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Material Flow Visualization for Metal Extrusion on Near Industrial Scale

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Abstract. In the simulation of bulk forming processes the validation of the simulation models is necessary to enable predictive simulation for process development. A visualisation method is an advanced way to create additional evaluation parameters. In this work, the upscaling of a newly developed non-destructive method from semi-industrial to near-industrial scale for metal extrusion of aluminium alloys is presented. A copper coating, which deforms with the billet material, was applied to one half of a cast billet (in the longitudinal direction) and detected by computed tomography (CT). The copper pattern was applied by a plasma coating technology to determine the deformation of the billet material during the process until the final profile. A detailed analysis of the upscaled method with improved geometric setup shows the superiority of the newly chosen properties, enabling a complete determination of strain state in the profile.

Introduction

Numerical process simulation plays an important role in the development of today´s industrial manufacturing processes. Therefore, simulation models have to describe the process with a satisfying accuracy before conducting predictive simulations, hence simulation results need to be validated with experiments. This comparison is mainly done by evaluation parameters like ram force or profile temperature. Other parameters are the material flow and the plastic strain in the profile. The determination of those two is difficult in any bulk metal forming process, especially in extrusion processes, where any access to the material during the core formation process itself is limited.

For the investigation of material flow in extrusion processes the inscribed matrix visualization method is commonly used [1]. Improvements of this method based on the Inscribed Grid Pattern (IGP) and Pin Grid Pattern (PGP) methods which are presented in [2] lead to further research work by LKR [3,4]. At those improvements continuous copper wires (joint IGP-PGP method) or a continuous copper mesh (Mesh Grid Pattern (MGP) method) [3,4] are applied onto the meridian section of an extrusion billet and are detected by computed tomography (CT) as a non-destructive investigation method. in contradiction to the basic methods presented in [1,2]. Conventional x-ray imaging at this application is prevented by the different x-ray absorptions due to the different distances. 3D imaging can compensate for the different lengths by considering several images during one rotation. Evaluation of the methods lead to the conclusion that the new methods can also show the material flow with reduced effort at preparation in terms of costs and time. Finally, the Plasma Coated Grid Pattern (PCGP) method [5] used in this work, was developed. The main advantage of the latter method is the feasible determination of quantitative strain in the extruded profile additional to the flow behaviour of the material inside of the container including the influence of wall friction on the material flow [1]. This is possible since at the PCGP method cross shaped copper markers with a specific distinctive cross geometry instead of the inscribed grid, inserted pins [1,2], continuous wires or mesh [3,4] are deformed.

Previous work [3-5] was conducted at a semi-industrial scale extrusion press at LKR. In this work the upscaling of the PCGP method from semi-industrial to near-industrial scale is investigated to evaluate the feasibility of this method for industrial use. This encloses not only the support of simulation activities but also investigations on the shop floor level, where the basic method are common. The information of the strain in the profile (and its development during the process) is an additional parameter for further improvement of the investigated extrusion process, which is not possible with the methods known in literature [1,2].

Experimental Method

Billets of EN AW-6082 with a geometry of 108 mm diameter and 300 mm length were cut into two halves with a side milling cutter, shown in Fig. 1 left. Later, one half of each billet was plasma coated with a 200 µm thick copper cross pattern using a template. Compared to the work described in [5] the ratio between the length and the width of cross arm was increased from 3:2 to 5:2, Fig. 1 right. The simultaneous increase of the spacing between two cross markers from 5 mm to 14 mm led to a 21x8 pattern on the midplane of the extrusion billets. After the coating process one uncoated and coated half were re-joined by welding around the edges.

