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Forging of Mg-Alloys AZ31 and AZ80

Schmieden der Mg-Legierungen AZ31 und AZ80

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Mg-wrought alloys recently became an engineer material of constantly increasing interest. The mechanical properties of extruded Mg-feedstock of the alloys AZ80 and AZ31 indicate their suitability for automotive applications in form of high-quality forgings. Therefore a detailed knowledge about the forming behaviour is of particular importance. In order to compare mechanical properties of available Mg-feedstock qualities compression tests at room temperature have been carried out by applying batches of AZ31- and AZ80-feedstock. Cylindrical specimens were made out of received continuously casted as well as extruded AZ31- and AZ80 - rods. A quantitative analysis of Mg-feedstock's microstructure has been carried out. The characterization of the deformability of applied Mg-feedstock under hot working conditions could be performed by means of uniaxial plain strain upsetting tests at temperatures between 300 and 450 °C as well as logarithmic strain rates of 10^{-1}, 1 and $10s^{-1}$. It is shown that the chosen parameter range ensures an enhanced deformability of continuously as well as extruded Mg-feedstock. The subsequently carried out determination of microstructural evolution could be related to obtained flow stress curves of applied batches of Mg-feedstock. Furthermore, FVM/FEM-systems have been employed in order to design a simplified geometry of heated forging dies suitable for forging tests. The tests have been carried out by means of a hydraulic press. During the tests their punch velocity has been varied between 1 and 40 mm/s. Hence numerically simulated results could be confirmed by practical tests. Exemplary forgings of a simplified shape were made out of all applied batches of Mg-feedstock. No remarkable failures have been detected.

Keywords: Mg-alloy, AZ80, AZ31, forging

Das Interesse an Mg-Knetlegierungen als Konstruktionswerkstoff für automobile Anwendung ist in jüngster Zeit stark gewachsen. Daher ist eine detaillierte Kenntnis der optimalen Parameter für die Massivumformung von besonderer Bedeutung. In der Absicht einen Vergleich der mechanischen Eigenschaften des Mg-Ausgangsmaterials des Typs AZ31 und AZ80 zu ermöglichen, wurden Druckversuche bei Raumtemperatur durchgeführt. Die Proben hierfür sind sowohl stranggegossenem als auch stranggepresstem Ausgangsmaterial beider Legierungen entnommen worden. Die Charakterisierung der Ausgangsmikrostruktur erfolgte mittels einer quantitativen Gefügeanalyse. Die Charakterisierung der Umformbarkeit beider Legierungen erfolgte durch Zylinderstauchversuche bei Temperaturen von 300 bis 450 °C und Umformgeschwindigkeiten von 10^{-1}, 1 und $10s^{-1}$. Es konnte gezeigt werden, dass die benannten Parameter einen Schmiedeprozess für alle verwendeten Typen an Ausgangsmaterial ermöglichen. Der Einfluss der Umformparameter auf das Ver- und Entfestigungsverhalten des verwendeten Ausgangsmaterials ist herausgearbeitet worden. Unter Verwendung eines FEM/FVM - Simulationssystems wurde eine Gravur für ein isotherm beheiztes Gesenk ausgelegt. Mittels einer hydraulischen Presse sind Schmiedeversuche bei eingestellten Stößelgeschwindigkeiten von 1 bis 40 mm/s durchgeführt worden. Schmiedestücke einer vereinfachten Geometrie konnten ausgehend vom AZ31- und AZ80-Ausgangsmaterial im stranggegossenen und stranggepressten Zustand ohne Auftreten äußerer Fehler hergestellt werden.

