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Extrusion of magnesium alloy hollow profiles with axial variable wall thickness

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Abstract. Industrially extruded profiles are characterized by a constant cross section along the length since rigid dies are applied in the process. However, if it would be possible to extrude profiles with cross sections that can be locally adapted (tailored) to the acting forces or stresses this would mean a significant potential for weight and material savings. Hence, in this study the extrusion of magnesium hollow profiles with axial variable wall thickness was investigated. Therefore, a newly developed porthole die was applied and extrusion trials conducted in order to show the feasibility of producing load adapted magnesium hollow profiles with axially variable wall thickness. Billets of magnesium alloy AZ31 were extruded and the required extrusion force was measured vs. process time. After the extrusion tryouts the manufactured hollow profile sections were measured with respect to the obtained wall thickness, inner and outer diameter of the thin-walled and the thick-walled sections, and in the wall thickness transition areas. The feasibility of manufacturing AZ31 hollow profiles with axially variable wall thickness was proven successfully. A maximal wall thickness variation of $\Delta t = 1.0$ mm was achieved.

INTRODUCTION

In conventional extrusion processes rigid dies are applied. Thus, the profile cross section remains the same throughout the extrusion process and hence along the length of the extruded profile. The profile cross section is designed according to the expected loads during technical use. Since these loads usually are not applied evenly over the length of an extruded component, areas of excessive thickness are unavoidable. For an effective lightweight design these areas should be avoided in order to reduce the weight of the technical component. Hence, manufacturing techniques that are able to produce varying cross sections along the length need to be developed. In the literature some experimental studies regarding the extrusion of profiles with axial variable cross sections can be found. Here only those where the focus was put on hollow profiles are mentioned. In [1, 2, 3] a mandrel with different cross sections was applied and its position in the die was changed during extrusion in order to vary the wall thickness of seamless extruded aluminum tubes. In [4] electromagnetic compression was applied behind the extrusion press in order to vary the outer diameter of aluminum hollow profiles locally. Selvaggio et al. [5] used moveable segments in a porthole die in order to change the wall thickness of an aluminum hollow profile. Recently, in [6] a porthole die was described that was able to vary the wall thickness by changing the inner diameter of an EN AW-6060 hollow profile throughout the extrusion process. Therefore, moveable segments were applied to the mandrel of the die to perform local wall thickness reductions on the upper and lower side of the profile. The segments were moved into the direction of the die bearing, increasing the profile's inner diameter. Moreover, the profile wall thickness would increase as the segments were moved back into their starting position. Figure 1 visualizes this process schematically. Movement of the sections was

FIGURE 1. Schematic principle of wall thickness variation, blue arrows indicating reduction and red ones increase of wall thickness.

driven by two hydraulic cylinders that were attached to the container.

EXPERIMENTAL

Since magnesium alloys are usually characterized by higher flow stresses at same temperature and strain rate compared to EN AW-6xxx alloys, higher forces are necessary to perform extrusion of same profile cross section. In order to investigate if the die design previously developed for easy to extrude aluminum alloy EN AW-6060 [6] could also be applied for extrusion of magnesium alloy AZ31, a die stress analysis was performed using the FE-software DEFORM 3D. The analysis was performed in 2 main steps. First a steady state simulation using the Eulerian approach was conducted to evaluate extrusion forces in a very quick manner if compared to the Lagrangian simulation type. A full 360° model was simulated, see Fig. 2a. For the simulation the die was already filled with billet material, a profile with length of 30 mm was “extruded” and the billet length in the container was 250 mm. The billet was meshed with 317000 elements (Fig. 2b). The hyperbolic sine law (Eq. 1) was used for flow stress calculation of AZ31 billet material. In that equation k_f describes the flow stress, $\dot{\epsilon}$ the strain rate, Q the activation energy while α , A and n are material constants. The materials’ parameters were derived from hot compression tests of cylindric specimens performed in a Gleeble System 3800 in the temperature range from 400 to 550 °C (in steps of 50 °C) and a range of strain rates from 0.01 to 10 s⁻¹ (in logarithmic steps). The obtained material parameters are specified in Table 1. The friction conditions for the AZ31-billet were modelled using shear friction with a friction coefficient of $m=1$. For the contact with the ram $m=0.7$ was applied. A heat transfer coefficient of 7000 W/m²K was used. 5 steady state simulation steps with a step increment of 1s/step were run.

