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Wrought magnesium alloys for structural applications

D. Letzig*, J. Swiostek, J. Bohlen, P. A. Beaven and K. U. Kainer

Wrought magnesium alloys are of special interest as lightweight structural components as a result of their more homogeneous microstructures and improved mechanical properties compared to cast components. Extrusion as a shaping technology offers the possibility to produce a wide variety of magnesium alloy profiles. In this contribution, the authors describe the role of extrusion parameters such as extrusion rate, ratio and temperature as well as the type of extrusion process on the microstructure of AZ series magnesium alloys and the resulting mechanical properties. The effect of microstructure on the tensile/compression deformation behaviour of the alloys has also been investigated. In a further step, extruded material has been used in die forging experiments. Aspects of alloy development and process optimisation designed to overcome technical and economic limitations and thus establish magnesium alloy profiles for industrial applications will also be discussed.

Keywords: Magnesium alloys, Indirect extrusion, Low temperature hydrostatic extrusion, Die forging, Microstructure, Tension–compression yield asymmetry

Introduction

Lightweight construction is currently one of the major issues facing the transportation industry as a result of the need to save natural energy resources via weight reduction. Magnesium and its alloys being the lightest available metallic, structural materials thus have a major potential for use in the automotive industry. Castings of magnesium and its alloys already find their use in many industrial applications, but the situation is much more difficult for semifinished, wrought products. The application of wrought magnesium alloys is hindered by the lack of knowledge on the influence of thermomechanical treatments such as extrusion or forging on the properties of the resulting components. Because the properties are critically dependent on the microstructure that evolves during processing, a better understanding is needed in order to optimise the microstructure property relationships of wrought components.

Extrusion is one possibility for the production of long, shaped and thin walled components that could extend the opportunities for magnesium alloys in lightweight construction. Although the technology for processing magnesium profiles is available and alloys for profiles have existed for more than 60 years,[1] there is no mass production of such components at present. Existing alloys show only a narrow range of properties and their ambient temperature formability is rather limited. All forming processes have to be carried out at elevated temperatures, as it is well known that at temperatures below 200−225°C, the workability of magnesium alloys is limited and may lead to cold cracking.[1–3] Typical processing temperatures for the direct or indirect extrusion of magnesium alloys are in the range 260–450°C.[4] An important issue in the extrusion of magnesium alloys is the extrusion rate that can be achieved during processing[5,6] as this will determine the economic viability of commercial products. Adiabatic heating can lead to incipient melting and hot cracking, especially in aluminium and zinc containing magnesium alloys. These have solidus temperatures that decrease significantly with increasing content of the added aluminium and contain intermetallic compounds with low melting temperatures.[8] These factors are responsible for limiting the processing window for the conventional extrusion of magnesium alloys. A similar temperature range has also been established for die forging and sheet forming.[7–9]

It is currently possible to obtain fine grained (about 1–4 μm) microstructures with equal channel angular extrusion (ECAE), multiple forging or powder metallurgy methods,[10–12] but these processes are associated with high cost and are mainly of academic interest. The authors' recent experiments have shown, however, that hydrostatic extrusion enables higher extrusion ratios and extrusion rates at lower extrusion temperatures to be used than in conventional direct and indirect extrusion.[2,13] The microstructure and texture of the resulting round bars have been analysed and related to the mechanical properties in previous publications.[14,15]

In this paper, the authors will compare the results of low temperature (100°C) hydrostatic extrusion trials for alloys of the magnesium AZ series with those obtained by indirect extrusion at 300°C and investigate the role of

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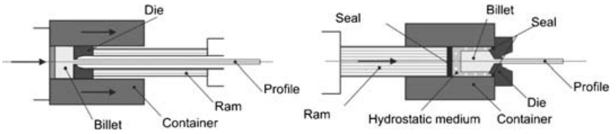


1 Schematic drawings of indirect (left) and hydrostatic (right) extrusion processes

microstructure on the well known tensile/compression yield stress asymmetry. To this end, the mechanical properties of the AZ series alloys have been determined as a function of the extrusion parameters. The authors will also report the preliminary results on the die forging of extruded feedstock of various magnesium alloys.

Experimental

Table 1 provides a summary of the alloy compositions used in the extrusion and die forging trials.