Schlüsselwörter: Mg-Legierung, AZ80, AZ31, Schmieden

1 Introduction

Although the application of Mg-alloys offers potentials for a weight reduction in automotive part design, their use is still limited. In comparison to competing light-weight materials, such as aluminium alloys, they are of small importance. In particular the application of Mg-wrought alloys represents a small part of industrial consumption for automotive part production [1]. Automotive components, made of Mg-wrought alloys, promise in addition to general advantages of Mg-materials, such as small specific weight, excellent machinability, nearly unlimited raw material resources as well as good recycability, further outstanding properties, including higher yield-strength and improved elongation values as well as superior dynamic properties [2]. Therefore the objective of this investigation is, to complete and extend the existing technological knowledge concerning the value-added chain for components, made of Mg-alloys AZ31 and AZ80. The exigencies of the formulation of additional know-how's for the production of high-quality Mg-forgings is accommodated in form of investigations concerning in particular the forging process. The further intention is, to evaluate possibilities for the implementation of a production of Mg-forgings of AZ31- and AZ80-alloys, excluding the commonly employed extrusion process. This shall ensure the opening of new potentials for cost savings in the value-added chain of Mg-forgings and requires the supplement of a fine-grained Mg-feedstock as result of the continuous casting process. The tests have to indicate orientations for further developments as well as potentials for improvements of mechanical properties of forged components. The parameter of the production process for the processing of continuously casted and extruded batches of Mg-feedstock have to be determined.

2 Characteristics of Mg-Feedstock Applied for Investigations

The characteristics of received Mg-feedstock are of vital importance for the deformation induced hardening- and soft-

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Table 1. Mechanical properties of received Mg-feedstock

Tabelle 1. Mechanische Eigenschaften des Mg-Ausgangsmaterials

Material	$\sigma_{0.2C}$		UCS [MPa]		El [%]	
AZ31 – cont. casted	38,4		263,5		21,8	
AZ80 – cont. casted	89.6		268.8		10,6	
AZ31 – extruded	L	LT	L	LT	L	LT
as received	94,7	56,3	397,6	278,0	11,8	15,8
solution heat treated	73,7	52,6	376,8	287,0	11,5	16,6
artifical aged	75,1	48,5	393,8	263,3	12,6	14,2
AZ80 – extruded	L	LT	L	LT	L	LT
as received	159,3	116,8	431,3	352,9	11,4	12,8
solution heat treated	104,3	82,0	420,1	366,2	12,5	16.5
artificial aged	159,2	126,7	457,6	373,6	10,5	11.7

ening behaviour under hot working condition as well as for achievable mechanical properties of AZ31- and AZ80-forgings. Thus in particular the initial grain-size and already existing strain values strongly influence the specific material behaviour during plastic deformation. In addition, the determination of Mg-feedstock properties leads to indications for achievable static properties of forgings to be manufactured in several tests.

The examination of mechanical properties by means of compression tests led to the results displayed in *Tab. 1*. In order to carry out these tests, cylindrical specimens of dimensions of Ø12.5 mm x 20 mm have been machined out of received feedstock (continuously casted as well as extruded). The orientation of the specimens of extruded feedstock, available in form of a round rod, has been varied parallel and perpendicular to the extrusion direction. In order to estimate the influence of heat treatment on mechanical properties of primarily deformed Mg-feedstock, the compression tests have been carried out by applying several heat treatment tempers as there are F, T4 and T6. The solution treatment of AZ31-feedstock was carried out at 390 °C and a dwell time of 12 hours. For the AZ80-feedstock a temperature of 410 °C was applied for 12 hours. The subsequent artificial aging was carried out at temperatures of 150 °C and 170 °C respectively 12 hours.

A strong dependence of applied solution treatment condition on mechanical properties has been clearly found for AZ80-feedstock. Variances in compressive strength values and compressive strains at failure are obvious. It is confirmed, that in particular plastic deformation of AZ80 material has to be carried out by taking into account the actual conditions of applied feedstock. Because of the solvus-temperature of the AZ80-alloy, located in the range of applicable forming temperatures, the accelerated creation of precipitations may be caused during the primary deformation process and subsequent forging steps. Thus the efficiency of a precipitation hardening treatment after the forging process is directly influenced by heat treatment conditions of received extruded feedstock and applied forging parameters. The displayed values for the compressive yield strength, compressive strength as well as achievable compressive strains at failure converge to the characteristics of the heat treatment condition T5 in case of application of a relatively low forming temperature. Basically, both of the Mg-alloys dispose of the constitutional assumption for the precipitation hardening process, although a technically useful enhancement of strength values is achievable for the AZ80-alloy in particular. An enhancement of notch sensitivity must be taken into account [4].

