Simulation of composite hot extrusion with high reinforcing volumes

Martin Schwane\textsuperscript{a,*}, Teresa Citrea\textsuperscript{b}, Christoph Dahnke\textsuperscript{a}, Matthias Haase\textsuperscript{a}, Nooman Ben Khalifa\textsuperscript{a}, A. Erman Tekkaya\textsuperscript{a}

\textsuperscript{a} Institute of Forming Technology and Lightweight Construction, TU Dortmund University, Baroper Str. 305, 44227 Dortmund, Germany
\textsuperscript{b}Department of Mechanical Energy and Management Engineering, University of Calabria, 87036 Rende, Italy

Abstract

Experimental results, which indicate a significant influence of the reinforcing elements on the material flow during composite extrusion with high reinforcing volumes, are presented. In order to analyze the process numerically, finite element simulations with models taking into account the reinforcing elements were carried out. The results are discussed with regard to the material flow and the load of the reinforcing elements.

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1. Introduction

The research on the composite extrusion of continuously reinforced aluminum profiles has been carried out for several years at the Institute of Forming Technology and Lightweight Construction (IUL). During composite extrusion, reinforcing elements (RE) are laterally fed within the supporting legs into the composite extrusion die. Here, the RE are deflected in extrusion direction and finally fed into the welding chamber through a mandrel (Fig. 1a). During the development of the longitudinal seam weld, which arises from the rejoining of the material streams

* Corresponding author. Tel.: +49 231 755 7229; fax: +49 231 755 2489
E-mail address: martin.schwane@iul.tu-dortmund.de
from different feeders, the bonding between the RE and the base material takes place under both a high temperature and a high pressure, before the composite profile exits the die. Typically, wires of high strength steel are used as RE in order to improve various mechanical properties of the profiles, such as strength, effective Young’s modulus and energy absorption during crash. Therefore, continuously reinforced aluminum profiles are suited for the application in lightweight constructions. The reinforcing volume of the produced profile cross sections has been gradually increased during the last years (Fig. 1b).

Besides experimental investigations, the finite element method (FEM) has been utilized in order to gain basic knowledge of the mechanical and thermal conditions during the process. Schikkora and Kleiner (2006) used a simple axisymmetric FEM model to investigate the influence of the die geometry on the material flow and the stresses in the RE during the extrusion of a round bar with a single RE in the center. Furthermore, Pietzka et al. (2013) considered a simplified approach in order to determine the deflection of the RE in a rectangular, flat profile. A slender strip with two RE was modeled to mimic the material flow near the symmetry plane of the profile. Due to the numerical effort and the high computation time, only the very initial stage of the process with little punch movement was simulated. In both of the aforementioned research works, Lagrangian FEM codes were used. In order to overcome the limitations of Lagrangian codes, in particular with regard to model complexity and necessary computation time, FEM based on the Eulerian formulation was applied. Schikkora and Kleiner (2007) used Altair HyperXtrude for the steady-state simulation of an I-beam profile. The position of the longitudinal seam welds was determined by optical inspection of flow lines and the distribution of the equivalent stresses. As the RE are embedded in the seam weld, the seam weld position gives an indication of the RE position in the profile cross section. The analysis of the composite extrusion process by Eulerian formulation was further improved by Kloppenborg et al. (2010), who introduced the particle tracing method. By means of this method, the RE positions in the profile cross section can be exactly determined (Kloppenborg, 2012). The RE are not considered physically in the Eulerian models, but only by virtual particles traced through the computed velocity field. However, the method provides reliable results for profiles with a low RE volume and a high RE diameter to profile thickness ratio.

In this paper, experimental results which indicate a significant influence of the RE on the material flow and the final geometry for profiles with high RE volumes are presented. Furthermore, approaches for the simulation of the composite extrusion process with the RE considered in the Eulerian FEM model are introduced in order to allow the broad analysis of such process conditions. The influence of the RE on the material flow is analyzed and validated with the experimental results. The load on the RE is assessed as well.