Extrusion trials were carried out using both indirect extrusion and hydrostatic extrusion. The principles of the processes are shown in Fig. 1. During indirect extrusion, the billet is placed in a container and deformation is realised by pressing a hollow ram with a die in front of it into the billet. During hydrostatic extrusion, the pressure is developed from the ram and passed on to the medium leading to a hydrostatic pressure from all sides on the billet to make it flow through the die. The differences between these two processes are the type of applied pressure on the one hand and the die geometry on the other hand.

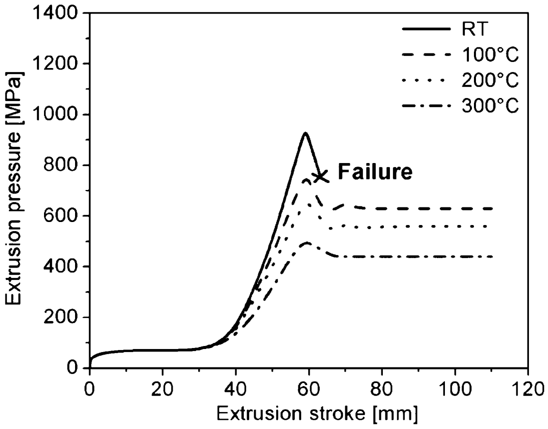
For all extrusion experiments, commercial direct chill (DC) cast feedstock (diameter: 95 mm) of the alloys AZ31, AZ61 and AZ80 was machined to billets (diameter: 80 mm). The billets were then heat treated for 12 h at 350°C (AZ31 and AZ61) or at 385°C (AZ80). All billets were subsequently air cooled.

Initial hydrostatic extrusion trials were carried out on the magnesium alloy AZ31 at temperatures from 300°C down to room temperature in steps of 100°C in order to determine the lowest possible extrusion temperature for the subsequent experiments. The rod profiles of the AZ31 alloy were extruded using a MoS_2 lubricant and an extrusion ratio of 1 : 28 at all temperatures. In order to avoid failure at the start of the extrusion process, the die was preheated to 300°C. An extrusion rate of 8 m min^{-1} was employed, which corresponds to the lowest possible speed for hydrostatic extrusion with the 12MN-ASEA-press used. In spite of the high extrusion rate and low forming temperatures, the limit of press capacity was not exceeded as can be seen in Fig. 2, where the extrusion pressure is plotted as a function of the extrusion stroke.

The subsequent hydrostatic extrusion experiments with AZ31 and AZ61 were performed at a processing temperature of 100°C. In preliminary extrusion trials of AZ80 carried out at 100°C, cold cracks were observed on the surface of the rods. For this alloy, the temperature was therefore increased to 110°C. As known from conventional extrusion trials on AZ61 and AZ80, extrusion rates of about 2 and 4 m min^{-1} respectively are regarded as maximum possible speeds.[16] All the authors' indirect extrusion experiments were carried out at a temperature of 300°C with an extrusion ratio of 23. Under these conditions, it was possible to extrude the alloy AZ31 at a rate of 8 m min^{-1}, but the maximum possible extrusion rates for AZ61 and AZ80 corresponded to 6 and 4 m min^{-1} respectively.

Table 1 Alloy compositions

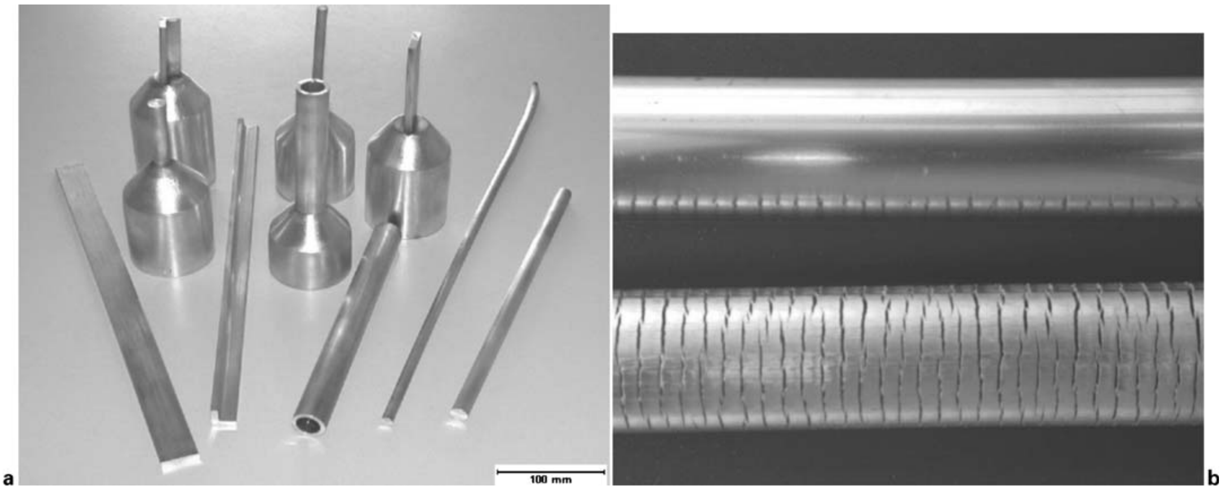
Alloy	Chemical composition, wt-%
AZ31	Mg–2·9Al–0·98Zn–0·29Mn
AZ61	Mg–6·5Al–0·99Zn–0·20Mn
AZ80	Mg–8·5Al–0·51Zn–0·31Mn
AZ80Ca	Mg–8·5Al–0·51Zn–0·31Mn–2·1Ca
ZK30	Mg–3·0Zn–0·58Zr
ZK60	Mg–5·8Zn–0·58Zr



