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Metal Forming of Magnesium Alloys for Various Applications

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Abstract

The chapter presents an analysis of selected magnesium alloys as structural materials to be used in production of parts as well as their technological parameters in some manufacturing processes: metal forming and joining. Taking into account the analysis of microstructure and mechanical properties of conventional and new magnesium alloys and requirements of their possible applications (aviation, automotive, sport, etc.), the study of forming parts/products based on description of plastic formability of magnesium alloys in the processes of bulk metal forming (forging, extrusion, KOBEX extrusion, rolling) and joining (friction stir welding) has been presented. Upsetting test, backward extrusion, and KOBEX extrusion of complex cross-sectional profiles and forging process were conducted using magnesium alloys such as AZ31, AZ61, AZ80, WE 43, and Mg alloy with Li for the production of thin-walled profiles and forged parts. The range of temperatures and extrusion rate for manufacturing of these profiles were determined. Tests also covered the analysis of microstructure of Mg alloys in the initial state as well as after the extrusion process. The recommendations for realization of metal forming and joining processes of selected magnesium alloys have been presented.

Keywords: magnesium alloys, plastic formability, forging, extrusion, KOBEX extrusion, rolling, joining, friction stir welding

1. Introduction

Mg-alloys are being considered as one of the most versatile material choices among the structural materials that exhibit both energy efficiency and environmental benefits. Mg-based materials (alloys and composites) have enormous and unlimited potential to replace aluminum, steel, and structural plastics in diverse industrial and commercial sectors such as automotive, aviation, defense, biomedical, sporting equipment, consumer electronics, etc. These applications result from the need to use magnesium and its alloys as a material with favorable physical properties, especially high relative strength (R_m/ρ). Due to the good casting properties of magnesium, it was used primarily in cast structural elements. Wrought alloys have been used on a smaller scale so far, but material research and plastic formability processes to produce semi-finished products from magnesium alloys are currently under intensive development. The development is caused by the possibility of using various types of light structures in the construction, including vehicles made of magnesium-based materials, for which, for example, thin sheets are the

basic initial material. This is mainly due to the attempt to reduce the weight of the structure and ensure adequate strength.

The interest in magnesium alloys for various structural elements, e.g., for the aviation industry, dates back to the 1940s. Examples of applications concerned, for example, the Northrop XP-56 plane, in which virtually all parts exposed to elevated temperature were made of magnesium and its alloys [1], B-36 bomber or [2], the S55 helicopter by Westland Aircraft Ltd. (1950 r.) [1, 3].

In later years, the use of magnesium alloys for aircraft structural elements was significantly limited, which was mainly due to the rapid corrosion of alloys (the main disadvantage), opinions about the flammability of magnesium, low metallurgical purity, low strength, high processing costs through plastic formability and poor machinability [4–7].

Since the beginning of the twenty-first century, there has been a renewed, significant increase in interest in magnesium alloys for applications in the aerospace industry. It results from the development of new coatings that can protect alloys against corrosion, new alloys, new technologies of obtaining semi-finished products by casting methods, and the improvement of various plastic forming technologies, which significantly improves the properties of the product and allows the use of these alloys wherever engineers look for very light construction elements, relatively durable and with anticorrosion protection at the same time [8–10].

The main problem in the development of techniques for processing magnesium alloys with metal forming methods is low formability [4, 11]. Low deformability at room temperature as well as temperature increased to 200°C of magnesium alloys result from a limited number of hexagonal lattice slip systems. The test results show that the microstructure of Al-Mg-Zn alloys deformed at temperatures up to 200°C shows bands slip and deformation twins [11]. In the range from 200 to 300°C, limited dynamic recovery and the formation of nuclei of dynamic recrystallization are observed. Continuous dynamic recrystallization takes place above 300°C, which results in an almost twofold increase in formability.

Metal forming of magnesium and its alloys is carried out, depending on the content of alloying elements, only in a narrow temperature range. Grains with an average diameter of up to 10 µm were obtained in magnesium alloys by thermo-plastic treatment. The fragmentation of the grains below 10 µm is only achieved by introducing large deformations. The use of unconventional methods of deformation allows for obtaining the grinding of magnesium alloys to sub-micrometric or nanometric sizes. Therefore, these deformation methods constitute a very significant support for conventional forming methods [12–14].

In magnesium alloys, deformation processes are carried out at an elevated temperature. Therefore, it is practically impossible to obtain nanometric grain sizes obtained by the development of shear bands. The most common methods of large deformation, leading to the grinding of the grains of magnesium alloys, are equal channel angular pressing (ECAP) [15, 16] or hydrostatic extrusion [14, 17].

Basic magnesium alloys for metal forming contain up to 8% Al and the addition of Mn (up to 2%), Zn (usually up to 1.5%), Si (about 0.1%), and traces of Cu, Ni, Fe. There are three basic groups of magnesium alloys for metal forming. The first group includes mainly alloys with the addition of aluminum, zinc, and manganese. The second group includes alloys containing mainly the elements Zn, RE, Y, Zr, Th, and the third group, which is in the phase of intensive research, consists of new ultralight alloys containing lithium.

Magnesium alloys for metal forming are still used to a relatively small extent, which results from technological difficulties in metal forming and high production costs [13, 18, 19]. The main disadvantage of magnesium and its alloys is low deformability at ambient temperature, which results from the type of crystal lattice.

At ambient temperature, only one in-plane glide system (0001) is active. In addition to low temperature slip, a significant amount of twinning is observed in magnesium alloys.

Hot forming of magnesium alloys, depending on the chemical composition and deformability, is performed using the following methods [20, 21]:

- rolling (mainly grades from the group of Mg Al-Zn and Mg-Zn-Mn alloys, as well as new alloys of the Mg-Th- (Mn or Zr) and Mg-Li-Al alloys,
- open die and die forging,
- extrusion (alloys AZ31 (Mg-Al-Zn), AZ61 (Mg-Al-Zn), ZM21 (Mg-Zn-Mn),
- KOBO extrusion (AZ31, AZ 61 Az80, WE43)
- sheet metal stamping after the rolling process in heated dies.