The mechanical properties give further indications for technical necessities of forming-processes suitable for Mg-wrought alloys. Whereas displayed strength properties of continuously casted Mg-feedstock are assumed as to be nearly isotropic, the processing of Mg-feedstock by extrusion causes their pronounced fibre texture. While plastic deformation occurs slip is preferred on (0001)-basal planes. This fact subsequently leads to their preferred basal–plane orientation in flow direction [5]. In consequence of this pre-orientation of the elementary cells the activation of different deformation mechanisms is caused in dependence on employed forming temperatures and loading directions. These, for hcp - metals typically inherent property, leads to less isotropic strength- and strain to failure values. Compressive loads of specimens, orientated perpendicular to the extrusion direction of extruded feedstock, enable eased slip movements in numerous pre-orientated basal planes. Published values in literature exhibit by far higher values for the tensile yield strength than for the offset yield strength in case of the orientation parallel to the extrusion direction. These differences may be explained by the creation of deformation twins in {1012}-second order pyramidal planes. In this case the chosen load acts parallel to the preferred basal-plane orientation. The comparison of tensile and compressive yield strength values in perpendicular orientation of extruded feedstock does not show such significant varieties [6, 7]. Finally the crystal orientation and the microstructural texture in form of elongated grains and precipitation bands, mainly caused by the extrusion process, influence the forming behaviour of AZ31- and AZ80-feedstock in different directions.

With regard to the production process of Mg-forgings it has to be reasoned that their requirements on the loading direction in service should be aligned with the concrete conditions of material flow inside the forming die. The forging of primarily deformed batches of Mg-feedstock by avoiding the recrystallisation process, what usually provides an enhancement of strength properties, in particular in case of application of

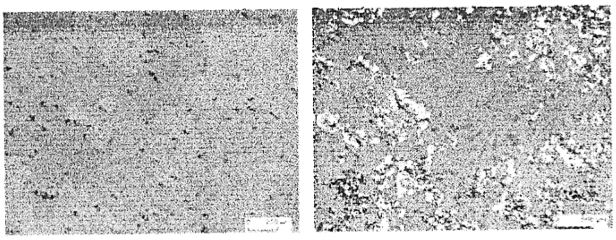

Fig. 1. Micrographs of continuously casted Mg-feedstock AZ31 (left /) / AZ80 (right /)

Abb. 1. Gefüge des stranggegossenen Mg-Ausgangsmaterials AZ31 (links/) / AZ80 (rechts /)

few subsequent forging steps, the consideration of existing fibre texture orientation is of vital importance. This fact becomes even more important, if the forging process does not result in further deformation in several cross section areas of the work piece geometry. Basically desired isotropic properties in Mg-feedstock can be attained by means of multiple open die forging in several directions. The quantitative microstructural analysis of Mg-feedstock, applied for the tests, led to the results displayed in *fig. 1*. The continuously casted material possesses average grain sizes in the range of 250 – 350 *μm* for both alloys, AZ31 and AZ80.

In comparison, the microstructure of extruded feedstock is characterized by a fine-grained microstructure of average grain sizes of 16 *μm* for the AZ31- and 20 *μm* for the AZ80-material (*fig. 2*). The most obvious difference between these two alloys is the existance of γ-phase-precipitations ($Mg_{17}Al_{12}$) in AZ80-feedstock due to 8 at% aluminium alloying addition in comparison to 3 at% in case of the AZ31-alloy (fig. 2).

3 Determination of Flow Stress Curves

The determination of flow stress curves meets various requirements. They mainly serve as data-basis for numerically simulation of forming processes in FEM/FVM-software systems. Furthermore, the achieved compressive strain at failure, attained by means of uniaxial upsetting tests, should provide first indications with respect to the materials deformability in critical cross section areas of the forging's geometry. A subsequent metallografical analysis was employed for the determination of microstructural evolution, caused by warm forming at temperatures between 300 - 450 °C. In this context the determination of the critical point for recrystallisation in dependence on employed forming temperature, strain rate and Mg-feedstock quality is of particular interest.

The flow stress curves, based on the Mg-feedstock of the alloys AZ31 and AZ80, have been determined for received continuously casted and extruded Mg-feedstock. For this purpose, cylindrical specimens of already explained dimensions were machined out of extruded rods in orientations parallel and perpendicular to the extrusion direction. The examinations have been performed at 300, 350, 400 and 450 °C. A servo-hydraulic testing machine "Schenck" was applied in order to carry out the deformation tests. The velocity has been kept constantly at logarithmic strain rates of 10^{-1}, 1 und 10 s^{-1}. In *fig. 3* are shown exemplary flow stress curves of extruded Mg-material of the alloys AZ31 and AZ80 at the temperatures of 300 and 450 °C and strain rates of 1 s^{-1}.