2 Development of extrusion pressure with increasing extrusion stroke for AZ31 at different temperatures: maximum pressure increases with decreasing extrusion temperature

All the forging experiments were carried out using pre-extruded magnesium alloys. Commercial DC cast feedstock with a diameter of 95 mm of the alloys ZK30, ZK60, AZ80 and AZ80Ca (AZ80 modified with 2%Ca) were machined to billets with a diameter of 90 mm which were then heat treated for 12 h at 400°C followed by air cooling. The materials were then hydrostatically extruded at 300°C with an extrusion ratio of ~8 and an extrusion rate of 3 m min^{-1} to 32 mm diameter round rods. Subsequently, the rods were machined to samples with 30 mm diameter and 40 mm length. Forging experiments were conducted using a mechanical press with a nominal force of 100 kN. With this machine, a higher forging speed than that of a typical hydraulic press could be realised. Round forgings with a simple shape were produced using preheated tools.

All experiments were accompanied by microstructural analysis using optical microscopy on polished and etched longitudinal sections. Samples were etched with a solution based on picric acid.[17] Tensile and compression tests were performed at room temperature with a commercial testing machine (Zwick Z050) with a maximum applied force of 50 kN at a strain rate of 10^{-3} s^{-1} in all cases. Tensile tests were carried out according to DIN 50125 specifications on round samples with diameter 6 mm, total length 60 mm and gauge length 30 mm. The cylindrical samples for compression testing according to DIN 50106 specifications were 11 mm in diameter and 16·5 mm in height. For each condition, three to five identical samples were tested in both tension and compression. The scatter in the results was minimal with variations of less than ±2 MPa between the individual measurements.



3 ***a* typical examples of profiles and remainders hydrostatically extruded at low temperature and *b* comparison of surfaces of hydrostatically (above) and conventionally (below) extruded AZ80 rod with similar extrusion parameters**

Results and discussion

Extrusion experiments

Hydrostatic extrusion trials were performed on the billets of AZ31, AZ61 and AZ80 which exhibited microstructures with rather coarse grains sizes in the range 300–500 μm following the homogenisation treatment. These resulted in extruded profiles with smooth surfaces at an extrusion temperature of 100°C for AZ31 and AZ61 and at 110°C in the case of AZ80 (Fig. 3*a*). The surfaces of the materials showed no evidence for hot or cold cracking (Fig. 3*b*). It should be emphasised that hydrostatic extrusion with a rate of 8 m min^{-1} was successful for all alloys. In particular, for the alloy AZ80, this corresponds to an extrusion rate which is four times higher than for conventional processing.