2. Experiment

A trial to produce a flat, rectangular composite profile with 16.4 % RE volume, which is defined as the total RE cross section area to the profile cross section area, was conducted on a 10 MN direct extrusion press at the IUL. 12 wires made of spring steel 1.4210 were embedded into AA6060 aluminum. During the initial stage of the process, the mandrel was damaged so that some of the RE were clamped and ruptured successively, as shown in radiographic analysis (Fig. 2a). It was found that the dimension of the cross section deviated from the desired cross section, which is usually determined by the geometry of the die orifice. In the section with 12 RE, the thickness is
significantly increased at the short edges of the profile and slightly increased in between (Fig. 2b). A characteristic material distribution can be further observed for the sections with reduced number of RE: In the center, where the RE are ruptured, a distinct increase of the wall thickness is found as well. The level of the swells at the edges and the center decreases along with the reduction of the number of RE embedded in the profile.

The experimental results showed an imbalanced material flow in the die orifice and a significant influence of the RE. It is supposed that the flow resistance at the edges and, after rupture of the RE, in the center of the profile is lower compared to the areas in between the RE. Therefore, the flow velocity is higher in these regions. After the profile has left the die the flow stress increases due to cooling of the material. The material with higher velocity cannot flow into the solidified profile and, hence, it piles up locally.

3. FEM analysis

3.1. FE model setup

Altair HyperXtrude 12.0 was utilized for the steady-state simulation of the process. Due to symmetry conditions, quarter models and half models were set up, in order to save computation time. In the FEM model the RE were incorporated by means of an appropriate boundary condition (BC), as depicted in Fig. 3. The solid wall BC with sticking and adiabatic thermal condition was set at the aluminum-RE interface. Here, the RE behave like rigid bodies that are moving with a prescribed velocity.

![Fig. 3. FEM model and boundary conditions.](image-url)
Unlike in the real process, in which the RE velocity \( v_{RE} \) results from the profile’s velocity, the RE velocity needs to be defined as a boundary condition. Assuming the desired profile cross section shown in Fig. 2b, the respective velocity \( v_{RE} \) was calculated by means of the following equation considering volume constancy:

\[
v_{RE} = v_{Punch} \frac{D_{Container}^2 \pi}{4} / \left( h b - n \frac{D_{RE}^2}{4} \pi \right),
\]

where \( v_{Punch} \) is the punch velocity, \( D_{Container} \) is the container diameter, \( h \) is the profile’s height and \( b \) its width, \( n \) is the number of RE, and \( D_{RE} \) is the RE diameter. Since the total cross section area of the RE is considered, Eq. (1) accounts for the increase of the extrusion ratio in composite extrusion.

3.2. Influence of reinforcing volume

Concerning the influence of the RE volume, i.e. the number of RE, the experimental results could be confirmed by the FEM simulations. Fig. 4a shows the normalized velocity, i.e. the velocity to RE velocity ratio, at the bearing exit along the profile width. As in the experiment, for the profile with 12 RE, a higher velocity is computed at the edges.

Furthermore, for the models with reduced number of RE, the maximum velocity can be observed in the cross sections with missing RE, located in the center of the profile. However, compared to the specimens from the experiment, where the swells at the edges and in the center exhibit similar thicknesses for each of the sections with reduced number of RE, thus indicating similar flow velocities in these regions, the simulated velocity at the edges is higher as well, but considerably lower than the respective velocity peak in the center. Nevertheless, the decrease of the flow imbalance, i.e. the difference of the flow velocities, resulting from the reduced number of RE is clearly predicted by the FEM results (Fig. 4b).