The determined hardening and softening behaviour of examined Mg-feedstock whilst plastic deformation basically matches the reference values in various publications [8, 9, 10]. Both kinds of Mg-alloys exhibit a prior hardening effect up to plastic strain values of 0.15. The hardening effect is accompanied by dynamic softening, that becomes more important as plastic deformation proceeds. The critical point of initial recrystallisation is characterised by softening as a result of nucleation processes. This leads to suddenly decreasing flow stress values, as much as softening overlays the hardening effect. Finally, as shown in fig. 3, the flow stress achieves the "steady-state" condition where hardening and softening-effects represent an equilibrium state.

It is remarkable, that achievable compressive strains are minor for AZ31 than for obtained values for AZ80. This, for the general understanding of AZ-alloys untypical fact, may be caused by the existence of large, in extrusion direction elongated grains in applied AZ31 feedstock. Several heat treatments, applied on AZ31-feedstock, did not result in alterations in microstructure. With regard to the grain size distribution, the extrusion process of AZ80 alloy is less critical for AZ80 than for AZ31 [11]. In addition to this the AZ80-specimens have been quenched in water directly after the solution treatment. This finally results in high cooling rates, which avoid the creation of γ-phase precipitations. The achievement of higher compressive strains at failure will be facilitated.

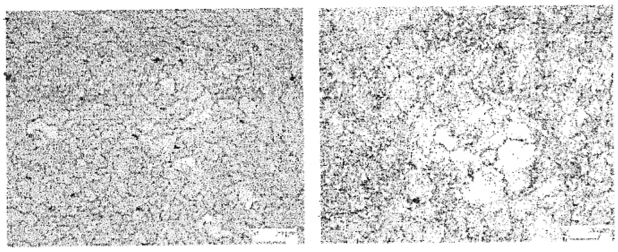

Fig. 2. Micrographs of extruded Mg-feedstock AZ31 (left) / AZ80 (right), (transversal)

Abb. 2. Gefüge des stranggepressten Mg-Ausgangsmaterials AZ31 (links) / AZ80 (rechts), (transversal)

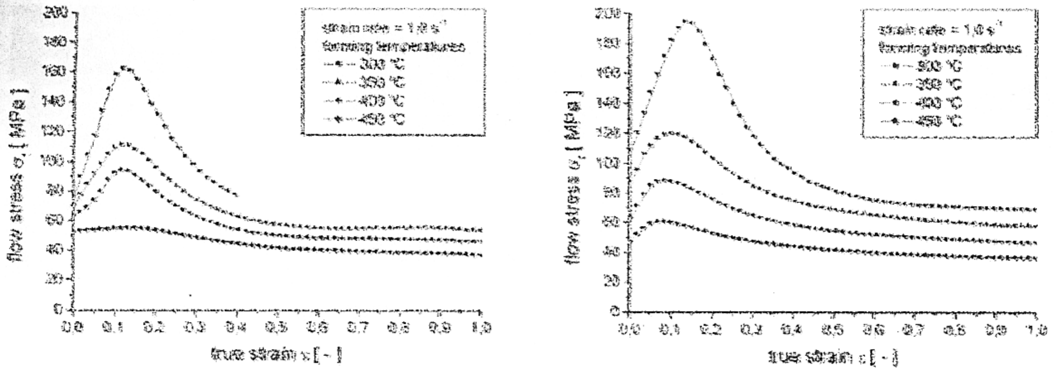

Fig. 3. Flow stress curves for AZ31 and AZ80 – extruded (longitudinal)
Abb. 3. *Fließkurven für AZ31 und AZ80 – stranggepresst (longitudinal)*

4 Analysis of Microstructure after Deformation

In order to enable a more detailed understanding of Mg-materials behaviour under warm forming conditions, in particular with respect to their softening behaviour, the deformed specimens have been examined by means of quantitative analysis of the microstructure. Therefore applied specimens of already mentioned dimensions have been cut in orientations parallel and perpendicular to the extrusion direction of received AZ31- and AZ80-rods. The upsetting of the specimens has been carried out comparatively at temperatures of 300 and 400 °C and at a logarithmic plastic strain rate of 1 s^{-1}. After deformation the specimens were quenched in water. The time between upsetting and quenching has been kept as short as possible. The average delay between these two tasks was always less than 10 seconds. Main objective of this procedure was the separation of occurring metadynamical softening processes, in particular metadynamical recrystallisation. Set up maximum logarithmic plastic strain values of 0.1, 0.2, 0.5 as well as 1.0 at the end of the upsetting test were of particular interest. The evaluation of microstructural evolution at distinctive points of the flow stress curves could be enabled.