Figure 1: Preparation of plasma coated extrusion billets – billet halves after cutting with side mill cutter (left) and detail of the template showing cross pattern geometry (right)

An 8 MN direct and indirect extrusion press (built by SMS Hasenclever) was used to perform the experiments. All billets were extruded in a container with 110 mm diameter to a tube profile with an outer diameter of 50 mm and a wall thickness of 5 mm, resulting in an extrusion ratio of 13.4:1, at 460 °C and a ram speed of 0,5 mm/s. The position of the billet´s midplane in relation to the porthole bridges was a special issue during the experiments, as shown in Fig. 2. In case of a horizontal midplane of the billet and a vertical positioning of one of the porthole bridges all the copper markers could flow freely into the portholes. Otherwise up to one half of the markers are supposed to be congested at the stagnation point of one porthole bridge. This reduces significantly the amount of copper markers which can be used for further analysis.

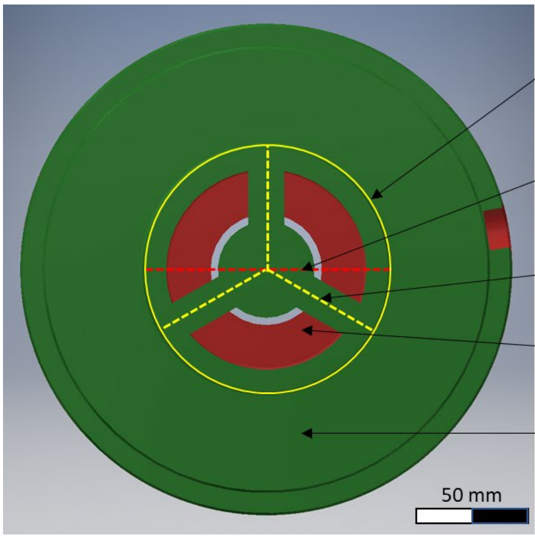

Figure 2: Sketch of the splitable extrusion die – position of midplanes at extrusion billet (red dashed line) and porthole bridge (yellow dashed line)

During the extrusion trials eight billets were processed in a "block-on-block" regime and the profile was cut off after extrusion of every billet resulting in eight profile sections, from which 150 mm long samples at the beginning, in the middle and the end of a profile (in total 24 samples) were extracted. At extrusion of the eighth billet the process was stopped at 230 mm stroke. Afterwards the extrusion profile was cut off and the remainder teared off from the material in the die. As shown in Fig. 3, further disassembly procedures, which was possible by the usage of a splitable die, lead to the nearly non-destructive extraction of the material between the porthole inlets and the tube-shaped outlet.

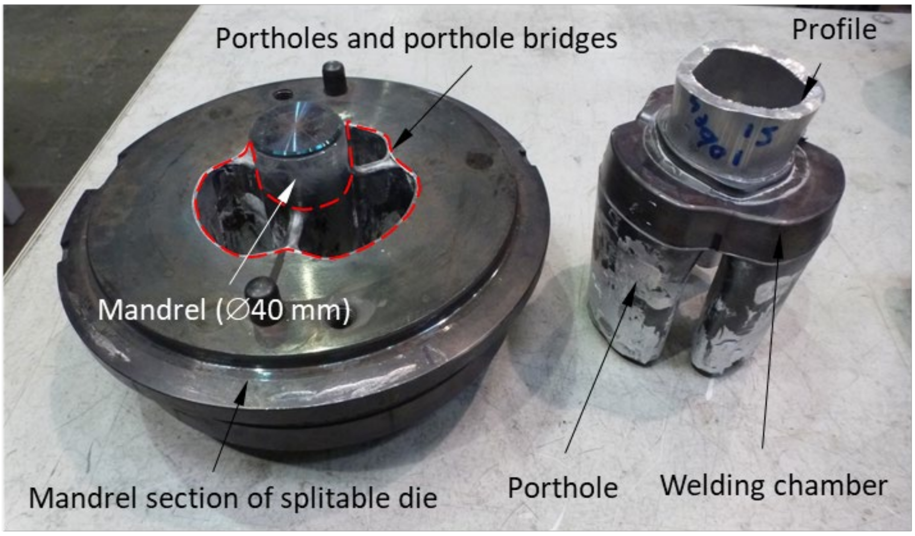

Figure 3: Mandrel section of the splitable die (left) and extracted material (right) after disassembly

Those sections together with the profile sections were then analysed by industrial CT (RayScan 250 E) to image the changes in the printed copper pattern due to the extrusion process.