The formability effect of magnesium alloys has been recently also used in a relatively new solid-state joining process, under the influence of frictional heat, i.e., Friction Stir Welding (FSW). There is no melting involved in the process unlike conventional Fusion welding processes. This method gives very good results in the creation of strong joints, competitive to other joining techniques that require additional joining materials (e.g., riveting, bolted connections, welding, and others). Joining elements (e.g., sheets) made of magnesium alloys with this technique are very effective and require careful selection of process parameters, taking into account the special features of the plasticization of magnesium alloys and the stirring effect in the joint area [4, 22–24].

2. Evaluation of plastic formability of Mg alloys

Various magnesium alloys for plastic deformation have difficulties in carrying out metal forming processes. The evaluation of the plastic formability of magnesium alloys can be conducted by determining the mechanical behavior of samples of tested materials in compression, torsion, and tensile tests. These tests reflect relatively well essential features of the state of stress or deformation in technological processes of metal forming, including extrusion, forging, and rolling, respectively.

To evaluate mechanical behavior of the material in extrusion process, the upsetting test was used to realize plastic deformation under various conditions and to look for adequate their choice for real deformation process. The grades AZ31, AZ61, AZ80, WE43, and magnesium alloys with lithium, as casted ingots and extruded preforms, were used in the research work. In order to study feasibility of these magnesium alloys in extrusion process, the upsetting test of cylindrical specimens was carried out and let to determine flow stress–strain relationships [25–30]. Before upsetting, the specimens were heated in a furnace to established temperature (Figure 1).

On the example of AZ31, AZ61, AZ80, WE43 alloys, and magnesium and lithium alloys, the determined flow stress–strain relationships between flow stress and strain for different values of temperature and strain rate allow for adequate adjustment of plastic deformation parameters based on specific relationships between the structure and deformation under conditions of hot compression test. Documented occurrence of two deformation mechanisms: slip and twinning in the presented relationships between plasticity characteristics such as: maximum yield

Figure 1.

a) Setup of the upsetting/test at high-temperature mounted on 1000 kN hydraulic press, b) flow stress-strain relationships for AZ 31 [28].

stress and strain corresponding to the maximum, and the Zener-Hollomon parameter allows for an appropriate interpretation of the effects of microstructure transformation [31]. In order to prepare technological process, it is necessary to define precisely the plastic properties and microstructure changes of those alloys. Comparison of the plasticity and microstructure of magnesium alloys with from 3 to 8% aluminum content from group Mg-Al-Zn-Mn let to choose proper parameters of the process. On the basis of tensile tests, the plasticity changes were determined at temperature from 150 to 450°C. Conducted compression test at temperature from 250 to 450°C and deformation speed from 0.01 to 10 s⁻¹ provided important data concerning the influence of process parameters on flow stress and microstructure changes connected with recrystallization process.

The characteristics of the relationships obtained in the compression test: flow stress σ_p - strain ϵ for the tested alloys AZ31, AZ61, AZ80, WE43 (**Figure 2**), and magnesium alloys with lithium (**Figure 3**) show the influence of temperature on their course, which allows for an adequate choice of technological parameters for plastic deformation methods with the dominant state of compressive stress (e.g., forging, extrusion).

Tests of magnesium and lithium alloys [32] with lithium content of 2.5, 4.5, 7.5, and 15% of the mass showed very different flow stress-strain relationship characteristics plasticizing from deformation, which results from the fact that alloys with 2.5 and 4.5% lithium form a lithium solid solution in magnesium and have a hexagonal structure. The 7.5% lithium alloy has an.

α + two-phase structure β ., where the α -phase with the hexagonal structure is a solid solution of lithium in magnesium and the β phase has a wall structure centered is a solution of magnesium in lithium. The 15% lithium alloy is a solution of magnesium in lithium and has a wall-centered structure. An example of the flow stress-strain relationship for Mg-7,5 Li alloy is shown in **Figure 3**.

Alloys that contain more lithium, which is 7.5%, have good formability at temperature of 150°C. The alloy content of 15% lithium demonstrates very good deformability. The shape of flow curves and microstructure of alloys after deformation at elevated temperatures show significant influence of dynamic recrystallization process.

Determination of the plastic formability can be made on the basis of the results of torsion test too [30].

Flow curves for the magnesium alloy AZ31, most commonly used so far, were determined using torsion test at 300, 400, and 450°C at the speed 1 s⁻¹ (**Figure 4**), while in the compression test at the temperature of 200, 300, 400, and 450°C at a strain rate of 0.01 and 1 s⁻¹, respectively (**Figure 5**). AZ31 magnesium alloy exhibits

Figure 2.
Flow stress–strain relationships for magnesium alloys AZ31, AZ61, AZ80, and WE43 obtained in compression test [28].

Figure 3.
Flow stress–strain relationships for magnesium alloy Mg-7,5 Li obtained in compression test [28].

an increase in deformability with an increase in the torsional temperature from 1.2 at 300°C to 5 at 450°C (Figure 4).

Axial-symmetric compression tests carried out on the Gleeble 3800 simulator with simultaneous “freezing” of the microstructure after deformation by rapid cooling with water, in the temperature range from 200 to 450° C with the strain rate $\dot{\epsilon} = 0.1 \text{ s}^{-1}$ and $1,0 \text{ s}^{-1}$, until the deformation $\epsilon = 1, 2$ (Figure 5) allows the assessment of the influence of these factors on the course of the characteristic and its use in the design of plastic forming processes.

The flow curves obtained in the compression test indicate a similar level of the value of flow stress of the alloy for comparable conditions of its deformation in relation to the torsion curves.

Figure 4. Flow curve of AZ31 alloy determined in torsion test at temperature of 300, 400, and 450°C with a strain rate 1 s^{-1} [30].

Figure 5. Flow curve of AZ31 alloy determined in compression test at temperature of 200, 300, 400, and 450°C with a strain rate: a) 0.01 s^{-1} , b) 1 s^{-1} [30].

Performing plastometric tests for a magnesium alloy allows the identification of two types of flow curves. Classical curve—where the dominant mechanism in the microstructure is slip (e.g., **Figure 6a**) and the characteristic curve, where the dominant mechanism in the microstructure is twinning (**Figure 6b**).

The relationship of the maximum yield stress σ_{pp} and strain ϵ_p as a function of $\ln Z$, where: Z – Zener-Hollomon parameter, $Z = \dot{\epsilon} \exp\left(\frac{Q}{RT}\right)$ is shown in **Figures 7** and **8**.