The results, obtained for the extruded AZ31-feedstock, exemplarily show that at a forming temperature of 400 °C and at a plastic strain of 0.1 twinning occurs (*fig 4*). As plastic deformation proceeds deformation twins become more obvious as well as the recrystallisation process is initiated due to the creation of nucleation at grain boundary areas. At a logarithmic plastic strain value of 0.5 the corresponding micrographs do not show any deformation twins as a result of proceeding recrystallisation. In comparison to this, it is remarkable that at a plastic strain of 0.1 and a deformation temperature of 300 °C deformation twins appear in smaller dimensions as already explained for a forming temperature of 400 °C [12].

The recrystallisation behaviour of specimens, machined out of received AZ80-feedstock, has been examined in the same way. At forming temperatures of 400 °C deformed specimens do not exhibit any twinning (*fig. 5*). In fact primary recrystallisation seems to dominate the material's softening behaviour directly after the deformation process starts. Flow stress curves determined from specimens that have been cut in an orientation radial to the extrusion direction of received rods, confirm, that during plastic deformation even at small logarithmic strain values the equilibrium state of hardening- and softening mechanisms is achieved. The softening behaviour of AZ80-alloys at forming temperatures of 300 °C is characterized by twinning. Primary recrystallisation becomes obvious when the logarithmic plastic deformation exceeds the value of 0.5.

The analysis of AZ31-specimen deformed up to the logarithmic plastic strain of 1.0 by the application of forming temperatures of 300 and 400 °C demonstrates that their micro-

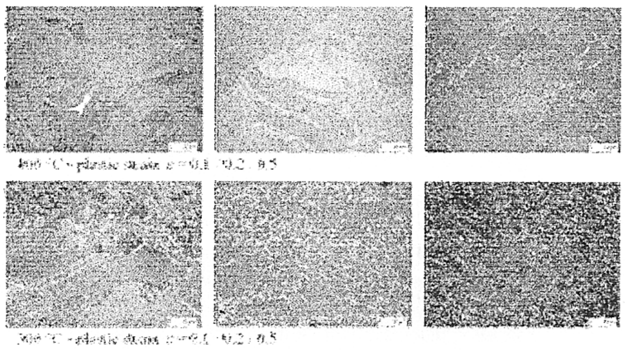

Fig. 4. AZ31 extruded / strain rate $\dot{\varepsilon} = 1\ s^{-1}$
Abb. 4. AZ31 stranggepresst / Umformgeschwindigkeit $\dot{\varphi} = 1\ s^{-1}$

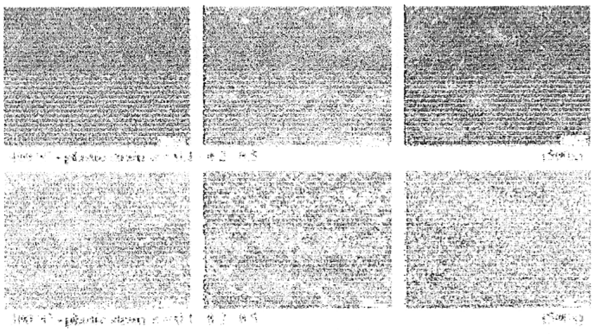

Fig. 5. AZ80 extruded / strain rate $\dot{\varphi}$ = 1 s^{-1}
Abb. 5. AZ80 stranggepresst / Umformgeschwindigkeit $\dot{\varphi}$ = 1 s^{-1}

structure is characterized by fine grains of an average grain size of 10 μm and 15 μm. For the AZ80-alloy values of 10 and respectively 20 μm were detected.