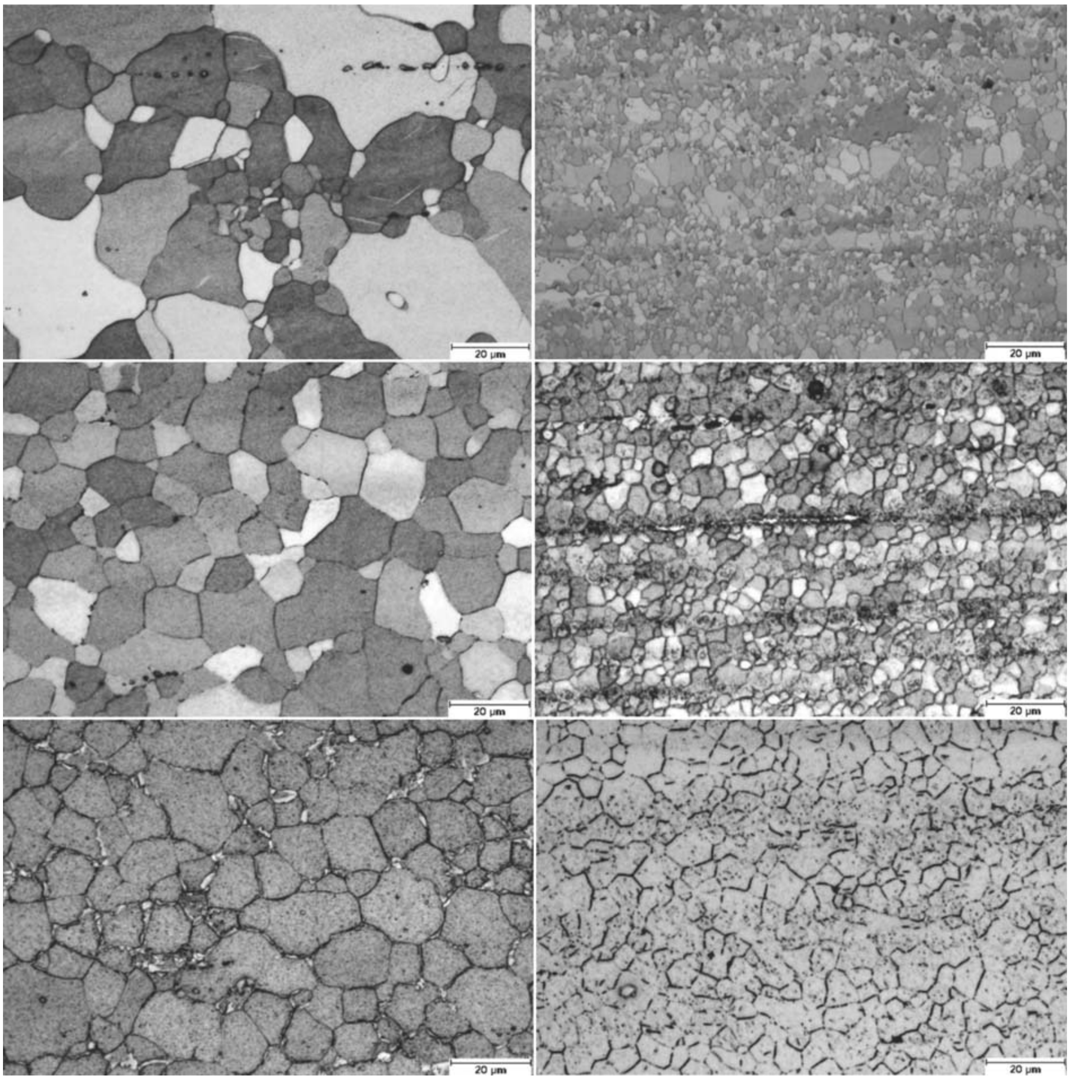
The micrographs shown in Fig. 4 reveal that extrusion led to almost completely recrystallised microstructures in each alloy as a result of dynamic recrystallisation. The microstructures of the AZ31 profiles were generally rather inhomogeneous with regard to grain size. However, the increased Al content in AZ61 and AZ80 appears to improve the homogeneity in terms of grain size. In general, the homogeneity of microstructure was better in the case of low temperature hydrostatic extrusion.

Measurements of the average grain size of each alloy showed that for all hydrostatically extruded rods, a significant reduction in grain size was obtained compared to the conventionally extruded profiles. Average grain sizes for the latter corresponded to $\sim$22 μm for AZ31 and $\sim$12 μm for AZ61 and AZ80. The grain sizes of the hydrostatically extruded AZ alloys appeared to increase with increasing aluminium content. Average grain sizes in the range 2–4 μm were measured for the AZ31 and AZ61 alloys. The development of such small grains could be explained by the lower temperature rise in the profiles during the hydrostatic extrusion process, but further experiments are necessary to verify this. In the case of AZ80, the mean grain size was about 6–7 μm. It should be noted that the grain sizes in AZ31 and AZ61 obtained by hydrostatic extrusion at 100°C are comparable to those achieved by ECAE.[10]

The yield strengths of the hydrostatically extruded AZ alloys with finer grain sizes exhibit higher values in agreement with the Hall–Petch relationship.[12] Figure 5 shows the mechanical properties of the hydrostatically extruded rods obtained from tensile and compression tests performed at room temperature. In all cases, it is found that the tensile yield strength (TYS) is similar or only slightly higher than the corresponding compressive yield strength (CYS). In Fig. 5, the elongation to fracture is also presented for each alloy. The largest elongation to fracture was measured for AZ31 which has the finest grain size of all the alloys studied.

