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Numerical and experimental evaluation of an alternative mechanism for wall thickness variations of hollow profiles applying a porthole die

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Abstract

The cross sections of conventionally extruded profiles remain constant along the length of the extrudates due to application of static, rigid dies. The profile cross section is dimensioned according to the expected loads applied during technical application. Mostly, the loads are not distributed homogeneously upon the length of a product. Thus, locally over-dimensioned profile areas are the result. In order to optimize the profile design and therefore obtain lighter products, load adapted tailored profiles should be manufactured. In this paper a mechanism for wall thickness variations of lightweight hollow profiles was investigated by finite element analysis (FEA) and experimental extrusion trials. The principle for manufacturing wall thickness variations is based on application of bending elements which work as bearing channel at the porthole die. Their deflection in direction of the die bearing would lead to wall thickness reductions. An increase of the wall thicknesses should be achieved by a deflection of the bending elements back into direction of their initial position due to the normal pressure of the flowing aluminum billet material. FEA of the material flow during extrusion was conducted in order to investigate the principle feasibility of the mechanism. The force requirements for wall thickness variations were also gained from the numeric simulations on the one hand. The force necessary for the deflection of the bending elements was also determined in an experimental test setup. The extrusion tryouts applying the developed mechanism revealed that the force of the hydraulic drive was successfully transmitted onto the moveable segments inside of the porthole die. Although subsequent to the extrusion experiments variations of the hollow profile wall thicknesses were observed, it was found out that they were not induced by the developed mechanism as intended. Instead, aluminum billet material filled even smallest voids and gaps inside of the mechanism causing deflection and failure of different components that effected the development of the wall thickness.

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Keywords: aluminum; extrusion; hollow profile; variable wall thickness; porthole die

1. Introduction

In today's extrusion industry the cross section of profiles is defined by rigid tools such as extrusion dies and mandrels. Conventionally, only profiles with constant cross sections can be produced. During the use of extruded products in technical applications the loads usually are not distributed homogeneously upon the length of a product. Thus, locally over dimensioned profile areas are the result. In order to avoid these and hence reduce the profile weight, extrusion dies need to be developed to offer more flexibility regarding the achievable profile cross sections. It would then be possible to manufacture profiles with (tailored) cross sections that are locally adapted to the acting loads. Due to weight reduction these innovative profiles could contribute to a reduction of fuel consumption as well as emissions of combustion gases when being applied for vehicles with combustion engines. Furthermore, the range of vehicles with electric drive could be extended by substitution of conventionally extruded components with these innovative load adapted tailored profiles. In order to develop the production of such extruded, modifications regarding the extrusion process and the die technology have been investigated, yet mostly for research purposes only.

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E.g. Makiyama and Murata [1] varied the cross section of full profiles (not hollow) by applying a prototype CNC variable vertical section extrusion machine that allowed the extrusion of profiles with axial variable height along their length. Jun et al. [2] applied two dies, one fixed and one moveable in order to achieve variable cross sections on full profiles, as one side remained a constant shape while the contour of the other side was varied throughout the extrusion process.

Murata et al. [3] applied a tapered mandrel and varied the mandrel position and thus the mandrel cross section inside the die during the extrusion process and were able to manufacture tubes with axial variable wall thicknesses. A similar approach was investigated by Negendank et al. with the difference that instead of a tapered mandrel a stepped mandrel was applied [4]. The authors were able to extrude tailored seamless aluminum alloy tubes with very abrupt as well as with graded wall thickness transitions. The microstructural development along the hollow profiles' lengths in regions with different wall thicknesses was evaluated in [5] and the mechanical properties in [6]. Based on a similar approach the company Otto Fuchs KG developed the manufacture of seamless aluminum tubes/pipes with axial variable wall thicknesses for drilling applications (Aludrill™) [7]. Rott [8] also applied an axial moveable stepped mandrel but the transition of the mandrel cross section was designed with multiple steps. This lead to a better dimensional stability of the outer tube diameter in the wall thickness transition regions.