For the second part of die stress analysis the upper die (with mandrel) was meshed with 320000 elements and the forces gained during steady state simulation were transferred onto the die by using the feature “force interpolation” in DEFORM 3D. The support of the die was modelled by setting the velocities for specific die surfaces to 0 mm/s in the necessary spatial directions. The velocity in extrusion direction was set to 0 mm/s at the contact face between upper and lower die. The normal and transversal direction velocity was respectively set to 0 mm/s at the circumferential area of the die ring that reached into the container. Afterwards, a Lagrangian step was conducted in order to calculate the distribution of state variables in the loaded die, especially the effective stress and the maximum principle stress. This was done to distinguish between tensile and compressive stresses.

$$k_f = \frac{1}{\alpha} \sinh^{-1} \left[\left(\frac{\dot{\epsilon} \cdot \exp\left(\frac{Q}{RT}\right)}{A} \right)^{\frac{1}{n}} \right] \quad (\text{Eq. 1})$$

TABLE 1. Material constants applied for flow stress calculation in FEM according to Eq. 1

α [1/MPa]	Q [kJ/mol]	A [1/s]	n
0.0048	218.921	$9.1486 \cdot 10^{12}$	4.331

FIGURE 2. (a) Geometric FEM-model and (b) billet mesh for steady state simulations.

Extrusion experiments were then carried out on the 8.2 MN extrusion press of the Extrusion Research and Development Center (FZS) at TU Berlin using the direct extrusion mode. The experimental setup is given in Fig. 3. It can be seen that the die package was longer than the ones used for conventional direct extrusions and that it stood out of the die holder. Thus, a heating jacket was heated to 500 °C prior to the trials in order to prevent cooling of the die. It was applied after the die was installed into the die holder. Three AZ31 billets were extruded. The extrusion conditions are given in Table 2. The first billet was necessary to fill the porthole die, with the second one a reference profile was extruded. It had a constant high wall thickness along the length, and was produced without any movement of the hydraulic cylinders. Finally, during extrusion of the third billet the hydraulic cylinders were moved in extrusion direction and against it (Fig. 3) in order to change the profile wall thickness on the upper and lower side of the profile.

TABLE 2. Extrusion parameters

T_{billet} [°C]	$T_{\text{container}}$ [°C]	v_{ram} [mm/s]	R [-]	$D_{\text{container}}$ [mm]
500	500	1.6	14:1 / 23:1	125

RESULTS AND DISCUSSION

Results of FEM die stress analysis

The steady state FEM simulation predicted a total force requirement for extrusion with the higher extrusion ratio 23:1 (low wall thickness) of 7.57 MN. Thus, the load capacity of the 8.2 MN extrusion press available for the experiments was expected to be sufficient for conducting the extrusion tryouts. In order to further ensure the feasibility

FIGURE 3. Experimental setup for extrusion experiments.

of the planned extrusions, the billet length for the real extrusions was reduced to 200 mm compared to the 250 mm applied in FEM simulation. Consequently, the extrusion force requirements should be reduced by this measure.

The results of the FEM die stress analysis applying elastoplastic material model for H13 tool steel die with HRC 45 are given in Fig. 4. The stress values in this figure are scaled in such a manner that values exceeding the yield strength of H13 tool steel of 850 MPa at 500 °C are displayed in red color. The FEM results revealed that the highest effective stresses are predicted present in the die webs adjacent to the portholes (Fig. 4a). However, these values never reached the H13 yield strength. The orange-colored regions mostly provided maximal stress values in the range of 730 MPa to 800 MPa. By plotting the distribution of maximal principle stresses it is possible to distinguish between areas loaded in tension (positive values) as well as compression (negative values). According to the plot of max. principle stress distribution in Fig. 4b most parts of the die are under tensile stresses since the stress values are positive. The simulation results indicate compressive stresses only in the rear part of the die which is positioned in the container, the middle of each web adjacent to the port holes as well as the front end of the mandrel where the moveable segments are positioned. The compressive values are rather low with values of only up to -280 MPa.

Consequently, since according to the FEM die stress analysis neither the effective stresses nor the maximal principle stresses reached critical values it was concluded that the die design should be able to withstand the loads during extrusion of the desired AZ31 hollow profile. Hence, the die was manufactured and extrusion experiments carried out.

Results of extrusion experiments

The extrusion experiments were conducted according to the descriptions above. Fig. 5a presents the load vs. process time diagram of the billet 3 where a variation of the cross section was attempted. Due to adaptations of the measuring system that had to be applied because of the unconventional length of the die set, here the development of the total extrusion force (F_{tot}) and the die force (F_{die}) could only be measured over process time and not as usual over ram displacement. Nevertheless, the diagram shows that at the start of the extrusion the overall force increases to a peak value of $F_{ov}=7.6$ MN. The die force reaches a peak value of $F_{die}=6.5$ MN. After the peak forces were overcome the force values reduced to significantly lower values of $F_{ov}=6.8$ MN and $F_{die}=6.1$ MN after a process time of 108 s. At that point the hydraulic cylinders were activated and moved the moveable segments in order to reduce the profile wall thickness by increasing the inner profile diameter. The force vs. process time diagram displays a small increase of $\Delta F_{ov}=0.12$ MN as well $\Delta F_{die}=0.10$ MN at that position (Fig. 5b). After a process time of 128 s the hydraulic cylinders were moved back to their initial positions. In the load vs. process time diagram the forces started to reduce but in a less significant manner compared to the prior increase.