Results

Visual inspection. The visual inspection of the remainder clearly shows the tear off region at all of the three portholes (areas with continuous line in Fig. 4 left), which corresponds with the torn off material in the porthole (Fig. 4 right).

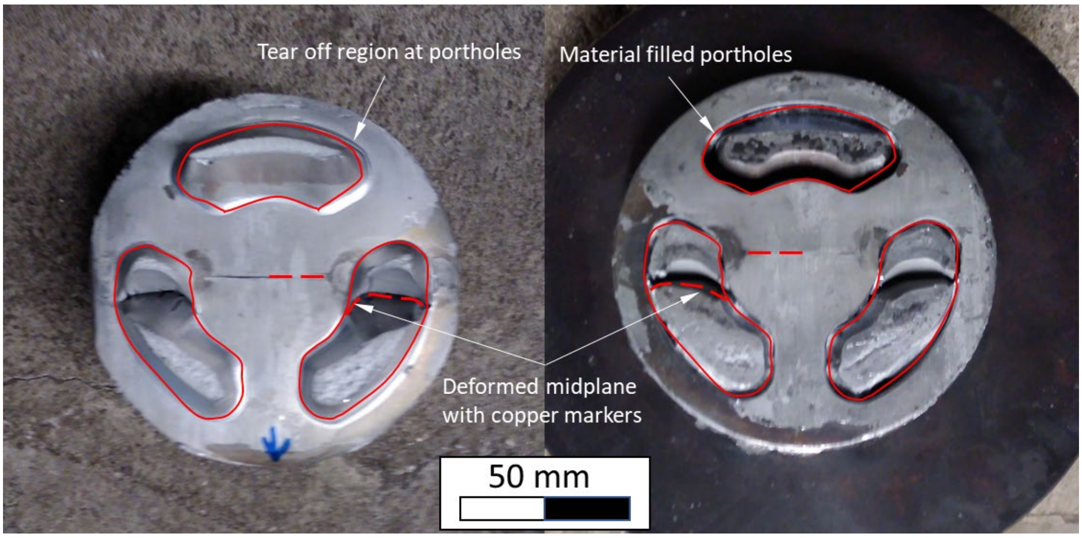

Figure 4: Remainder (left] and mandrel section containing the extracted material before disassembly (right) after extrusion of billet 8– shapes of tear off region and billet midplane.

At the centre of the remainder, the midplane containing the copper markers can be observed as a straight line (dashed lines in Fig. 4). For the sake of a better view on the appearance of the midplane only one half of the curvature is marked with a dashed line. Due to the flow of the material over the porthole bridge a section of the midplane is deformed out of the meridian section to the centre of the porthole. Corresponding markings can be found on the die plane. Being transparent for the deformed midplane in the two portholes, a slight change in colour is recognisable between the portholes on the aluminium material sticking to the die. The deformed midplane from visual inspection is a first hint at the determination of material flow prior to computed tomography.

Computed tomography. Both images of scanning the remainder and the extracted material inside the extrusion die (Fig. 3) show very good visibility of the applied copper markers (Fig. 5). The tear off region can be observed at the scan of the remainder (Fig. 5 left). In the case of the material inside the die (Fig. 5 right) it cannot be identified in the scan since the characteristic cone shape of the tear off region, caused by necking of the material, was destroyed by upsetting during the disassembly operation.