For the extrusion of profiles with more complex cross sections or with multiple hollow profile chambers a porthole die needs to be applied. Hence, a wall thickness variation mechanism for a porthole die needed to be developed. Selvaggio et al. [9, 10] applied a mechanism with moveable bearings for the variation of the outer profile height along the hollow profile length. The general feasibility was shown successfully since a wall thickness variation of up to 0.7mm was achieved over a profile length of 3m. Negendank et al. also developed a mechanism for the axial variation of the hollow profile wall thickness. In contrast to Selvaggio et al. their mechanism aimed on the wall thickness variation based on varying the inner profile height and keep the outer profile dimensions constant. The mechanism based on moveable segments attached to the mandrel of the porthole die, that could be moved in vertical direction to change the inner profile height and thus the wall thickness. A maximal wall thickness variation of 1.2mm for aluminum alloy EN AW-6060 (AA6063) [11] and 1.0mm for the magnesium alloy AZ31 [12] was achieved in experimental extrusion tryouts. But the described development lacked reliability and reproducibility since billet material flew into small gaps between the moveable segments of the wall thickness variation mechanism.

For that reason, an alternative mechanism was developed. Numerical investigations of the material flow and the required forces to achieve wall thickness variations were carried out. First results are described in this paper.

2. Experimental

Based on the observations of the previously developed mechanism [11, 12] for wall thickness variation during extrusion by application of a porthole die, an alternative mechanism was designed (Fig. 1). It is mainly based on wedges with an inclination angle of 10° that are positioned beneath sheet-like bending elements. The wedges are mounted to an inner mandrel that can be axially moved in as well as against the extrusion direction (ED). The movement is generated by an external drive consisting of two hydraulic cylinders positioned beside the porthole die and that transfer their stroke synchronously onto a cross bar. The inner mandrel on the other hand is connected to the cross bar. Thus, when the cross bar and hence the wedges are moved by the hydraulic cylinders in direction opposite to ED, the bending elements will be deflected towards the die bearing. Subsequently, with increasing displacement of the wedges the deflection of the bending elements also increases leading to a reduction of the profile wall thickness. On the other hand, when the cross bar is moved in ED, the normal pressure of the billet material in the die bearing should deflect the bending elements towards the mandrel and hence increase the profile wall thickness.

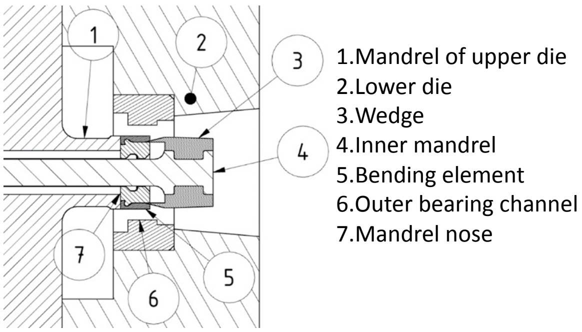

Fig. 1. Schematic setup of the wall thickness variation mechanism, ED→.

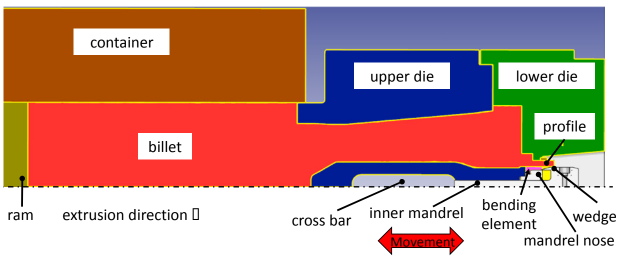

Fig. 2. Geometric model for FEM simulations, ED→.

In order to investigate if the described mechanism would be able to achieve the desired wall thickness variation in axial profile direction during the extrusion process, an analysis of the metal flow was conducted using the FEM software code DEFORM 3D. Due to process symmetry only a 90° model was applied for the problem in order to save solving time and disc space (Fig. 2). The lagrangian method with a shear friction factor of m=1 and a heat transfer coefficient of $h=11000 W/m^2K$ were applied. The billet material was aluminum alloy EN AW-6060 and the material model for flow stress calculation was applied from an earlier project [13]. Fig. 3 displays the thick-walled and the thin-walled cross sections that should be manufactured within the same extruded profile. It becomes clear that the wall thickness will only be varied on the upper and lower profile side. Another aim of the FEM analysis was to estimate the force requirements necessary for the deflection of the bending elements during the extrusion process and the additional force required to deform the flowing aluminum billet material. The bending elements should be manufactured from H13 hot working steel but in a non-hardened condition. In the hardened state the pressure of the billet material in the die bearing could not be high enough to achieve a deflection of the bending elements into direction of the initial position. As material model “H13 machining” was selected from the DEFORM 3D database and the material behavior was defined as elasto-plastic. All components were set to 500°C and the ram speed was 3mm/s.