Currently, plastic forming of magnesium alloys is limited to a few basic grades from the group of Mg Al-Zn (AZ21, AZ31, AZ61) and Mg-Zn-Mn (ZM21) alloys. AZ31 magnesium alloy as the most widely used for rolling metal sheets shows good formability under hot-forming conditions. The obtained flow curves depending on the deformation parameters show two different types of the deformation process. For higher temperatures and lower strain rates, the curve follows the classical course of changes in the yield stress. At lower temperatures and higher strain rates, the course of stress changes is different and characteristic for the process based on the twinning mechanism, which was confirmed in structural studies. It has been shown that there is a relationship between the maximum yield stress σ_{pp} and the

Figure 6.
Microstructure of magnesium alloy AZ31: a) after deformation at temperature of 350°C—Slip domination, b) after deformation at temperature of 250°C—Twinning domination, strain rate 0.1 s⁻¹ [30].

Figure 7.
Maximum yield stress σ_{pp} as a function $\ln Z$ [31].

Figure 8.
Deformation ϵ_p corresponding to the maximum yield stress on the flow curve σ_p as a function $\ln Z$ [31].

corresponding strain ϵ_p , and the Zener-Hollomon parameter (**Figures 7 and 8**). A worse fit occurs for curves where twinning dominates, which changes the shape of the curve [30]. Flow stress–strain curves of alloy AZ31 are characteristic for alloy in which during deformation a mechanism of plastic strain called twinning occurs [33].

The microstructure of AZ31 alloy after deformation by hot compression at the temperature of 200, 300, 400, and 450°C with strain rate of 0.01 s^{-1} and 1 s^{-1} , respectively, was examined, and an example is shown in **Figure 9**. It was observed after the compression test at 200°C for strain =1.2, for both the strain rates used, the microstructure of the primary elongated grains and the ultrafine grains dynamically recrystallized (**Figure 9**). Samples deformed at a lower strain rate are characterized by a greater advancement of the recrystallization process. Recrystallized grains are observed both at the boundaries and within the primary grains.

The microstructure of AZ31 alloy, after deformation at the temperature of 300°C with the speed of 0.01 s^{-1} , consists of fine grains that are dynamically recrystallized. For a higher strain rate, chains of recrystallized grains at the boundaries of the deformed primary grains are observed. Increasing the temperature to 400 and 450°C intensifies the recrystallization processes and grain growth. Few deformation twins are also observed (**Figure 10**).

The presented results of plasticity tests of AZ31 magnesium alloy indicate its good formability during hot deformation. The fine-grained recrystallized microstructure was obtained at the temperature of 300°C for a low strain rate. Increasing the temperature leads to the growth of recrystallized grains. Consequently, the average grain diameter after deformation at 450°C is much higher than before deformation.

Traditionally, the compression test specimens are circular in cross section. Taking into account the geometrical profiles of plastically formed products, e.g., in the

Figure 9. Microstructure of the AZ31 alloy after compression at temperature 200°C: a) with a strain rate 0.01 s^{-1} , b) with a strain rate 1 s^{-1} [31].

Figure 10. Microstructure of the AZ31 alloy after compression at temperature 450°C: a) with strain rate 0.01 s^{-1} , b) with strain rate 1 s^{-1} [25].

process of forging or extrusion, the cross-sectional geometries are usually more complex. The analysis of the influence of the geometry of the deformed sample in the non-standard compression test when the cross sections of the deformed sample are not circular (**Figure 11**) shows that the differences are significant in the mechanical behavior of the material (the level and course of the forming force, the change in the geometry of the upset sample).

Taking into account the different geometry of the initial material in the evaluation of the impact of the strain rate and temperature on the forging (upsetting) effect of magnesium alloy specimens (as a material test before designing the forging process) allows for determining the appropriate process parameters.

The results of modeling the upsetting process of magnesium alloys obtained in the form of temperature distributions, stress and strain distribution as well as strain rates provide the basis for determining the conditions of the actual process leading to a product without defects and with high-quality requirements.

The analysis of force courses as a function of displacement during the upsetting process of magnesium alloys showed that the value of the force required for deformation decreases with increasing temperature. The value of the force is strongly influenced by the shape of the upset specimen, including the geometrical parameters (number of corners, the measure of angles, axes of symmetry, and planes of symmetry) (**Figure 12**).

Both in numerical simulation of upsetting and in experimental tests, the values of the force needed to deform individual specimens are convergent. The more complicated the cross-sectional shape, the greater the force needed to deform a given specimen of metallic material.

Figure 11.
Upsetting test specimens.

Figure 12.
The effect of different geometry of initial material (shape of the cross section of the sample) on the force of deformation during upsetting test.

Figure 13.
Influence of temperature on the course of force values during the upsetting of magnesium alloy a) AZ31, b) WE 43.

The results of upsetting test for the forging process demonstrate different mechanical behavior of various Mg alloys: e.g., AZ31 and WE 43, and they are useful to determine plastic formability (**Figure 13a and b**).

On the basis of their analysis, it is possible to assess ability to deformation of magnesium alloys on the basis of determining:

- limit deformations, deformations leading to cracking, and force parameters during the process of metal forming.

3. Processes of metal forming: forging, extrusion, KOB0 extrusion, rolling, and joining: friction stir welding. Mechanical properties, microstructure, and quality of the final product. Examples of applications

The analysis of magnesium alloys and their possibilities of deformation by plastic forming shows that they are prospective due to the development of a number of new technologies. The purposefulness of work on the development of the plastic forming technique [34] is primarily determined by the better mechanical properties of plastically processed magnesium alloys compared with the cast ones. Now, there are main groups of magnesium alloys available for plastic deformation:

- *Mg-Al-Zn alloys*—The magnesium alloys Mg-Al-Zn are the most popular ones. Four basic alloys AZ31, AZ61, and AZ80 are distinguished. The alloy AZ31 shows relatively low mechanical properties, but it is weldable and perfectly suitable for rolling, stamping, and extrusion. This grade is used to produce sheet metal designed mainly for drawpieces. The alloys AZ61 and AZ80 are

characterized by a larger content of alloyed components, and they show more advantageous mechanical properties. The alloy AZ61 is weldable, plastically worked by extrusion and forging methods. The alloy AZ80 demonstrates the best mechanical properties in the group of plastically worked alloys; however, its susceptibility to plastic working is relatively low. It is suitable for making only simple forgings.