3.3. Influence of reinforcing element velocity

Since the measured cross section area is larger than the cross section of the die orifice for all inspected specimens, it can be concluded that, due to the volume constancy condition, the profile velocity and hence the RE velocity during the experiment was lower compared to the RE velocity resulting from Eq. (1). Therefore, simulations with reduced RE velocity were carried out in order to investigate the effect on the flow conditions. The
results for the model with 8 RE are shown Fig. 5. Here, the initial RE velocity resulting from Eq. (1) was defined 100 % $v_{RE}$. The reduced RE velocities with 85 % and 70 % of the initial value are labeled 85 % $v_{RE}$ and 70 % $v_{RE}$, respectively. The decrease of the RE velocity increases the flow imbalance. This effect is more pronounced at the bearing entrance (Fig. 5a) than at the bearing exit (Fig. 5b) due to the transition from sticking to sliding friction. At the entrance, the aluminum sticks to the bearing surface (velocity is zero) as well as to the RE surface (velocity corresponds to RE velocity). Due to the velocity gradients and the volume constancy, the material is accelerated in the remaining cross section area. The higher flow velocity at the edges compared to the area between the RE can be attributed to the better material flow from the lateral region of the welding chamber, illustrated by the flowlines in Fig. 5c, as well as to the difference of the distances bearing to RE and RE to RE, which is 4 mm and 2 mm, respectively. At the bearing exit the aluminum slides along the bearing surface, so that the velocity distribution is more homogeneous in the profile cross section (Fig. 5b). Here, the flow velocity of the aluminum in between the RE is equal to the RE velocity, while it is still higher in the profile center and at the edges.

A transition from sticking to sliding friction in the bearing channel was experimentally verified by Maa et al. (2012).

Fig. 5. Velocity ratio (a) at the bearing entrance and (b) at the bearing exit (c) velocity distribution in the profile and deformation (scale factor 1) for different RE velocities.

### 3.4. Analysis of load on reinforcing elements

In order to assess the load on the RE during the process, models were set up in which the RE were meshed and assigned with appropriate material data, i.e. Young’s modulus = 180 GP and Poisson’s ratio = 0.3. Here, the RE velocity as well as the temperature (470°C) were defined at the RE inflow surface.

For the model with 12 RE and 100 % $v_{RE}$, the velocity distribution and the axial stress of the RE in the welding chamber region are depicted in Fig. 6a. The results regarding the position of the maximum stress in the RE verify the explanation from Kloppenborg (2012): In the welding chamber, the aluminum flow velocity in the vicinity of the RE continuously increases from the dead metal zone behind the mandrel to the sticking friction region in the bearing channel. As a result, the flow velocity exceeds the RE velocity near the bearing entrance. At this critical position, the sign of the shear stresses acting on the RE surface reverses, i.e. first the shear stresses are directed opposite to the extrusion direction, and behind the critical position, they are directed in the extrusion direction.

Furthermore, the influence of the RE velocity on the stress level was investigated. For two RE velocities, the normalized axial stresses, i.e. the stresses related to the stress of RE #6 at 100 % $v_{RE}$, are shown in Fig. 6b. A clear increase of the stress level can be observed when the RE velocity is reduced from 100 % to 85 %. This difference is due to the increase of the shear strain rate at the RE surfaces, which results in an increase of the flow stress and, hence, in a higher load on the RE. Furthermore, the highest stresses in each case can be found at RE #1. This is also due to the increased velocity difference between RE and aluminum at the edge, compared to at the profile’s center.
Conclusions

A composite extrusion process to produce a flat aluminum profile with high reinforcing volume was carried out. The experimental result indicated a significant influence of the steel wires, which were used as reinforcing elements, on the profile geometry and, hence, on the material flow. In order to allow the analysis of the process, Eulerian finite element simulations, which considered the reinforcing elements, were conducted. Thus, the influence of the process conditions on the material flow could be examined. It was found that the number as well as the velocity of the reinforcing elements affect the imbalance of the material flow in the die orifice, thus resulting in local swelling of the profile. Furthermore, the stresses in the reinforcing elements could be assessed. It turned out that the increase of the difference of the flow and the reinforcing element velocity in the vicinity of the particular reinforcing element results in higher stresses.

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