Online Measurement of the Radial Workpiece Displacement in Electromagnetic Forming Subsequent to Hot Aluminum Extrusion*

A. Jäger[1], A. E. Tekkaya[1]

[1] Institute of Forming Technology and Lightweight Construction, TU Dortmund University, Germany

Abstract

Electromagnetic compression was integrated into the process chain of hot metal extrusion in order to reduce the cross section of the workpiece locally. To integrate both processes, a tool coil for electro-magnetic compression is positioned behind the die exit and coaxially to the extrudate. Additionally, a counter die in the shape of a mandrel can be mounted to the mandrel of a porthole extrusion die, which extends into the working area of the tool coil. Experiments were conducted on hollow profiles which were compressed by electromagnetic forming subsequent to extrusion. Due to an extremely short processing time of the high speed forming process, a compensation of the relative speed between the workpiece and the tooling can be ignored. For determine the workpiece displacement during the electromagnetic forming process, a new measuring strategy based on the Photon Doppler Velocimetry was developed.

Keywords

Electromagnetic forming, High speed forming, On-line measurement

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1 Introduction

Hot metal extrusion is used to produce straight, semi-finished products in mass production [1] with a constant cross section over the length and homogeneous mechanical and microstructural properties [2]. Frequently aluminum sections are used as construction elements. As, in general, the loading conditions of structure elements in technical constructions differ locally, the constant cross section, which is attributed to the peculiarity of the extrusion process itself, mostly represents a compromise between the functionality and the component design. This may result in local oversizing and excessive use of resources. A local adaption of the geometry could be suitable in order to adapt the locally specific demands on the structure properties. For this reason, the development of innovative forming technologies is indispensable in order to manufacture products with graded properties as well as locally adapted geometric shapes.

In order to modify the geometry of a tubular extrudate locally, electromagnetic compression was integrated as a hot forming operation into the process chain of hot metal extrusion. By process integration of both processes the heat of extrusion is used for the successive forming operation.

2 Description of the Concept

While hot metal extrusion is used to produce tubular semi-finished products with a constant cross section quasi continuously, electromagnetic compression can be used to reduce a workpiece's cross sections locally. To integrate both processes, a tool coil for compression was positioned behind the die exit and coaxially to the extrudate in order to reduce the workpiece cross section locally (Figure 1). Due to the favourable relation between resulting exit speed in extrusion (typical 50 m/min) and the processing time in electromagnetic compression (typical 100 µs), a longitudinal translation between the workpiece and the tool coil during the compression process can be neglected. Therefore, the application of electromagnetic compression subsequent to extrusion is possible without a compensation of the relative speed between the workpiece and the tooling. The tool coil can be placed stationary behind the die exit.

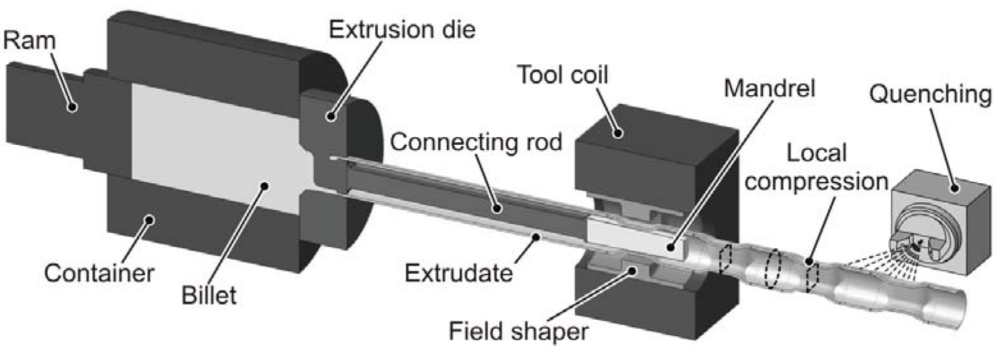

***Figure 1**: Concept of extrusion and integrated electromagnetic compression (longitudinal section, schematic)[3]*

To achieve a more defined geometry, in comparison to a free forming operation, and to increase the geometrical complexity of locally compressed areas, a counter die in the shape of a mandrel can be used. This is mounted to the mandrel of a porthole extrusion die and extended into the tool coil [4].