The anisotropy of mechanical properties is always a concern in magnesium alloys and is a factor that limits their application. The hexagonal lattice structure is associated with strongly orientation dependent deformation mechanisms that lead to a distinct asymmetry in tensile and compression yield strength.[18,19] Further tests were therefore conducted to investigate the role of microstructure in the differences between the TYS and CYS of the extruded AZ alloys. As an example, Fig. 6 shows the stress–strain curves of the AZ31 alloy measured in tension and compression. The form of the curves is quite typical for the AZ series alloys with the deformation behaviour in compression being characterised by high levels of work hardening and stress–strain curves with a 'concave' shape. This behaviour is generally ascribed to the effects of {10–12} twinning. The most striking feature in Fig. 6 is the difference between the indirectly and hydrostatically extruded AZ31 samples.

The differences between the tensile and compressive yield stresses $\Delta\sigma$ determined from these tests on AZ31, correspond to $\sim$100 MPa for samples indirectly extruded at 300°C (average grain size: $\sim$22 μm) compared to $\sim$12 MPa for samples hydrostatically extruded at 100°C (average grain size: $\sim$3 μm). This behaviour may be attributed to the suppression of the contribution made by twinning as a deformation mode in fine grained microstructures.[21] In the case of the AZ alloys with higher aluminium contents (AZ61 and AZ80), the samples indirectly extruded at 300°C show $\Delta\sigma$ values that are significantly lower than for AZ31. This reduction in $\Delta\sigma$ is the largest at the highest aluminium content. By comparison, the hydrostatically extruded samples of AZ61 and AZ80 show the lowest values of $\Delta\sigma$. These reductions in yield stress asymmetry suggest



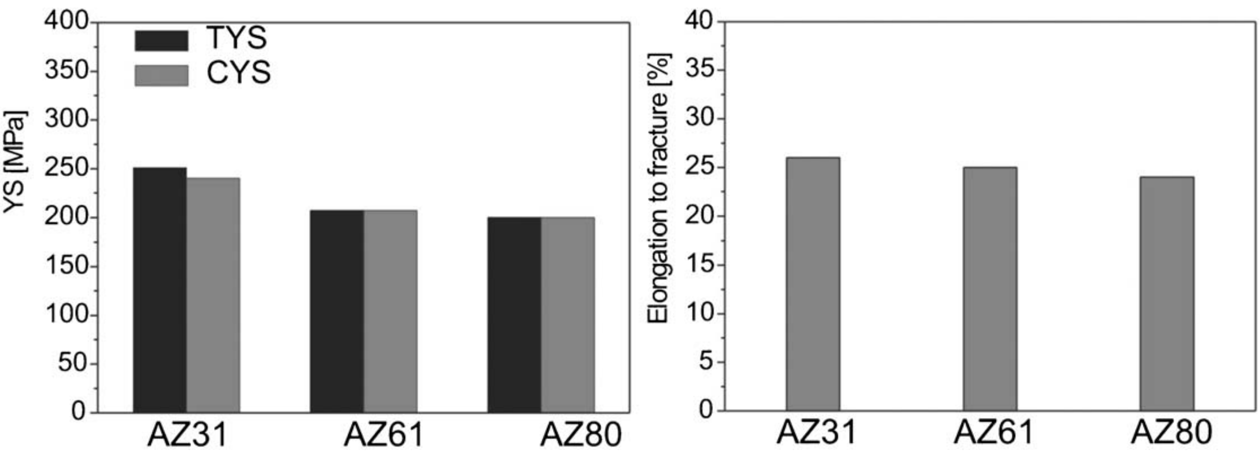
4 Light micrographs of extruded AZ31, AZ61 and AZ80 after indirect extrusion (left) and after hydrostatic extrusion (right)

that not only grain size but also the precipitation of the $Mg_{17}Al_{12}$ phase have similar effects on twinning.