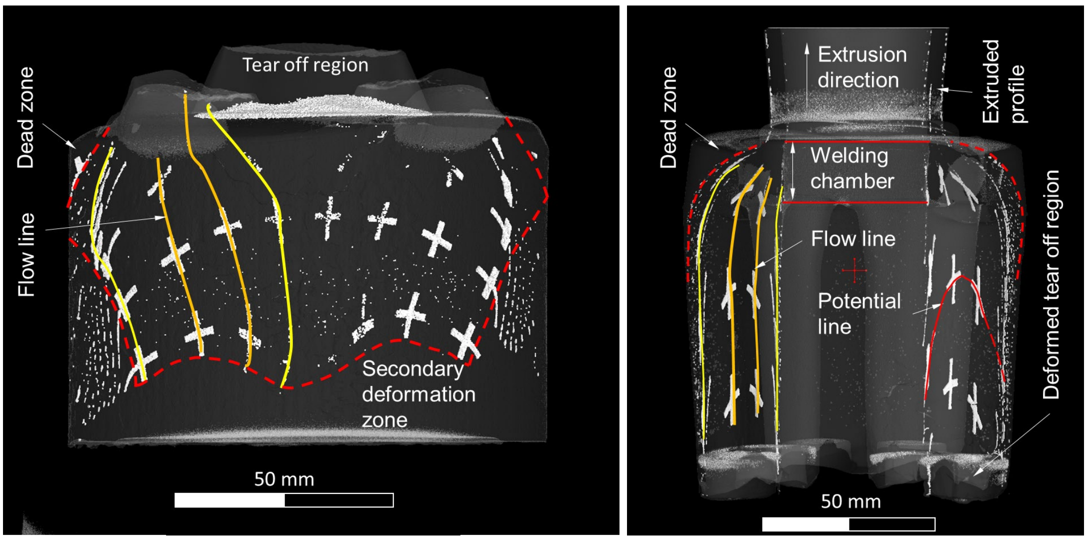

Figure 5: Maximum intensity projection of CT-data for remainder (left) and extracted material from the welding chamber (right) after extrusion of billet 8

The two types of arms of a copper marker can be used to describe the flow pattern. While the longitudinal arms of every marker´s column form the flow lines, the transversal arms represent the potential lines in the pattern. To some extent the latter can be interpreted as the velocity distribution in the material. The dead zone is clearly visible in the remainder and in the welding chamber. The difference is that the dead zone in the welding chamber can only be identified by the outer flow lines. In the remainder also the undeformed remains of the outer markers in the first row are observable while the rest is sheared off at the first filling of the welding chamber. So, the identification of the dead zone is easier in the remainder than in the welding chamber.

At the back of the remainder a significant volume contains no copper markers (Fig. 5 left). This correlates with the secondary deformation zone [1] which is caused by the accumulation of the shell material during the extrusion process at the back of the billet. The reason for the lack of debris in this zone - in contradiction to [3,4] - is the fact that in this setup, and also in [5], markers do not reach the thin area near the billet surface. Due to the sticking of billet material at the container wall this thin area forms the secondary deformation zone during the extrusion process. The additional hint for the formation of the secondary deformation zone is the appearance of the outer markers near the billet surface. At first the outer arms of the markers are deformed in shearing conditions while keeping their full integrity, see also [5,6]. Then, they are sheared off, see markers near the tear off region in Fig. 5 left and [3,4]. This and further destruction of the torn off markers produces debris which also follows material flow. During the extrusion process the sticking material at the shell pushes the markers at the end of the billet towards the centre of the billets, see also [3-5].

In the welding chamber the number of identifiable cross markers is significantly reduced by the friction between the tool on both sides (outer shell and mandrel) and the deformed material. Only the deformed markers at the two columns in the middle of each half are observable and measurable, orange flow lines in Fig. 5. Due to the heavy deformation and scattering into small particles along the contact path on the container and the welding chamber the outer markers, outer yellow flow line in Fig. 5, are only usable for determination of the flow lines At the inner markers, i.e. the markers neighbouring the symmetry axis – inner yellow flow line in Fig. 5 –, some are usable for determination of the local longitudinal strain and the potential line. This determination is possible because in comparison to the outer markers the length of frictional contact of the newly established surface is much lower. But an inner marker, which reaches the welding chamber, is deformed so heavily and scattered into small particles like the outer markers, that longitudinal and transversal arms cannot be distinguished.