In order to verify the forces gained from the FEM simulations a simplified test setup was designed that could be positioned in the universal tension/compression testing machine MTS 810. Fig. 4 shows the experimental setup where the width of bending elements and wedges is only half those that would be applied in the extrusion experiments. The tests were conducted at T=420°C. At the beginning of the test the wedges were moved towards the bending elements with a velocity of 1mm/min for a maximum stroke of 5mm. The force (F_d) necessary to deflect the bending elements was measured. Afterwards the stroke was reset to 0mm and the wedges were pulled out (removed) beneath the wedges. The therefore needed force (F_r) was measured.

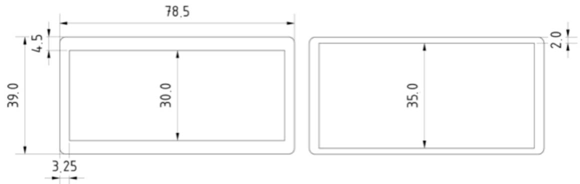

Fig. 3. Schematic representation of the two desired profile cross sections.

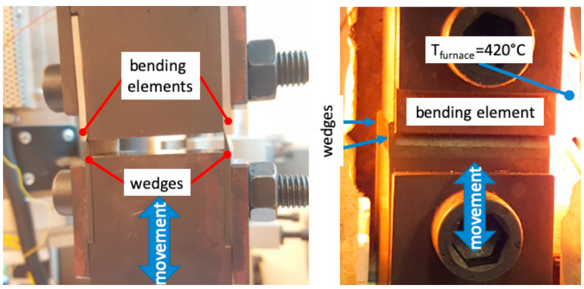

Fig. 4. Test setup for experimental determination of required forces for bending element deflection (a) side view without furnace (b) front view during testing at T=420°C.

Finally, after all necessary components were manufactured extrusion experiments were carried out in order to investigate the feasibility of axial wall thickness variations with the developed concept. The components of the inner mechanism (inside the porthole die) are given in Fig. 5.

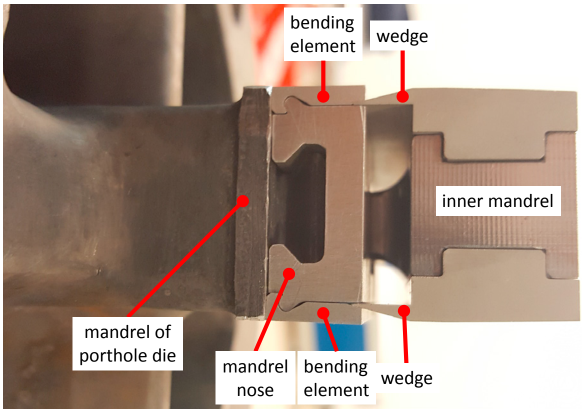

Fig. 5. Inner mechanism for wall thickness variation, ED→.

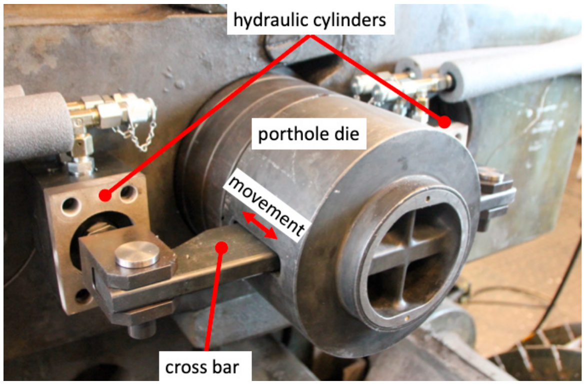

Fig. 6. Outer mechanism/drive without heating jacket.