The examinations on continuously casted AZ31- and AZ80-feedstock have been carried out in the same way as already described for extruded rods. The flow stress curves for a logarithmic strain rate of 1 s^{-1} are shown in *fig. 6*. In comparison to flow stress curves already acquired on extruded Mg-feedstock, expected deviations could be determined. The influence of material's softening in relation to their hardening effect whilst plastic deformation is less pronounced for continuously casted Mg-feedstock.

The steady-state-area could not be achieved up to the plastic strain value of 1.0. By means of quantitative analysis of microstructure the reason for this behaviour could be clearly pointed out. Temperatures of 300, 350 and 400 °C have been taken into account in order to examine specimens deformed up to the plastic strain values of 1.0. The results show, that in particular the initial grain size as well as lacking prior hardening influences their forming behaviour. A remarkable characteristic is the in relation to the grain volume smaller percentage of grain boundary areas results in decreased nucleation. The nucleation in coarse grained material is less randomly distributed and occurs mainly in form of a typical "necklace"-structure. For the AZ31 alloy this can be confirmed for all forming temperatures according to *fig. 7*. In recrystallized grain boundary areas shear movements are detectable which may contribute to the softening behaviour as plastic deformation proceeds. In addition to this, these shear areas may be pointed out as a reason for further nucleation activities. Commonly published arguments for the description of influences of the initial grain size on the deformation behaviour also include the fact that stored energy tends to increase with a decrease of initial grain size [12]. The results, obtained by applying the continuously casted AZ31-feedstock could not point out remarkable differences in recrystallization behav[illegible]

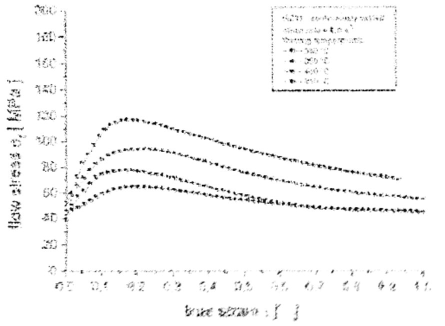

Fig. 6. [illegible]
Abb. 6. [illegible]

Fig. 7. AZ31 – [illegible]
Abb. 7. AZ31 – [illegible]

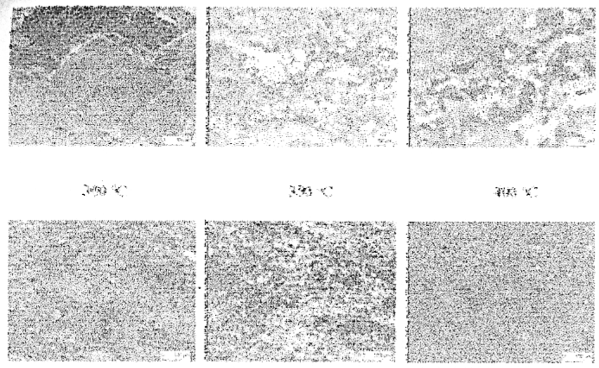

Fig. 8. AZ80 – continuously casted – true strain ε = 1, strain rate $\dot{\varepsilon} = 10^{-1}\ s^{-1}$

Abb. 8. AZ31 – stranggegossen – Umformgrad φ = 1, Umformgeschwindigkeit $\dot{\varphi} = 10^{-1}\ s^{-1}$

Opposite to this, the deformation of the continuously casted AZ80-alloy under given forming parameters is characterised by a lack of recrystallisation at forming temperatures of 300 °C even at a plastic strain value of 1.0. The stress relief, that displays the forming behaviour of Mg-materials whilst plastic deformation, is obviously provided by shearing movements between the grains. In the grain boundary areas no further nucleation is apparent. In addition to this it is assumed, that only dynamically initiated recovery processes can contribute to the material's softening. However, the deformation at comparatively elevated temperatures of 350 and 400 °C is characterised by a fine-grained microstructure, whereas the already explained dependence of recrystallized grain size on the forming temperature could be confirmed as well (*fig. 8*).