- *Mg-Zn alloys*—Two alloys ZM21 and ZC71 are distinguished in this group. The alloy ZM21 includes zinc up to 2% and manganese in the amount of about 1%; it is susceptible to rolling and stamping and characterized by good weldability. A fine-grained structure of average grain size of about 15 μm can be obtained after extrusion. ZC71 is a new magnesium alloy with zinc, copper, and manganese that is characterized by high strength of up to 360 MPa. It can be formed by extrusion and forging methods, and this alloy is weldable.
- *Mg-Zn-Zr alloys*—This group comprises the alloys ZK30, ZK40, and ZK60 that includes 3–6% Zn and 0.4–0.6% Zr. An addition of zirconium leads to an intensive grain refinement. These alloys are characterized by high strength, and they are formed in forging and extrusion processes.
- *Mg-Y-Re-Zr alloys*—The alloys of such a type are formed by the plastic working methods, most often via extrusion. It can be mentioned that the alloy WE43 that, as main component, includes yttrium in the amount of 4.0% and rare earth elements RE, i.e., about 3.5%. After extrusion and heat treatment, the alloy WE43 shows tensile strength R_m equal to 420 MPa, yield point $R_e = 340$ MPa, and elongation $A = 15\%$. This alloy is characterized by good creep resistance at the increased temperatures
- *Mg-Li alloys*—Magnesium-lithium (Mg-Li) alloys thus have distinct advantages over conventional magnesium alloys. However, Mg-Li alloys possess relatively low strength and oxidation resistance. Alloying is well known to be an effective method to improve mechanical and chemical properties. Small additions to Mg-Li system, e.g., aluminum may improve mechanical properties. Mg-Li-Al (LA 143) alloys with high strength and plastic deformability were prepared through a combination of heat treatment and multidirectional forging in a channel die (MDFC). The maximum specific yield strength of the Mg-Li-Al alloy in this study is $263 \text{ kN} \cdot \text{m} \cdot \text{kg}^{-1}$. The limit of reduction during cold rolling of all MDFCed LA143 samples exceeded 99%. The high specific yield strength could be attributed to severe plastic deformation. LA143 alloys with excellent mechanical properties can be prepared by heat treatment and severe plastic deformation [35].

Designing the processes of metal forming of structural elements made of magnesium alloys requires precise determination of the influence of process parameters on the microstructure and consequently on the mechanical properties of the manufactured elements. This is of particular importance when designing products in aviation [36, 37], automotive, medical, and other applications. Plastic forming tests carried out under laboratory and industrial conditions indicate that selected magnesium alloys can be formed especially in the process of rolling, forging, and extrusion. When forming AZ61, AZ80, and WE43 alloys, the temperature range is significantly limited, both at the beginning and the end of the deformation process. Therefore, to carry out plastic forming, especially forging, it is necessary to have devices that enable the process to be carried out in isothermal conditions. For AZ31

alloy, the range of temperatures of good formability is greater due to the greater tendency of this alloy to the recrystallization process.

The beneficial properties of magnesium alloys are obtained thanks to thermo-plastic treatment. In magnesium alloys, an intensive process of dynamic recrystallization takes place during plastic deformation, which promotes grain refinement and improvement of mechanical properties. Plastic forming of magnesium and its alloys can be carried out, depending on the content of alloying elements, only in a narrow temperature range.

Examples of the use of magnesium alloys in the formation of products/semi-finished products in the processes of plastic forming and joining processes involving plastic deformation (friction stir welding) show the enormous potential of these materials and the clear benefits of using these technologies in the forming of various types of products.

3.1 Particularities of metal forming processes of Mg alloys

3.1.1 Rolling

Rolling of magnesium alloys is currently limited to a few basic grades from the group of Mg-Al-Zn and Mg-Zn-Mn alloys. The new alloys Mg-Th- (Mn or Zr) and Mg-Li-Al are also susceptible to rolling [30, 32, 35, 38, 39].

The process of rolling magnesium alloy products is very expensive and time-consuming. This is due to the necessity to carry out annealing between successive operations. As a result of the current growing interest in sheets of magnesium alloys, the so-called “twin rolls casting” technology has been developed, which reduces the number of rolling and heating operations by casting between rolls and subsequent rolling [32].

Rolling AZ31 alloy with heating the billet in a chamber furnace to the temperature of 470°C for 30 minutes and cooling it in the air to the rolling temperature, in the range from 200 to 450°C, allows for obtaining a product with the required mechanical properties at the level of $R_m = 220\text{--}265\text{ MPa}$ and $A_{50} = 10\text{--}12\%$.

Examples of the microstructure of AZ31 alloy bands after the hot rolling process are shown in **Figures 14** and **15**. In the microstructure of the specimens rolled with a total draft of 44%, it shows a partially recrystallized structure (**Figure 14a**). The presence of primary grains and recrystallized grains was found (**Figure 14b**) fully recrystallized structure with fine grains. The analysis of the microstructure of the

Figure 14.

Microstructure of bands from alloy AZ31 after rolling process by total draft: a) 44%, b) 82% [32].

Figure 15. Microstructure of the AZ31 alloy rolled plate: a) in the surface of the plate, b) in the longitudinal section of the plate, c) in the cross section of the plate [30].

AZ31 alloy bands shows that it is precisely the application of large creases (here 82%) that allows obtaining a fine-grained structure without visible areas of primary grains.

The existing industrial application of magnesium alloys is currently focused on the utilization of semi-finished products such as sheets. The effects of processing parameters and special aspects of the rolling process on the mechanical properties and sheet formability is examined, and recent developments is presented in [37, 40].

3.1.2 Forging

Among the most common forming processes, forging is a promising candidate for the industrial production of magnesium wrought products. The basics of magnesium forging practice are described, and possible problems as well as material properties are presented and discussed in many papers. Several alloy systems containing aluminum, zinc, or rare earth elements as well as biodegradable alloys are evaluated to focus on the process control and processing parameters, from stock material to finished parts including mechanical properties and analysis of microstructure [37, 40, 41].

The final properties of the forgings made of Mg alloys depend on the type of alloy and the string technological process leading to the final product. Most often feet cast magnesium is plastically deformed into semi-finished products, mainly by extrusion or rolling. Usually, forgings are made of semi-finished products in the form of extruded bars or rolled plates, which can be supplied in various conditions depending on the type of heat treatment applied. Forgings after being forged are subjected to precipitation hardening, recrystallization annealing, or stress relief annealing or leaving heat untreated. Each stage of the production line affects the structure and final properties of the product.