FIGURE 4. Results of FEM die stress analysis (a) effective stress distribution (b) distribution of maximal principle stresses.

FIGURE 5. (a) Load vs. process time diagram of billet No. 3 (with wall thickness variation), (b) Enlarge section of load vs. process time diagram, arrows indicate activation of hydraulic cylinder movement for wall thickness variation.

Towards the end of the extrusion experiment the hydraulic cylinders initiated several movements in and against the extrusion direction but the influence on the extrusion force was very limited (Fig. 5b).

After finishing the extrusion experiments the profile with intended wall thickness variation was cut in order to verify wall thickness variation. In Fig. 6a a thick-walled section and one with reduced wall thickness taken from the same profile are presented. It was revealed that indeed the wall thickness on the upper and lower profile side was varied successfully. In Fig. 6b a longitudinal cut through a wall thickness transition area is displayed. The wall thickness transition (marked with black arrows) itself occurred within a very short length of the profile which means it was rather abrupt. In order to quantify the geometric variations of the profile obtained with the applied extrusion die, the outer and inner diameter of profile as well as the wall thickness parallel to the extrusion direction was measured. The results are plotted in Fig. 7. In the displayed area of Fig. 6b the wall thickness (t) was changed from $t=4.3$ mm to $t=3.3$ mm so that a maximal wall thickness variation of $\Delta t=1.0$ mm was achieved. The wall thickness transition occurred over a profile length of only 20 mm, so that it can be characterized as abrupt or sharp. Before and after the transition area no significant changes were noticed. Fig. 7 shows that the outer diameter (D_{out}) remained about constant at $D_{out}=39.8$ mm throughout the thick-walled, thin-walled and the wall thickness transition area. Only at the point where the wall thickness starts to decrease the outer diameter was found to be slightly increased by 0.2 mm to $D_{out}=40.0$ mm. Regarding the inner diameter of the profile (D_{in}) it was between $D_{in}=32.00$ mm and $D_{in}=32.20$ mm before the wall thickness transition. But then it started to increase slightly to $D_{in}=32.40$ mm. This increase occurred 25 mm before the reduction of the profile wall thickness. As the wall thickness reduction took place the inner diameter increased significantly from $D_{in}=32.40$ mm to $D_{in}=33.80$ mm.

FIGURE 6. Sections of extruded profile (a) thick-walled and thin-walled section of same profile (b) longitudinal cut through a wall thickness transition area of an AZ31 hollow profile with local wall thickness reduction from $t=4.3$ mm to $t=3.3$ mm ($\Delta t=1.0$ mm), arrows indicate wall thickness variation, extrusion direction $\leftarrow$.

FIGURE 7. Longitudinal development of wall thickness t , inner profile diameter D_{in} and outer diameter D_{out} at a wall thickness transition area.

The measurement of other parts of the profile did not reveal any other significant variations in the profile geometry. It seems like the moveable die segments were not be able to move or move enough in order to vary the wall thickness significantly afterwards. It is probable that they were blocked due to AZ31 material flowing into small gaps between the upper die and the segments during the extrusion process, hence, preventing further movement.

Future investigations will focus on FEM-analysis of the material flow during wall thickness transitions as well as on the influence of wall thickness variations on microstructure and mechanical properties.

SUMMARY

In this publication the feasibility of extruding AZ31-hollow profiles with axially variable wall thickness was investigated. Therefore, a die with moveable segments previously developed for extrusion of aluminum alloy EN AW-6060 was investigated by FEM to check if it could withstand the higher loads during extrusion of AZ31. The results showed that the stresses were below the yield strength of the H13 tool steel. The simulations also predicted that the extrusion force of the 8.2 MN extrusion was sufficient in order to successfully extrude the desired profile cross sections. Then, the extrusion trials were conducted successfully and the feasibility of extruding AZ31-profiles with axial variable wall thickness was proven to be realistic. A maximal wall thickness variation of $\Delta t_{max}=1.0$ mm was obtained when the wall thickness on the upper and lower side of the profile was varied from $t=4.3$ mm to $t=3.3$ mm.

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