The external mechanism is displayed in Fig. 6 and the setup for the extrusion experiments in Fig. 7. The porthole die was preheated to 520°C and subsequently put into the die holder of the 8MN extrusion press at the extrusion R&D Center at TU Berlin. Since the die holder did not feature a die heating system the porthole die was covered by a heating jacked (T=510°C) in order to reduce significant die cooling during the installation and connection phase of the external drive. The EN AW-6060 billets with diameter of 122mm were heated to 500°C in an induction furnace. After the extrusion experiments were carried out, the manufactured profiles were cut and the wall thicknesses were measured to reveal their development in axial profile direction. The extrusion ratio for the thick-walled (t=4.5mm) profile sections was 14:1 and 23:1 for the cross section with reduced wall thickness (t=2.0mm).

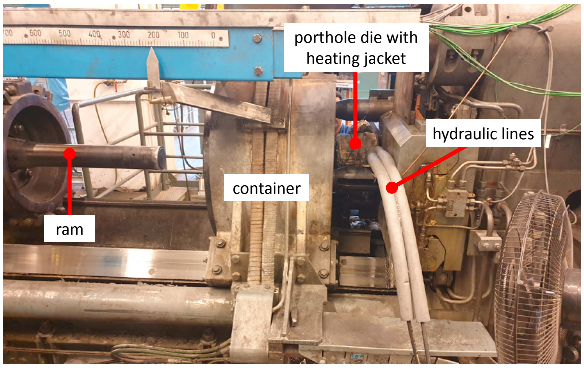

Fig. 7. Experimental extrusion setup, ED→.

3. Results and discussion

The results of the FEM material flow analysis are given in Fig. 8 for different stages during the process. Fig. 8a shows the situation after a processing time of 1.5s when the inner mandrel starts to move in direction opposite to ED. The beginning of the extruded profile had just exited the die bearing. In Fig. 8b the inner mandrel reached its maximal stroke at a processing time of 6.0s and thus, the wedge forced the bending element to its maximal deflection. Hereby the wall thickness of the hollow profile was reduced successfully. In Fig. 8c the inner mandrel was moved to its initial position. It can be noticed that the bending element was also deflected close to its initial shape only due to the normal pressure applied by the flowing aluminum in the region of the die bearing channel. Subsequently, the wall thickness of the hollow profile was successfully decreased and hence a full wall thickness variation cycle achieved. Thus, the results of the FEM material flow analysis suggest that the developed mechanism should be able to manufacture hollow profile segments with different wall thicknesses along the axial profile direction.

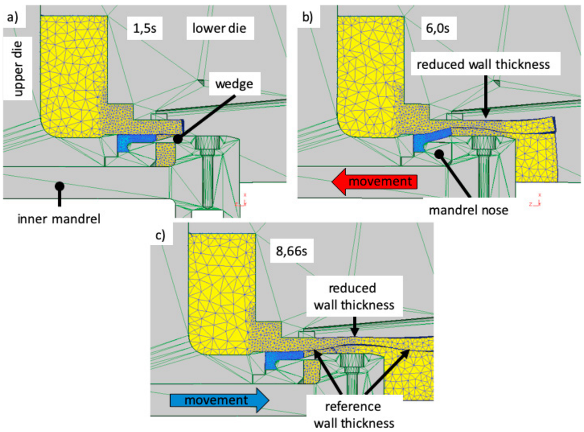

Fig. 8. Results of FEM analysis of material flow, ED→.

The axial force necessary to achieve the maximal deflection of the bending element with the "H13 machining" material model provided by the DEFORM 3D material data base was determined to up to F_d=3.4kN in the 90° simulation model, when no aluminum billet material was present. Hence, this value corresponds to F_d=13.6kN in a full 360° model. On the other hand, when the flowing billet material is present the necessary force to deflect the bending elements and to reduce the wall thickness of the hollow profile increased to about F_d=55kN (Fig. 9)

An experimental test setup (Fig. 4) was applied in order to measure the necessary force to deflect the bending elements (F_d) and thus to verify the force determined by FEA. In a subsequent second experiment the necessary force (F_r) to pull out the wedges beneath the bending elements was measured. A deflection of the bending elements into their initial position was not possible with the simplified test setup. Fig. 10 displays the load vs. stroke diagram of the experiments. It was revealed that a force of up to F_d=11kN was necessary to fully deflect the bending elements (H11 hot working steel, not hardened). This is comparable to the F_d=13.6kN determined by FEA. Up to F_r=3kN were needed in the experiment to pull the wedges out beneath the bending elements. The fluctuations in the displayed graph (Fig. 10) are caused by stick-slipping conditions.