Forging as a process of forming the material through multistage deformation for magnesium alloys is a typical process based on hot forming at a narrow temperature range. An example of multistage forging of the airplane wheel hub and the AZ31 magnesium alloy control system lever of the helicopter is shown in **Figure 16** [42–44].

Forging should be carried out on hydraulic or low-speed hydraulic presses. In specialist literature, it is not recommended to use die hammers and high-speed presses due to the cracking of the material during forging. When designing the transverse flow tendency of the magnesium alloys, the rod axis as well as difficult flow in the longitudinal direction should be taken into consideration. Die blanks should be polished to facilitate material flow and avoid surface defects. Free removal of the forging from the blank is possible thanks to forging inclinations equal to 3°, and in some cases even smaller [45, 46].

Figure 16. View of forgings from AZ31 alloy: a) semi-hub of wheel, b) lever after process at beginning temperature of 410°C [28].

A very important process parameter is the temperature of the charge and tools. Magnesium alloys are good heat conductors and quickly cool down in contact with the tools, the more so that during forging, the material deformed over a relatively long time is in contact with a large surface with the die shape. For this reason, the temperature of the tools should be kept slightly below the load. Too much cooling of the billet leads to the formation of cracks. Conversely, too high a temperature also causes cracking due to the occurrence of hot brittleness. Lubrication is applied during the forging operation. Greases based on graphite or molybdenum disulfide are recommended for the forging temperature range of magnesium alloys.

Magnesium alloys are highly strain rate sensitive and exhibit good workability at a narrow forging temperature range. Consequently, parts made of these materials are usually forged with low-speed hydraulic presses, using specially designed tool heating systems in order to ensure near isothermal conditions. This study investigates whether popular magnesium alloys such as Mg-Al-Zn can be forged in forging machines equipped with high-speed forming tools.

Results presented in work [47] have demonstrated that AZ80A is not suitable for forging with either the screw press or the die forging hammer, that AZ61A can be press- and hammer-forged but to a limited extent, and that AZ31B can be subjected to forging in both forging machines analyzed in the study.

Examples of the application of magnesium alloys in aviation structures obtained by forging indicate the effective use of the possibilities of this technology (Examples shown in **Figures 17–22**).

Figure 17. Stages of forging of AZ31 semihub of wheel, for aeroplane at temperature of 410°C.

Figure 18.
Stages of forging the helicopter control system lever: a) forging, b) forging AZ₃₁ alloy.

Figure 19.
Drop forgings made in industrial conditions: (a) AZ₃₁B, screw press; (b) AZ₃₁B, forging hammer; (c) AZ₆₁A, screw press; (d) AZ₆₁A, forging hammer [47].

The forging process was carried out on a drop forging hammer. The initial material was ingots heated to the initial forging temperature equal to 350°C and 410°C, followed by upsetting, forging, forging in a die blank. The correct forging was obtained for the alloy annealed at 410°C [41–44].

The results of the research on the forging process in industrial conditions of two selected parts of aircraft structures: i.e., the aircraft wheel hub and the helicopter control system levers showed that the appropriate geometric parameters of these magnesium alloy elements and the determination of the conditions of the hammer forging process allowed for obtaining final products without defects with the required final properties (geometric and mechanical properties).

3.1.3 Extrusion

The conventional process of extrusion of magnesium alloys is carried out at a temperature range from 320 to 450°C, at a speed of 1–25 m/min. The developing

method of hydrostatic extrusion allows for plastic deformation at lower temperatures and to obtain greater grain grinding of magnesium alloys [28, 43, 48, 49]. The extrusion process was carried out on a counter-press with a heated container. AZ31, AZ61, AZ80, and WE43 magnesium alloy ingots with a diameter of 100 mm, heated to a temperature of 400°C, were extruded at various speeds from 0.04 to 0.16 m/s and with a different extrusion ratio of 6,25–25. The most favorable effect on the microstructure was observed after billet extrusion with an extrusion ratio of $\lambda = 25$ (**Figure 20a–d**). As a result of plastic deformation and recrystallization, fine recrystallized grains were obtained, although in the case of AZ61 and AZ80 alloys, a banded microstructure was observed (**Figure 20b and c**).

Microstructure	Mechanical properties	Application
a) AZ31	YS = 170MPa UTS = 264MPa, A ₅ = 15%	sheets, extrusion profiles, forging of complex design, fully weldable alloy
b) AZ61	YS= 240 MPa, UTS =325 MPa, A ₅ =15,4%	extrusion of complex profiles, forging of complex design, fully weldable alloy
c) AZ80	YS =255 MPa, UTS = 340 MPa, A ₅ =13,5%	complex shape of extrusion, forging of simple design, fully weldable alloy
d) WE43	YS =280 MPa, UTS = 330 MPa, A ₅ = 15 %	high temperature aerospace alloy up to 250°C, complex shape of extrusion, forging of simple design, flat products

Figure 20.
Microstructure and mechanical feature of magnesium alloys after indirect extrusion [28].

Different shapes of cross section of profiles for aviation application were obtained in the way of backward hot extrusion process. Some results of final products are presented in **Figure 21**. It is possible to obtain profiles of complex shape with elements of varied wall thickness and with thin walls. Microstructure of tested alloys in initial condition after extrusion is shown in **Figure 20**. Before deformation the tested alloys AZ31 and AZ61 were characterized by single-phase microstructure of solution α -Mg, whereas in microstructure of alloy AZ80 the presence of inter-metallic phase γ -(Mg₁₇Al₁₂) was found and which was confirmed by prior X-ray tests. The extrusion of profiles with a complex cross-sectional shape and large differences in wall thicknesses (**Figures 21 and 22**) allowed the assessment of high plastic deformation possibilities of these alloys, favorable microstructure, and obtaining very good mechanical properties [28, 49–51].

Figure 21.
Complex shape profiles of Mg alloys obtained during indirect extrusion [28].

The measurements of the grain size (acc. to ASTM E 112) and the microhardness HV0.1 of the magnesium alloy on the cross section of the extruded profile in the characteristic areas A, B, C (**Figure 22**) show different values of microhardness and grain size (**Table 1**), which proves the influence of the cross-sectional geometry on the microstructure and properties of the magnesium alloy.