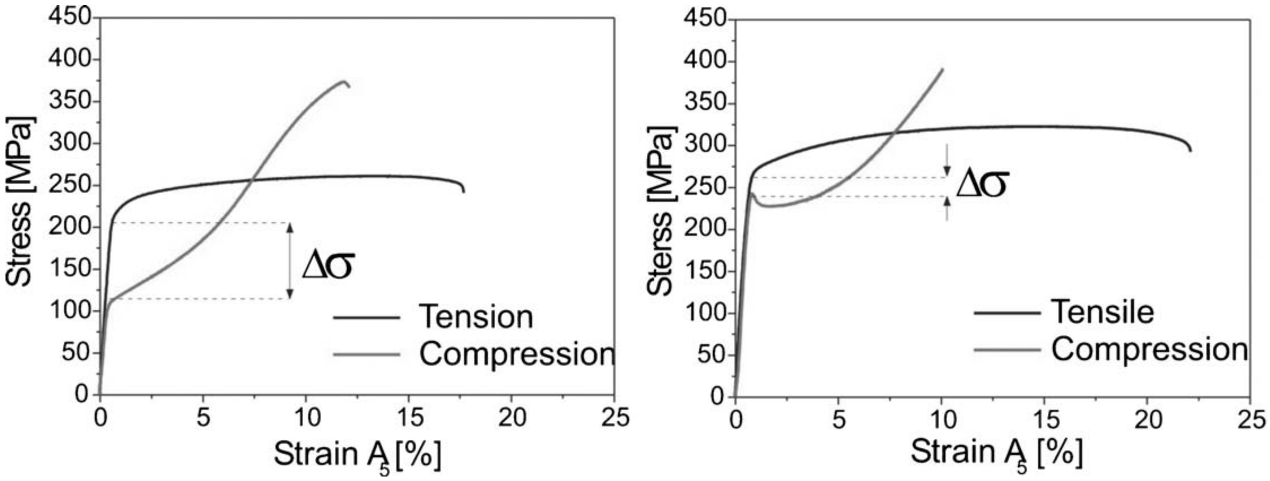
Forging experiments

The preliminary die forging experiments carried out at 350°C on extruded feedstock demonstrated that this process offers the possibility to produce forgings of various magnesium alloys with no evidence for hot or cold cracking (Fig. 7).

In the case of the AZ series, alloys homogeneous and fully recrystallised microstructures were observed whereas recrystallisation during forging led to inhomogeneous



5 Tensile and compressive yield strengths together with fracture elongations of AZ alloys after low temperature (~100°C) hydrostatic extrusion: TYS, tensile yield strength; CYS, compressive yield strength; YS, yield strength



6 Stress–strain curves in tension and compression for AZ31: left indirectly extruded at 300°C and right hydrostatically extruded at 100°C

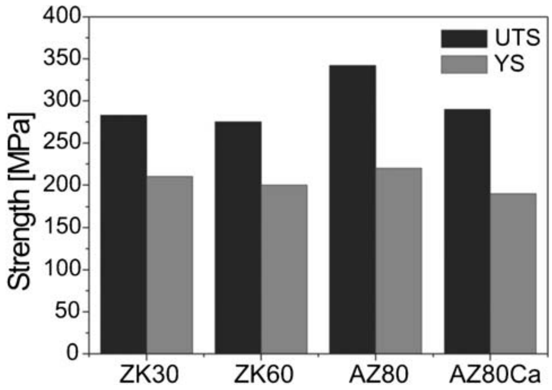
grain size distributions in ZK30 and ZK60. The strength properties of the forged alloys are shown in Fig. 8. The highest ultimate tensile strength (UTS) and yield strength (YS) were obtained for alloy AZ80 followed by ZK30 and ZK60. With respect to the alloys used in this study, the commercial wrought magnesium alloy AZ80 is of special interest for die forging.

Summary

The behaviour of magnesium alloys during hydrostatic extrusion has been investigated and it is shown that this process offers the possibility to decrease the extrusion temperature to 100°C for AZ31 and AZ61 and 110°C for AZ80. In comparison to conventional extrusion, the hydrostatic extrusion of AZ series alloys at these temperatures leads to more homogeneous microstructures with significantly finer grain sizes and guarantees improved mechanical properties. Higher yield strengths are achievable without any detrimental effects on fracture elongations. Moreover, this is accompanied by a reduction in the magnitude of the tensile/compressive yield stress asymmetry which is especially dramatic in the case of the AZ31 alloy.