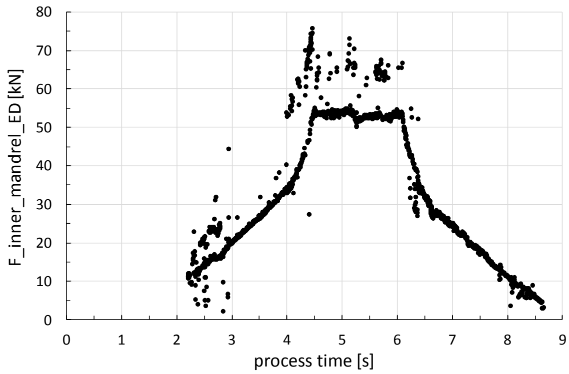

Fig. 9. Force necessary to deflect bending elements and reduce hollow profile wall thickness during extrusion determined by FEA.

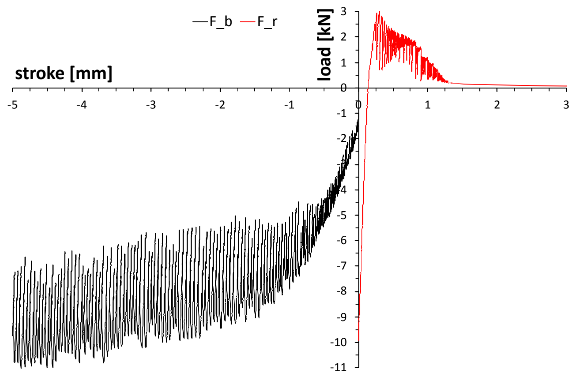

Fig. 10. Load vs. stroke diagram for deflection of bending elements (F_d) and for removing the wedges beneath the bending elements (F_r).

The extrusion experiments were carried out in two campaigns. In the first campaign (I) the general feasibility of the developed mechanism as well as the influence of the applied pressure for the external drive (hydraulic cylinders) on the maximum deflection of the bending elements should be investigated. The pressure of the two hydraulic cylinders as well as the resulting forces of each of the hydraulic cylinders are given in table 1. Six EN AW-6060 billets were extruded during the first campaign. The first billet was extruded in order to fill the porthole die and no wall thickness variation was attempted. During extrusion of each of the following five billets the hydraulic cylinders were driven in extrusion direction (ED) as well as in direction opposite to ED multiple times. Fig. 11 shows that the stroke of the hydraulic cylinders had an influence on the extrusion force. The extrusion force slightly increased as the cylinders pushed the crossbar in opposite ED aiming on a wall thickness reduction and the force decreased when the cylinders were driven in ED attempting to increase the wall thickness of the hollow profile. The development of the wall thickness along the length of the hollow profile was analyzed on the upper and lower profile side and the results are displayed in Fig. 12.

Table 1. Pressure settings and resulting forces for each of the two hydraulic cylinders.

billet no.	pressure [MPa]	compression force [kN]	tension force [kN]
I.1	0	0	0
I.2	10	15.7	9.3
I.3	16	25.1	14.8
I.4	16	25.1	14.8
I.5	22	35.6	20.4
I.6	25	39.2	23.2

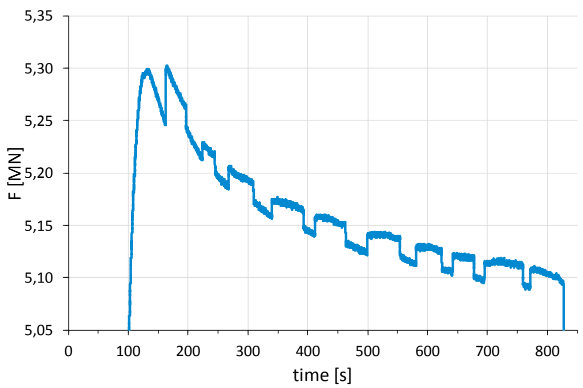

Fig. 11. Extrusion force vs. processing time for extrusion of billet I.4.