5 FVM/FEM – Simulation / Sample Geometries

The confirmation of the workability of received batches of the AZ31- and AZ80-feedstock, is accompanied by a series of forging tests, performed by means of simplified testing geometries. For experimental purposes an isothermal forging die has been designed and manufactured. Based on the results, regarding the hardening and softening behaviour of continuously casted and extruded Mg-feedstock in form of flow stress curves have been implemented in FEM- and FVM-models. In order to enable a basic understanding of the intended forging process real die geometries were used for modelling. A more detailed understanding of the local distributions of equivalent plastic strains and equivalent plastic strain rates (v. Mises) has been enabled by means of subsequently performed thermo-mechanical calculations. The temperature of modelled dies have been reproduced according to measurements under real forging conditions, material-specific mechanical properties, such as temperature dependent density, specific heat and thermal conductivity, were taken from various publications [13, 14]. In order to reproduce friction conditions between die-surface and work piece as well as possible, supplementary plane strain ring compression tests by detailed parameter variation have been realized. Exemplarily shown screenshots in *fig. 9* document that velocities of 40 mm/s result in an effective strain rate of more than 30 s^{-1}. Effective strains (v. Mises) could be determined with maximum values of 1.5.

The forging behaviour of received material has been confirmed by means of forging tests applying small simplified die geometries. Thus enables the possibility of a comparison of numerically calculated forces, available as results of the FEM /FVM simulation tasks, and obtained values taken from a load cell implemented in the applied die. For the forming tests a hydraulic press has been applied. Comparative punch velocities in the range of 1 and 40 mm/sec have been set up. A graphite-suspension in oil served as a lubricant. It demonstrably provides a good performance with respect to the friction behaviour. The forming temperatures have been varied. As an exemplary result it has been shown, that forging was easily to realize for all applied kinds of Mg-feedstock. No failures at critical points of the geometry were detected (*fig. 10*).

6 Conclusion

In the range of presented investigations the typical forming properties of continuously casted and extruded Mg-feedstock, alloys AZ31 and AZ80, have been determined and compared. The mechanical properties, determined by means of plain

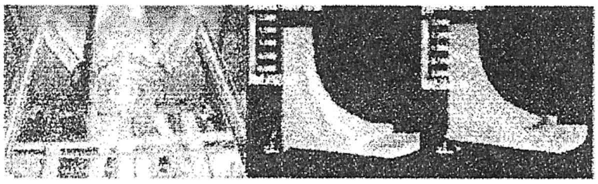

Fig. 9. Distribution of effective strains ε_g and effective strain rates $\dot{\varepsilon}_g$ in cross section of applied sample geometry (T_{Ofen} = 350 °C, $v_{Stößel}$ = 40 mm/s)

Abb. 9. Verteilung von Vergleichsumformgraden φ_v und Vergleichsumformgeschwindigkeiten $\dot{\varphi}_v$ im Querschnitt einer Versuchsgeometrie (T_{Ofen} = 350 °C, $v_{Stößel}$ = 40 mm/s)

Fig. 10. Test – forgings
(v_{punch} = 40 mm/s, T_{form} = 300 °C)
Abb. 10. Versuchs-Schmiedestücke
($v_{Stempel}$ = 40 mm/s, T_{Umf} = 300 °C)

strain compression tests of extruded and continuously casted Mg-feedstock have been characterized and compared in relation to results obtained by means of metallografic analysis. Due to the hcp-elementary cell structure of Mg-alloys, a strong influence of the specimen orientation, longitudinal or perpendicular to the extrusion direction, on mechanical properties was described and characterized. For the extruded AZ31- and AZ80-feedstock, applied for the investigations various tempers (F, T4 and T6) were taken into consideration. It has been pointed out that in particular the mechanical properties of Mg-forgings, made of AZ80-alloy may be strongly influenced by present heat treatment tempers of applied feedstock. In order to provide the necessary data base for FEM/FVM-simulation tasks, plain strain upsetting tests have been carried out, considering a forming temperature rage between 300 and 450 °C and logarithmic strain rates of 10^{-1}, 1 as well as $10\,s^{-1}$. The upsetting tests were accompanied by metallografic analysis. The typical hardening- and softening behaviour of AZ31- and AZ80-specimens, taken in an orientation perpendicular to the extrusion direction, have been described and associated with results obtained by means of metallografical examination. Differences of activated deformation mechanisms during plastic deformation at elevated temperatures have been described and compared for all kinds of applied Mg-feedstock. A numerical simulation by means of FVM/FVM has been employed in order to create a suitable geometry for forging trails. An isothermal forging die were designed and applied for the forging tests. It has been shown, that simplified shapes could be formed out of all kinds of Mg-feedstock. Even at relatively high punch velocities no failures were detected at critical areas of demonstrator-forgings.

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