The process parameters employed in this work such as extrusion ratio and extrusion rate are similar to typical industrial parameters, but the use of the hydrostatic extrusion method allows the processing temperature to be reduced significantly. Although hydrostatic extrusion trials conducted at room temperature proved unsuccessful, it is not yet clear whether the processing window can be extended further in terms of extrusion ratios and rates. Further experiments are planned in this connection and to verify the relationships among microstructure, texture and the resulting mechanical properties.

7 Magnesium alloy forgings worked at 350°C after pre-extrusion



8 Comparison of ultimate tensile strength (UTS) and yield strength (YS) after die forging at 350°C

Preliminary experiments have shown that employing extruded materials as feedstock enables die forging to be carried out successfully at 350°C with no evidence of either cold or hot cracking.

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References

1. A. Beck: 'Magnesium und seiner legierungen'; 1939, Berlin, Springer-Verlag.
2. A. den Bakker, W. H. Sillekens, J. Bohlen, K. U. Kainer and G. Barton: Proc. 6th Int. Conf. on 'Magnesium alloys and their applications', (ed. K. U. Kainer), 324–330; 2004, Weinheim, Wiley-VCH.
3. E. F. Emley: 'Principles of magnesium technology'; 1966, Oxford, Pergamon Press.
4. K. B. Müller: in 'Magnesium technology 2002', (ed. H. I. Kaplan), 187–192; 2002, Warrendale, PA, TMS.
5. J.-F. Lass, A. Metz, M. Wappelhorst, E. Hombergsmeier, H. Lanzerath, P. Baumgart and P. Cordini: Proc. 6th Int. Conf. on 'Magnesium alloys and their applications', (ed. K. U. Kainer), 1026–1033; 2004, Weinheim, Wiley-VCH.
6. W. H. Sillekens and J. Bohlen: Proc. 6th Int. Conf. on 'Magnesium alloys and their applications', (ed. K. U. Kainer), 1046–1051; 2004, Weinheim, Wiley-VCH.

7. N. Ogawa, M. Shiomi and K. Osakada: *Int. J. Mach. Tools Manuf.*, 2002, **42**, 607–614.
8. M. M. Avedesian and H. Baker (eds.): 'Magnesium and magnesium alloys'; 1999, Materials Park, OH, ASM International.
9. J. Bohlen, F. Chmelik, P. Dobron, F. Kaiser, D. Letzig and K. U. Kainer: *J. Alloys Compd*, 2004, **378**, 207–213.
10. H. Watanabe, T. Mukai, K. Ishikawa and K. Higashi: *Scr. Mater.*, 2002, **46**, 851–856.
11. A. M. Galiyew, R. O. Kaibyshev and G. Gottstein: in 'Magnesium technology 2002', (ed. H. I. Kaplan), 181–185; 2002, Warrendale, PA, TMS.
12. C. Sanchez, G. Nussbaum, P. Azavant and H. Octor: *Mater. Sci. Eng. A*, 1996, **A221**, 48–57.
13. J. Goeken, J. Swiostek, D. Letzig and K. U. Kainer: *Mater. Sci. Forum*, 2005, **482**, 387–390.
14. J. Bohlen, J. Swiostek, W. H. Sillekens, P.-J. Vet, D. Letzig and K. U. Kainer: in 'Magnesium technology 2005', (ed. N. R. Neelameggham *et al.*), 241–246; 2005, Warrendale, PA, TMS.
15. J. Bohlen, J. Swiostek, H.-G. Brokmeier, D. Letzig and K. U. Kainer: in 'Magnesium technology 2006', (ed. A. A. Luo *et al.*), 213–217; 2006, Warrendale, PA, TMS.
16. G. Fischer: Proc. Conf. on 'Magnesium im fahrzeugbau', Sindelfingen, Germany, April 2003, IIR Deutschland GmbH. 1
17. V. Kree, J. Bohlen, D. Letzig and K. U. Kainer: *Pract. Metallogr.*, 2004, **5**, 233–246.
18. C. H. J. Davies, F. Xiong and M. Battaini: in 'Magnesium alloys and their applications', (ed. K. U. Kainer), 433–438; 2003, Weinheim, Wiley-VCH.
19. P. G. Partridge: *Met. Mater.*, 1967, **1**, 169–194.
20. M. R. Barnett, Z. Keshavarz, A. G. Beer and D. Atwell: *Acta Mater.*, 2004, **52**, 5093–5103.

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