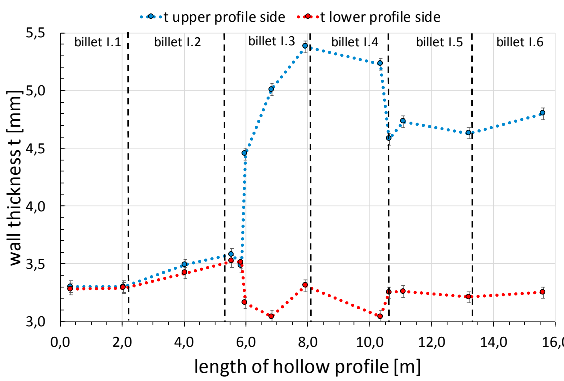

Fig. 12. Axial development of hollow profile wall thicknesses on upper and lower side of the hollow profile (extrusion campaign I).

According to Fig. 12 at the beginning of the profile (I.1) the wall thicknesses on the upper and lower side of the profile remained constant at t=3.3mm over the profile length since no variation was attempted. During extrusion of billet I.2 the external drive was activated multiple times using a pressure of 10MPa (100bar) for each of the two hydraulic cylinders. The wall thickness was found to be increased gradually to t=3.5mm in axial profile direction. A wall thickness reduction was not observed. For the section of profile I.3 the wall thickness on the upper profile side was found to be increased significantly up to t=5.4mm (Fig.12). On the other hand, the wall thickness on the lower profile side slightly decreased to t=2.9mm. A section of profile I.3 with macroscopically visible wall thickness variations is given in Fig. 13. In the displayed profile area, the wall thickness was first reduced from t=3.3mm to t=2.9mm. After that reduction the bending element was ripped out of its bearings and got stuck in the profile. Obviously, the bulged profile surface was a result of that process. Behind the ripped out bending element the profile wall thickness increased to t=4.4mm (Δt=1.1mm) on the upper side of the profile but decreased from t=3.3mm to t=2.9mm (Δt=0.4mm) on the lower profile side.

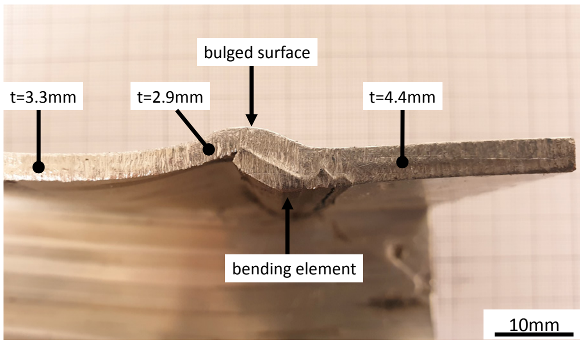

Fig. 13. Wall thickness transition area of on upper side of profile I.3 with displaced bending element, ED←.

The analysis of the upper die (of the porthole die) revealed the reason for the described observations. The aluminum billet material flew into the openings between the mandrel nose and the mandrel and finally lead to plastic deformation of the mandrel nose (Fig. 14). Due to this deformation the bending element on the upper profile side was ripped out of its bearing and got stuck in the hollow profile. The deformation occurred into direction of the lower profile side, leading to the observed wall thickness reduction on the lower side of the profile and the increased wall thickness on the upper side (Fig. 12). Subsequent parts of the hollow profile (after billet I.3) were extruded under unspecified conditions, where the material flow in the die bearing area could have led to local wall thickness variations without that the authors could give a reasonable explanation.