Parameters of the direct and hydrostatic extrusions are presented in **Table 2**. In the field of extrusion of magnesium alloys, the method of hydrostatic extrusion has been developed quite intensively in recent years. Due to favorable thermo-mechanical conditions, the hydrostatic extrusion process can be carried out at lower-temperatures and a greater grain grinding of magnesium alloys [52, 53].

The comparison of microstructures of various magnesium alloys after plastic forming during extrusion with the same extrusion ratio $\lambda = 25$ for alloys: AZ31, AZ61, AZ80 WE43 (**Figure 23**) indicates diametrical differences in the final plastic

Figure 22.
Grain size measurements on the cross sections of the extruded profiles: Square, Isosceles triangle, circle, and profiles 1, 2, and 3 of complex shape of cross sections and the billet ($\varnothing 100$ mm) [28].

Alloy	Cross section	zone	Grain size—G, Plate I, ASTM E 112	Microhardness HV0.1
AZ31	Billet– Ø 100 mm		7.5	65
	Square		7.5	58
	Isosceles triangle		8.5	65
			7.5	56
	Profile 1	A	10.5	
		B	10.5	
		C	10	
	Profile 2	A	10	
		B	9.5	
	Profile 3	A	10	
		B	9.5	
		C	10	
AZ61	Billet– Ø 100 mm		8.5	65
	Square		9	56
	Isosceles triangle		9.5	62
			9.5	63
	Profile 1	A	9	
		B	10.5	
		C	9,5	
	Profile 2	A	9	
		B	10	
	Profile 3	A	9	
		B	9	
		C	9	
AZ80	Billet– Ø 100 mm		7.5	60
	Square		9.5	58
	Isosceles triangle		9.5	60
			9.5	59
	Profile 1	A	9.5	
		B	9.5	
		C	9.5	
	Profile 2	A	9	
		B	10	
	Profile 3	A	9	
		B	9	
		C	9	

Table 1.
Grain size and hardness HV0.1 of magnesium alloys profiles after extrusion.

deformation effect and let to choose adequate alloy for requirements of given possible application.

Research work using magnesium alloys AZ31, AZ61, AZ80, WE 43, and Mg alloy with Li for production of thin-walled profiles showed the potential of the backward extrusion process of magnesium alloys and KOBO extrusion process to apply them for aeronautical applications. It gives the possibility for indicating the best materials and parameters of the process to use, e.g., bridge dies to produce different types of complex shape of cross sections, which are the interest of aviation industry in light extruded products in order to save energy, costs, etc., by reducing aircraft weight.

Mg alloy	Direct extrusion	Direct extrusion	Hydrostatic extrusion	Hydrostatic extrusion
	temperature [°C]	Speed [m/min]	temperature [°C]	speed [m/min]
AZ31 (Mg-Al-Zn)	320–380	8–15	190	45
AZ61 (Mg-Al-Zn)	320–380	2–4	200	10
ZM21(Mg-Zn-Mn)	320–380	3÷5	200	30

Table 2.
Parameters of the direct and hydrostatic extrusion.

Figure 23.
Microstructures of magnesium alloys after extrusion with the degree of = 25: a – AZ31, b – AZ61, c – AZ80, d – WE43 λ plastic forming.

3.1.4 KOBO extrusion

Processes of severe plastic deformation (SPD) are defined as metal forming processes in which a very large plastic strain is imposed on a bulk process in order to make an ultrafine-grained metal [54]. Possibility to influence on the microstructure and the mechanical properties by heat treatment is also important to plan an SPD process [52, 55]. The KOBO extrusion process as SPD process is an unconventional extrusion method based on the idea of cyclical deformation path change during the process and localized plastic flow [53, 56]. The deformation path change is carried out by setting the die into an oscillating rotary motion around its axis. The method combines the extrusion of the material with an additional plastic deformation caused by reversible

torsion of die. Being induced this way super plastic mode of deformation makes possible to deform metals with very high deformation (SPD process) at low temperature (room temperature). Hence, despite very low load capacity of the press, the methods allow for the variety of metallic products to be extruded at room temperature from the billet, with size and dimensions with value of extrusion ratio λ up to several hundreds. The example for KOBO extrusion of MgLi4 is presented in **Figure 24**.

Superplastic behavior of a metals under such deformation conditions is proven also in exact filling of a die opening, regardless how complicated it is and mode of extrusion forward or sideways. The most important advantage of the KOBO method is the ability to deform metals with a very high λ coefficient (extrusion ratio) [53, 57–59] in the “cold” process (without preheating the billet or tooling), regardless of the hardening state of the initial material. The use of the KOBO method allows for reducing the work of deformation, so the extrusion forces are incomparably lower than in conventional extrusion processes. The examples of measured parameters of KOBO process for magnesium alloys AZ31 and WE43 are shown in **Figure 25**.

KOBO extrusion is a process carried out in a system of concurrent extrusion with an oscillating matrix. In turn, the possibility of forming the products of a specific cross-sectional shape, as in conventional extrusion processes, makes it possible to obtain products, not only specimens, with very fine grains and favorable mechanical properties, which qualify the KOBO method for potential industrial implementations. The significant reduction of the extrusion load and the lack of the need for preheating make the method very economically attractive. Another, extremely attractive feature of the KOBO method is the possibility of low-temperature consolidation of postprocessing chips [28, 53, 57–64] and obtaining a solid product as a result of plastic deformation in the process. The deformation effects of magnesium alloys, both in the form of a solid billet and in the form of consolidated postprocessing chips, are shown in **Figure 26**.

Figure 24.
a) Scheme of KOBO extrusion process, b) extruded wire of Mg Li4 alloy, extrusion ratio $\lambda = 10,000$.

Figure 25.
a) Extrusion of magnesium alloy AZ31 round bar with stable extrusion speed. b) Extrusion of magnesium alloy WE43 round bar with stable extrusion speed. c) Extruded round bar $\phi 3$ mm.

Figure 26.
 Extrusion of metal chips in the KOBO process: a) a chip before and after compaction of chips into billet, b) an extruded monolithic profile, c) extrusion of solid profile of complex shape of cross section.

Low temperature—above 200°C in KOBO extrusion technology of magnesium alloys, possibility to control the final properties of the extruded profiles let to maintain a fine grain structure of the alloys [65]. It comes from the number of KOBO process parameters, such as amplitude and frequency of die oscillations. It is possible to use the backward extrusion and KOBO processes for bulk metals and chips. To determine proper parameters of extrusion process, it is necessary to know exact information on initial features of given magnesium alloy—its macro and microstructure, mechanical properties, and final results of transformation of the internal structure under conditions of plastic deformation.

