the appropriate system configurations for the production of sheets. Moreover, these plants are designed and constructed for the complex, conventional technology (described in chapter 2.2). Currently there are no mills available for a complete magnesium strip production.

2.1. Requirements on the feedstock

A major problem in the production of magnesium sheets often is the bad quality of the cast condition. A high volume of pores and cavities, strong macro- and micro-segregations and precipitations of the γ-phase, which are stable and hard in the solid state or precipitations of an AlMn-combination are all obstructive. The forming ability of the cast material can be improved by homogeneous annealing.

The cast condition regarding the homogeneity of the structure formation can be improved considerably through faster cooling. The influence of the cooling speed is examined in [3] (see Fig. 2). An increase in cooling speed leads to a noticeable refinement of the cast structure regarding the dendrite morphology and the specification of the γ-phase-precipitations.



a) b) c)

Fig. 2. Influence of the cooling velocity (a - 1,3 K/s, b - 2,7 K/s, c - 300 K/s) on the microstructure of the alloy MA2-1 (200-fold) [3]

Rys. 2. Wpływ szybkości chłodzenia (a - 1,3 K/s, b - 2,7 K/s, c - 300 K/s) na mikrostrukturę stopu MA2-1 (200x) [3]

2.2. Conventional sheet production

The conventional process of sheet production comprises the following steps:

casting of slabs ⇨ homogeneous annealing ⇨ mechanical processing of the surface ⇨

⇨ multi-stage hot rolling with trimming and intermediate annealing ⇨ finishing heat treatment

The continuous-cast slabs are rolled on a reversing mill. Due to its low heat capacity the rolling material cools down fast to below the critical rolling temperature. As a result, the forming capacity decreases drastically and edge cracks develop. Consequently, the rolling process must be interrupted for trimming and annealing the cast material between operations, before rolling can be continued. The finishing heat treatment is done in a temperature range between 300 and 400°C.

2.3. New developments in the field of casting-rolling

The complex conventional sheet production of continuous-cast slabs is a great challenge for the economic application of magnesium in comparison to its competitive material aluminium. Therefore developments in economical technologies for magnesium flat products concentrate on processes that reduce the forming and annealing costs on the one hand, but increase production and improve the quality of the cast condition regarding homogeneity on the other hand.

Within the scope of an integrated research project supported by the Development Bank of Saxony (SAB - Sächsische AufbauBank), the MgF Magnesium Flachprodukte GmbH has built a casting-rolling pilot mill (Fig. 3) in Freiberg [4]. The first project for testing the casting-rolling technology was carried out in collaboration with the Institute of Metal Forming of the TU Bergakademie Freiberg and was completed successfully in 2005.

The economic advantages of this process in comparison to the conventional sheet production result from the small pre-strip thickness in the range of < 6 mm, which requires only a few hot rolling passes until the finishing strip thickness (< 1,5 mm) is reached. Furthermore, the pass reduction can be increased to >50% because of the very good forming ability, so that the finishing process can be further reduced. Additionally, the combination of strip production with hot rolling utilizing the casting heat will make the process more economical. [5]

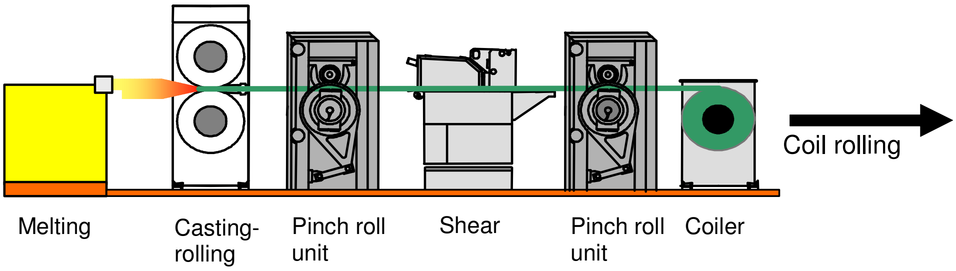


Fig. 3. Principle of the casting-rolling pilot mill of the MgF Magnesium Flachprodukte GmbH

Rys. 3. Zasada prototypowej maszyny odlewniczo-walcowniczej MgF Magnesium Flachprodukte GmbH

3. MATERIAL PROPERTIES OF SHEETS MADE OF CAST-ROLLED STRIPS

The plastic properties of AZ31 sheets produced by the casting-rolling technology are at a high level. These sheets with total elongations between 20 and 25% and yield strengths between 150 and 200 MPa at room temperature, match and exceed, respectively, the properties of conventionally produced sheets [6].

The influence of temperature on the mechanical properties is shown in Fig. 4. It can clearly be seen that with increasing temperature the yield point and the tensile strength decrease, while total elongation increases.

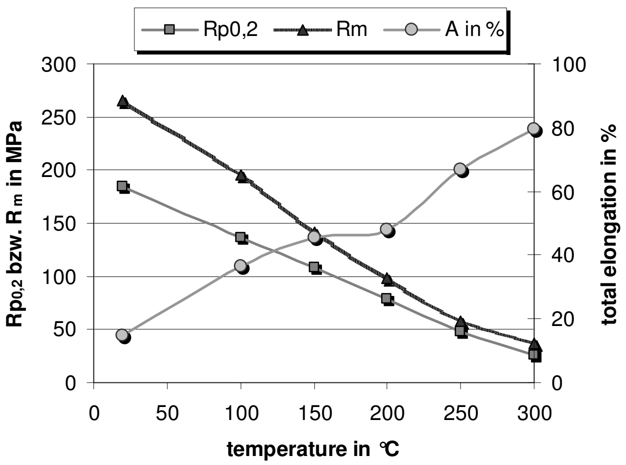


Fig. 4. Influence of temperature on the mechanical properties, specimen taken transverse to rolling direction

Rys. 4. Wpływ temperatury na właściwości mechaniczne, próbka pobrana poprzecznie do kierunku walcowania

It is obvious that the total elongation rises considerably between 20 und 100 °C. At above 100°C the values remain at a relatively constant level of 40 to 45%, and above 200 °C the elongation continues to increase because the pyramidal slip of dislocations begins (Fig. 4). As with increasing temperature the ability for strain hardening decreases, consequently the difference between tensile strength and yield point decreases.