Based on the observations of the first extrusion campaign several modifications were applied for the second campaign (II) of extrusion trials. Firstly, the side gaps on a newly manufactured mandrel nose were closed by inserting hardened (48 HRC) H11 steel plates in order to prevent billet material from filling these gaps (Fig. 14). In contrast to campaign I the experiments of the second campaign were conducted with a hydraulic cylinder pressure of 25MPa (250bar). Additionally, two different geometries of bending elements were manufactured. The first set of bending elements featured a reduced cross section of 0.5mm instead of 2.0mm as applied in campaign I. The lower cross section was supposed to improve the bendability of the bending elements, especially when they need to be deflected into direction of the initial position for manufacture of an increased wall thickness. During extrusion of billet II.1 it was observed that the bending elements broke right at the start and got stuck in front of the profile.

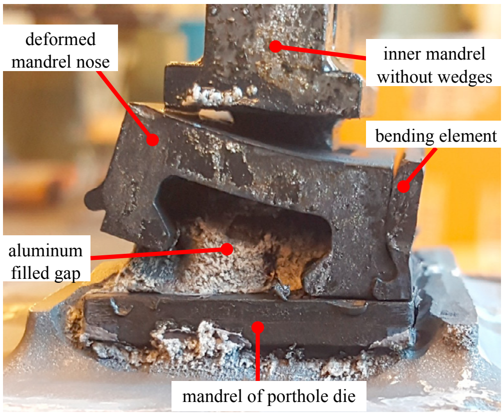

Fig. 14. Deformed bending element and deformed mandrel nose also filled with aluminum after initial etching for die cleaning with NaOH.

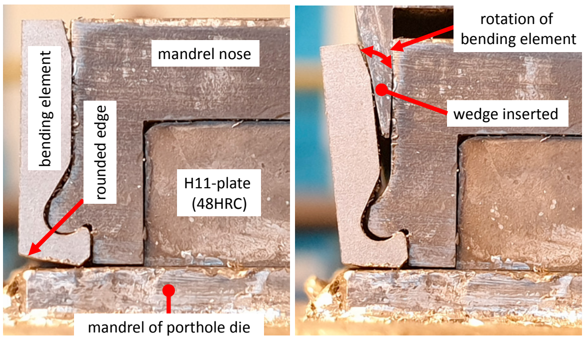

Fig. 15. Adjustments of the inner mechanism for the second extrusion campaign.

For the billets II.2 to II.4 bending elements with the initial thickness of 2.0mm were applied again, but in contrast to campaign I their edges towards the mandrel were rounded a bit as indicated in Fig. 15. The rounded edges were applied in order to achieve the wall thickness variations not only by plastic deformation of the bending elements but partly through their slight rotation as illustrated in Fig. 15. Fig. The results of the second campaign regarding the development of the wall thicknesses in axial profile direction are given in Fig. 16. Accordingly, the wall thicknesses were successfully reduced during extrusion of billet II.2 from t=3.8mm to t=3.27mm on the upper profile side and from t=3.6mm to t=2.9mm on the lower side of the hollow profile. Although the hydraulic cylinders were driven back and forth multiple time during extrusion of billet II.2 no reduction of the wall thicknesses was observed. Instead the seam welds on both sides of the hollow profile were found to be separated starting at a profile length of 0.5m to 2.5m and the profile surfaces were extremely waved in this profile section. The reason for the profile separations was found at the end of the separations since the H11 plates stuck in the side walls cutting the profile open.

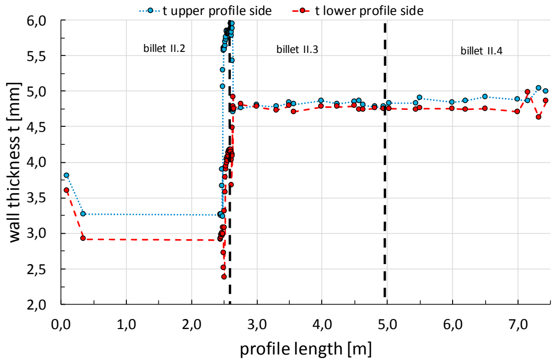

Fig. 16. Axial development of hollow profile wall thicknesses on upper and lower side of the hollow profile (extrusion campaign II), ED←.