3.1.5 Joining. Friction Stir Welding

Joining. Friction Stir Welding FSW is solid-state joining process under the influence of frictional heat. There is no melting involved in the process unlike conventional fusion welding process. The FSW process was originally invented in institute TWI in the United Kingdom in 1991 [65–67]. The principle of utilizing the frictional heat between a rotating tool and the two joining metal interfaces is shown in **Figure 27**.

The rotating tool serves two basic purposes: heating of the workpiece materials due to friction and plastic deformation and stir movement and containment of materials to produce joint. Rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and subsequently traversed along the joint line. Advancing and retreating side orientations require knowledge of the tool rotation and travel directions. It is especially important when FSW process is designed for given metallic material. Magnesium alloys require special attention from the point of view of adequate parameters choice, especially for joining very thin sheets, because FSW process is very sensitive to the technological parameters of welding. From the point of view of plasticization of metals, the FSW process is very complex. The rotating tool in the first phase of the process supplies more and more heat, then the welded material is strongly deformed plastically. The material, in contact with the pin of the moving tool, experiences a state of stress and deformation comparable to that in extrusion and forging. The last stage is cooling of the weld [67]. It is important to know the influence of the selected technological and geometrical parameters of the process on the plasticization of the materials to be joined.

Figure 27.
Scheme of linear Friction stir welding process.

Assessment of joint quality on the basis of tests of the mechanical properties of the obtained joints (static strength, fatigue strength, microhardness), microstructure tests in the area of weld, and parent material as well as the measurement of forces acting on the tool as a material response to the load resulting from the adopted process conditions. As a result of the conducted research on linear, FSW stir-mixed butt welding of thin sheets with a thickness of 0.5 mm made of AZ31B magnesium alloy, the basic goal was achieved, which was to obtain a solid, durable, free from defects connection of elements. When welding 0.5 mm thick sheets, the variable parameters were the rotational speed and the tool feed. The friction stir welding process was carried out with the use of magnesium alloy sheets, including AZ31B, 0.5 mm thick. The FSW joining process was carried out as a butt joint. An example of a connection is shown in **Figure 28**.

Figure 28.
FSW joints: a) view of joint with advancing and retreating sides, b) FSW joint of the AZ31B magnesium alloys, a) face and ridge of joint FSW joint of AZ31 B sheets of 0.5 mm of thickness, l = 180 mm.

Due to the difficult conditions for the implementation of the process, an important issue is the selection of an appropriate tool with the appropriate geometry and kind of material of the tool. During FSW welding of magnesium sheets a cemented carbide tool was used. Taking into account the interdependence of mechanical and structural effects in the FSW process, special attention should also be paid to the analysis of the microstructure in the joint area, identification of characteristic zones as a result of the transformation of the microstructure resulting from the plasticization of the joined materials and the generated heat due to friction and plastic deformation, heat dissipation, among others in contact with the tool and tooling and the overall heat balance resulting in the final state of the joint. These are issues for thin sheets, especially for light metals (aluminum alloys, magnesium alloys) [68, 69]. **Figure 29** shows the FSW weld microstructure of a sheet with a thickness of 0.5 mm of AZ31B alloy. The presented sample was made with the welding speed of 80 mm/min and the tool rotation speed of 2000 rpm. It is difficult to identify the zones characteristic for the FSW joint in the case of welding very thin sheets. In this case, the locations of areas such as the heat affected zone, the thermomechanical interaction zone, and the weld core were estimated based on the dimensions of the tool. The area of direct contact of the rim of the tool resistance is characterized by fragmented grain due to high plastic deformation. Equal-axis grain was also observed in the HAZ (heat-affected zone) and TMAZ (thermomechanical-affected zone) as shown in **Figure 28**.

The presence of equiaxed grains in the HAZ and TMAZ zone indicates that the material has fully recrystallized during the FSW process. The dynamics of recrystallization affects the grain size. Magnesium alloys are more prone to dynamic recrystallization than aluminum alloys because the Mg recrystallization temperature is approximately 523 K—lower than that for aluminum alloys. The factor that inhibits grain growth as a result of high temperature is also the cooling rate. In ultrathin materials (sheet thickness equal to or less than 0.5 mm), it is relatively high—the material cools down quickly, which is noticeable already during the process. The joint shown in **Figure 30** does not contain any crater defects or discontinuities.

The obtained results of the FSW joining process of magnesium alloys showed that the process of linear friction stir welding (FSW) is a favorable method of joining difficult-to-weld magnesium alloys [70–73]. Appropriate selection of parameters allows for obtaining joints free from defects. The assessment of the quality of the joints made on the basis of: the results of the joint microstructure analysis, measurements of the microhardness of the joint and the base material as well as the static tensile test of the weld material allowed for an unambiguous determination of the joint effectiveness. Proper selection of technological and geometric parameters allows for obtaining a connection with approximately 90%

Figure 29.
Typical scheme of zones of butt FSW joint (SZ – Stir zone/nugget zone, TMAZ – Thermomechanically affected zone/HAZ – Heat-affected zone/BM – Base material/parent material, RS – Retreating side, AS – Advancing side).

Figure 30.

Typical microstructures of an FSW joint made at different rotational speed and welding speed. a) Microscopic structure of FSW welded AZ31B of 0.5 mm in thickness. View of base material BM. b) Microscopic structure of FSW welded AZ31B of 0.5 mm in thickness. View of HAZ and TMAZ zone from the retreating side. c) Microscopic structure of FSW welded AZ31B of 0.5 mm in thickness. View of stir zone SZ and TMAZ of advancing side.

efficiency in relation to the parent material, determined on the basis of a static tensile test. During the tensile test, all joints broke in the thermomechanical impact zone on the retreating side. This is due to the resulting structural notch at the boundary of the weld nucleus and the thermomechanical influence zone. When welding 0.5 mm thick sheets of Mg AZ31B alloy, the maximum force acting on the tool in the Z axis was 4.5 kN. The values of the forces acting on the tool in the radial direction range from 40 to 100 N. After making a total of approximately 20 m of linear FSW weld, the tungsten carbide tool was not worn according to visual assessment. The FSW process is an excellent alternative to riveting or conventional welding. It does not require the use of an additional connector, which contributes to reduce the weight of the structure. Friction stir welding of the FSW joint allows for the creation of a high-quality, durable, defect-free joint with high mechanical properties (static and dynamic tests) and favorable internal structure of the AZ31B alloy sheet material.