The plastic forming of metals is based on the movement of dislocations on particularly suitable planes. With magnesium alloys the forming is possible in the temperature range of up to 200 °C by a slip of dislocations on the closely packed base planes (0001) and in two linear independent directions as well as by twinning. Therefore, at low temperatures magnesium alloys are formable only to a limited extent (e.g. small reductions). Furthermore, precipitations in the grains and on the grain boundaries complicate the movement of dislocations. In particular the adding of aluminium brings about solid solution hardening. Due to these processes high strengths and small elongations are the result for temperatures of up to 200 °C (Fig. 4). At temperatures above 200 °C simple prism and pyramidal slip as well as c+a-pyramidal slip are activated. In addition, the better forming at elevated temperatures is owed to thermal activated softening processes (dynamic recovery and recrystallisation). [7]

Forming Limit Diagrams

For further evaluation of the forming properties of magnesium sheets, forming limit diagrams are used. These diagrams help to asses the forming behaviour as well as the limit of forming at different stress- and forming states.

Fig. 5 shows the forming limit diagrams in the temperature range between 150 and 300 °C. At elevated temperatures the limit curves are displaced towards higher φ_1-values, which means that the forming limit ability increases. The best forming limit ability was reached at 300 °C. Depending on the applied condition the forming limit can be by 100% higher at 300 °C compared to 200 °C.

It can be seen from the forming limit curves that the forming limit increases at all temperatures, when going from uniaxial homogeneous tension ($\varphi_2 = 0$) to uniaxial tension ($\varphi_1 = -\varphi_2$). The forming limit curves, which run on a high level, illustrate the potential of these magnesium alloys.

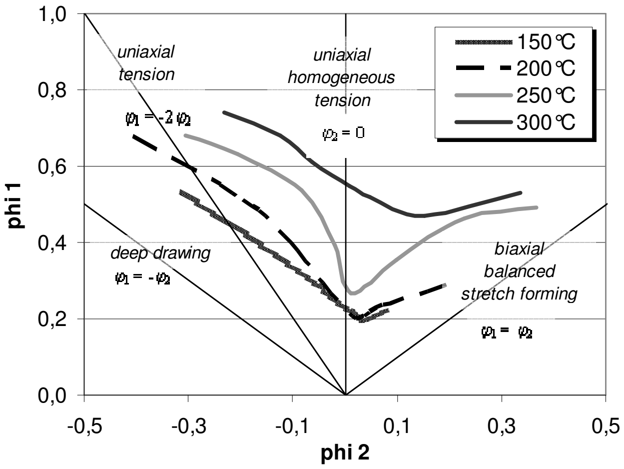
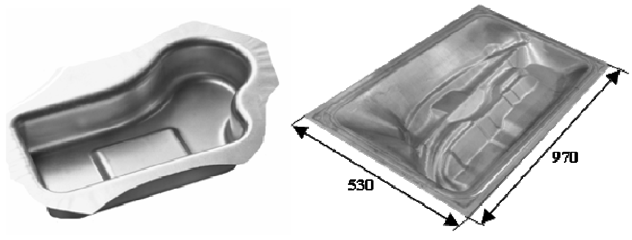


Fig. 5. Forming limit diagrams in dependence of the temperature

Rys. 5. Wykresy odkształceń granicznych w zależności od temperatury

The optimization potential regarding the mechanical properties is not yet exhausted at the new pilot plant. The project partners are working to examine and improve this potential with the help of numerical and experimental methods. Experience from numerous tests on the further processing ability of thin sheet has shown that these sheets can be worked into complex sheet components very well with various technologies. Fig. 6 shows two examples of deep-drawn parts.



a) Thyssen Krupp Umformtechnik b) IFU Stuttgart

Fig. 6. Examples of deep-drawn parts

Rys. 6. Przykłady części głęboko tłoczonych

4. SUMMARY

The production of magnesium sheets and strips with the conventional method is very expensive. Although some applications have been tested in vehicle construction, there is no serial application for magnesium sheets in the automotive industry due to their high cost. If this situation is to be changed, considerably cheaper processes have to be developed. Near net shape casting and forming processes give such solutions. The Institute of Metal Forming at the TU Bergakademie Freiberg and the MgF Magnesium Flachprodukte GmbH have developed a casting-rolling process for the production of strip.

The plastic properties of AZ31 sheets produced by casting-rolling technology are up to a high level. Those sheets with total elongations between 20 and 25 % and yield strengths between 150 and 200 MPa at room temperature match and exceed, respectively, the properties of conventionally produced sheets. Forming limit diagrams were used for a further evaluation of the forming properties of magnesium sheets. At elevated temperatures the limit curves are displaced towards higher φ_1-values, which means the forming limit ability increases. The best forming limit ability was reached at 300 °C. Depending on the subjected condition the forming limit can be by 100% higher at 300 °C compared to 200 °C.

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