Obviously, aluminum billet material was able to first dislocate the H11 plates so that they sliced the profile sides open. Then the H11 plates were squeezed out. Afterwards the profile seams on the sides were welded correctly again. At the end of the extrusion of billet II.2 the wall thicknesses drastically increased from t=3.3mm to t=6.0mm on the upper profile side and from t=2.9mm to t=4.9mm on the lower side (Fig. 16). Subsequent observations of the profile in that section found that both bending elements were ripped out of their bearings in this region (Fig. 17). Additionally, as previously observed for profile I.3 (Fig.13) bulges formed again on the profile surfaces where the bending elements got stuck. Fig. 18 visualizes the development of profile wall thicknesses in this specific profile section between billets II.2 and II.3 more closely. The wall thickness on the lower profile side first decreased from t=3.1mm to t=2.4mm at a profile length of about 2.5m. This hints to the conclusion that the profile wall thickness was varied successfully by the developed mechanism in this case. Afterwards, an increase to t=4.2mm was observed. But at a profile length of about 2.6m the lower bending element was ripped out of its bearings. The increased wall thickness of up to t=4.7mm seemed to corresponding with that. Until the end of the extrusion the wall thickness then remained constant. On the upper side of the profile the wall thickness increased significantly from t=3.2mm to t=5.6mm at a profile length of 2.49m (Fig. 18). Later it further increased up to t=6.0mm This increase was found to correspond with the loss of the upper bending element. The displayed decrease in wall thickness at a profile length of 2.63m took place as the bending element on the lower side of the profile was displaced. Hence, these later wall thickness variations were induced by the loss of the bending elements as well as subsequent variations of the material flow and not due to the activation of the developed wall thickness variation mechanism.

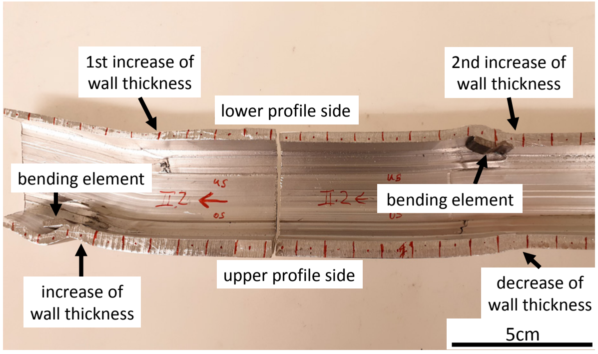

Fig. 17. Section of transition area between billet II.2 and II.3 with visible wall thickness variation and displaced bending elements, ED←.

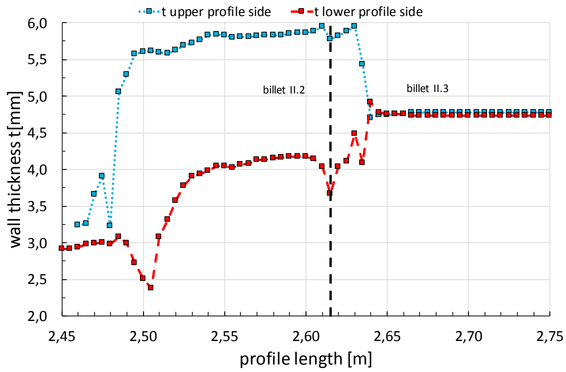

Fig. 18. Axial development of hollow profile wall thicknesses in transition area between billets II.2 and II.3, ED←.

Conclusions

A mechanism for the wall thickness variation of lightweight hollow profiles by applying moveable segments in a porthole die was developed. Wall thickness variations should be achieved through bending elements integrated into the porthole die. FEA of material flow indicated the principle feasibility of the mechanism. Experimental extrusion trials proved the functionality of the external wall thickness variation mechanism, meaning that the force of the two hydraulic cylinders was successfully transferred via a cross bar to an inner mandrel. The functionality of the inner mechanism which consisted of wedge plates that were mounted onto the inner mandrel and should induce the strain of the bending element could not yet be proven on a reliable and reproduceable basis. In the experimental tryouts aluminum billet material was squeezed into even the smallest gaps of the inner mechanism leading to the displacement of bending elements and other components.

Future developments will focus on improving the support and the bearings of the bending elements as well as on a constructive solution that does not feature any voids or gaps where the billet material could flow in and block or destroy the wall thickness variation mechanism or its components.

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