The average obtained connection efficiency with appropriately selected input parameters of the process ranges from 85 to 95% compared with the parent material. These values are fully acceptable to the aviation (min. 80%) and automotive (min. 70%) industries. The analysis of the variability of forces generated during the FSW process requires knowledge of material properties and process conditions. It is necessary to adequately select the process parameters to the type of alloy and thickness of the joined elements (**Figure 31**).

The estimated value of the FSW process temperature should be approximately 0.8 solidus temperature. In this case, for alloy AZ31B, solidus temperature is 605°C, so temperature for FSW process is 430°C. AZ31 alloy with aluminum as the main alloy additive is very brittle at room temperature (only one slip plane (0001)). Only when the temperature of 200°C is exceeded, other slip planes are activated, which facilitates further plastic deformation. Reaching the temperature of 200°C is associated with the phenomenon of recrystallization. Achieving these conditions during welding is possible while providing the rotating and plunging tool with a sufficiently long time stoppage. This treatment is necessary to heat the material due to the pressure and friction of the rotating tool (dwell time). The recorded force courses may indicate the most favorable time to achieve the plasticizing effect and achieve the appropriate plasticization conditions of the material over 450 MPa, which exceeds the value of the yield stress for AZ31B alloy. A sudden increase in radial forces acting on the tool was noticed. Then the welding stage begins, where the stabilization of both axial and radial forces was observed. Very

Figure 31.
Matrix of technological parameters for joining AZ31B alloy sheets of 0.5 mm thickness [68].

good results of joining thin sheets of the AZ31 B alloy [64–69, 74, 75] prove the purposeful use of friction stir welding to join sheets of various thicknesses. Butt joints with smooth surface, without voids and flash, can be obtained by cylindrical flat shoulder and pin tool made from tungsten carbide. Tensile tests revealed a durability increase up to 90% compared with BM, which is thought to be mainly attributed to the preferred basal orientation and the activation of the extension twins. The SZ and TMAZ experienced full dynamic recrystallization and thus consisted predominantly of equiaxed grains. The grain size in SZ increased with increasing heat input.

During the FSW, the process must be carried out at the temperature preferably higher than the recrystallization temperature of the base material BM to be joined for the dynamic recrystallization to take place in the SZ. With increasing tool rotational speed or decreasing welding speed supplied more heat energy and generated a higher temperature in stir zone SZ. This led to a weaker or more random texture stemming from the occurrence of more complete dynamic recrystallization. After the FSW of AZ31B alloy of 0.5 mm in thickness, the lowest hardness occurred at the center of SZ through the HAZ and TMAZ of the welded joints; however, the differences are minor.

The welding speed and rotational speed had a strong effect on the UTS (ultimate tensile strength). When choosing the technological parameters for the process, tool feed rate played an important role compared with a tool rotation speed. The plastic flow in the welded regions is also observed with uniform grain orientation.

4. Summary

The development of plastic forming processes as well as joining processes, such as FSW, is primarily determined by better mechanical properties of plastically processed magnesium alloys compared with castings. Designing the technology of plastic forming of structural elements made of magnesium alloys requires precise determination of the influence of the process parameters on the microstructure and consequently on the mechanical properties of the manufactured elements. This is of particular importance when designing products made of magnesium alloys for structural elements for the aviation industry. The selected results of plastic forming research carried out in material tests and technological processes, under laboratory or industrial conditions presented in this chapter, indicate that selected

magnesium alloys can be formed by plastic forming methods, especially by rolling, extrusion, and KOBEX extrusion and forging. When forming AZ61, AZ80, and WE43 alloys, the temperature range is significantly limited, both at the beginning and the end of the deformation process. Therefore, to carry out plastic forming, especially forging, it is necessary to have devices that enable the process to be carried out in isothermal conditions. For AZ31 alloy, the range of temperatures of good formability is greater due to the greater tendency of this alloy to the recrystallization process. Thus, it is possible to manufacture AZ31 alloy products on conventional devices, but the obtained mechanical properties are less favorable than other magnesium alloys.

Magnesium-lithium alloys deserve attention due to their plastic formability, mechanical properties, and low specific weight, which makes them very attractive wherever lightweight and durable structures are desired. Elements manufactured by plastic processing of magnesium alloys and new technologies involving plastic deformation, including joint friction welding (FSW) technologies, are currently successfully implemented in various sectors of the economy.

Magnesium and its alloys are mainly used as a construction material (most often in the form of castings from magnesium alloys, but also plastically formed products), as an alloy additive to aluminum alloys, and for desulfurization of iron and steel. Due to the low specific mass and high relative strength, magnesium alloys in the form of castings or plastically formed products are used in such industries such as: aviation and aerospace, for the production of aircraft and rocket parts, including engine parts, gearbox components, hinges, fuel tanks, wing elements; automotive, for the production of, among others car rims, various types of housings, engine blocks, steering wheels, seat frames, windows and doors, body parts; sports and recreational, for bicycle parts and elements of various sports equipment articles; electronic, mainly for the production of various types of electronic equipment housings; medical, for strengthening elements in bone fractures. Examples of applications of magnesium alloys in the aviation industry include: Rolls Royce gear housing made of ZRE1 alloy Pratt & Whitney Canada PW535 engine housing made of ZE41 alloy, helicopter parts. In the automotive sector, the examples are steering wheel, boot lid; manufacturer GM, BMW engine block; cross section of the outer layer made of Mg alloy revealing the inner layer of Al alloy.

Now it is time for the successful application of magnesium-based materials. It is particularly important to promote exchange of information and discussion in which development trends and application potential in different fields such as the automotive industry and communication technology in an interdisciplinary framework [37, 72, 73].

Acknowledgements

The author gratefully acknowledges the collaboration and discussions with. Prof. Eugeniusz. Hadasik and Prof. Andrzej Gontarz, who provided support and information on magnesium research and application.

Financial support of Structural Funds in the Operational Program–Innovative Economy (IE OP) financed from the European Regional Development Fund–Project “Modern material technologies in aerospace industry,” Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

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