On the scan of a profile (Fig. 6), four flow paths of marker material are present. The two paths next to the surfaces (yellow dashed lines in Fig. 6). show heavy scattering into small particles caused by the frictional contact at the container and in the die, The two paths inside the profile contain high integrity copper markers, where both arm types are still recognisable and measurable (orange dashed lines in Fig. 6). Connecting the intersections of all flow paths with the profile cross section, the shape of the distorted midplane can be drawn (red dashed curve in Fig. 6). The appearance of the different flow paths corresponds with the findings concerning the welding chamber.

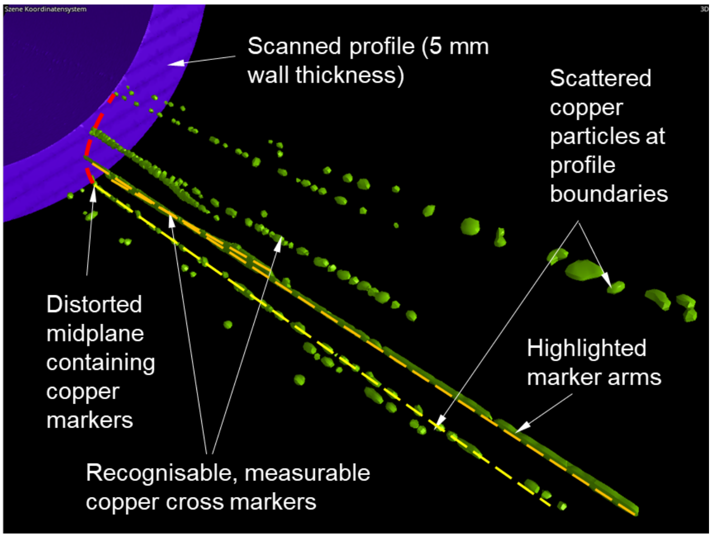

Figure 6: Maximum intensity 3D projection of CT-data for end section of profile 2 containing scattered copper particles (yellow dashed line), recognisable, measurable copper cross marker arms (orange dashed line) and distorted midplane (red dashed line)

Discussion

When comparing the results with ones at semi-industrial scale in [5] the PCGP method is capable of visualising the material flow properly in both scales. Again, the PCGP method acts in near-industrial scale as an additional evaluation method to improve numerical process simulation model for extrusion. Furthermore, the detailed analysis reveals the advantages of the new geometry setup of the copper markers (Fig. 1 right). Due to the higher length-to-width ratio of the cross arms also the tilted transversal arms are clearly identified in the final profile, which was not the case in [5] due to the compact, quadratic geometry of a single cross arm. Compared to visualisation methods conducted during the development process of this visualisation method [3,4], the most important feature is the determination of strain even in the profile.

Outlook

In [5] the strain in the profile is only calculated by the longitudinal arms of a marker. This is not sufficient for the calculation of the effective strain in three-dimensional deformation state. Therefore, the separate determination of the arm geometries and deformation path is necessary to obtain data for the establishment of the strain tensor and the corresponding effective strain.

For the determination of strain tensor, the exact formulation of transferring the measurements of the copper markers into the elements of the strain tensor is subject of further research, but in general the following assumptions can be used as a starting point:

- Usage of a cylindrical coordinate system,
- Determination of tensile and compression strain by length of markers and
- Determination of shear strain components by change of the marker arm angles.

The shear strain of the longitudinal marker arms is calculated by the evolution along the deformation and cannot be determined by simple comparison of the deformed cross markers with the original marker geometry as it is possible for the other deformation parameters. Since STL-Files containing all of the scanned copper markers can be extracted from the CT-scans, machine learning algorithms can be significantly used for the determination of strain distribution.

Conclusion

With the help of the computed tomography, the initial non-destructive method developed and primarily tested at the semi-industrial scale has been successfully scaled up to the near-industrial scale and can be easily used for any profile shape. The improved geometry setup of the copper markers enables the future calculation of the effective strain of the complex strain condition in the profile. Since the strain in the profile cannot be determined by the other process parameters, e.g. extrusion force and profile temperature, the method can be used for improving the quality of simulation models at extrusion.

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