3 Setup and First Trials

For the evaluation of the concept, a test rig was built (Figure 2). In order to reduce the workpiece cross section locally different solenoid tool coils (Poynting GmbH), connected to a 32 kJ pulse power generator (Maxwell-Magneform series 7000), were positioned behind the die exit of a 250-t direct extrusion press (Collin PLA250t). To adapt the tool coil and the extrudate geometry, field shapers made out of a CuCrZr-alloy or an EN AW-6060 alloy, insulated with a polyimide foil, were used. Beyond shaping and concentrating of the electromagnetic field, by using a field shaper also an overheating of the tool coil by thermal radiation of the processed hot extrudate is prevented. Guiding rollers made out of brass are arranged pairwise at the inlet and runout side of the tool coil to assure a uniform air gap between the field shaper and the workpiece. For heat treating of the extruded and subsequently hot deformed workpieces made of heat treatable alloys, an additional quenching setup using air atomized water mist as a coolant was integrated behind the coil. The whole setup is designed compactly in order to ensure that the temperature of the extruded aluminum does not decrease too much before the subsequent forming and heat treatment operation.

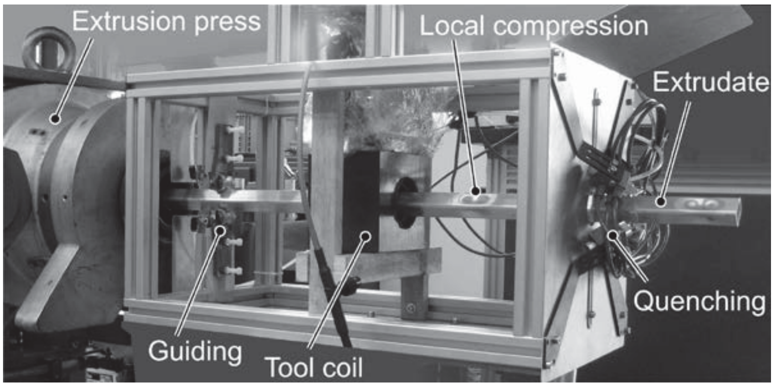

***Figure 2**: Setup for hot extrusion and subsequent electromagnetic compression [3]*

In order to expand the range of geometrical shapes with cross-sections other than that of the extruded aluminum, a mandrel can be used to define the cross section geometry. A squared mandrel for the processing of a round tube was chosen and specially designed to prevent force fit between the workpiece and the die. To prevent a force fit between the extrudate and the mandrel, the corners of the mandrel are chamfered with a radius of 5 mm and a draft angle of 0.5° in extrusion direction is applied. Additionally, a squared field shaper in combination with the round tube was used to adapt the air gap between the field shaper and the workpiece (Figure 3 a)) and accordingly the pressure. For proving this concept, a simplified finite element simulation of the magnetic field was carried out using FEMM 4.2 developed by Meeker [7]. For calculation of the electromagnetic field distribution in the initial condition (neglecting the effect of deformation) a 2D-axisymetric-model of the working area according to Figure 3 b) was prepared and calculated in different planes/angels θ (f = 4.5 kHz, I_{max} = 60 kA).

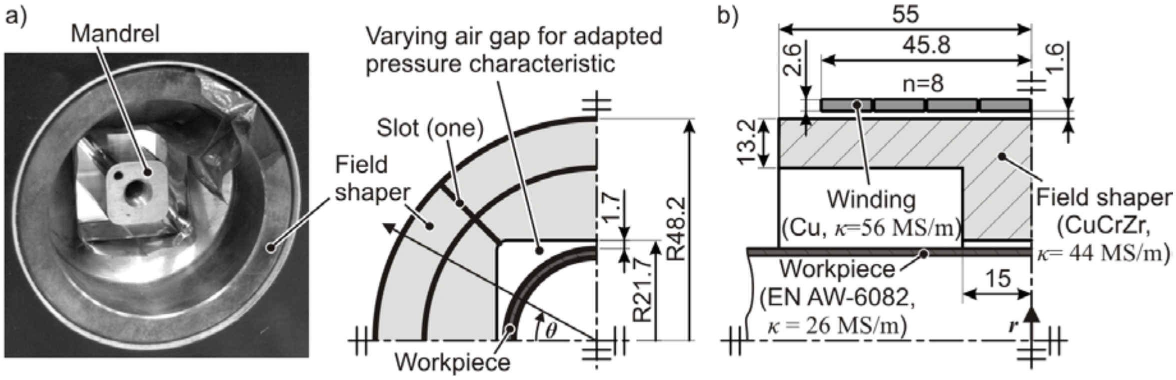

***Figure 3**: a) Field shaper with squared cross section for adapted pressure characteristic, b) Geometry of the working area for finite element simulation*

The results of this simplified calculation are presented in Figure 4. For the analysed configuration, where the length of the concentrator is short in comparison to the diameter of the workpiece, the aspired variation of the magnetic flux density, which is higher at lateral faces and lower at the corners of the mandrel, could be detected.

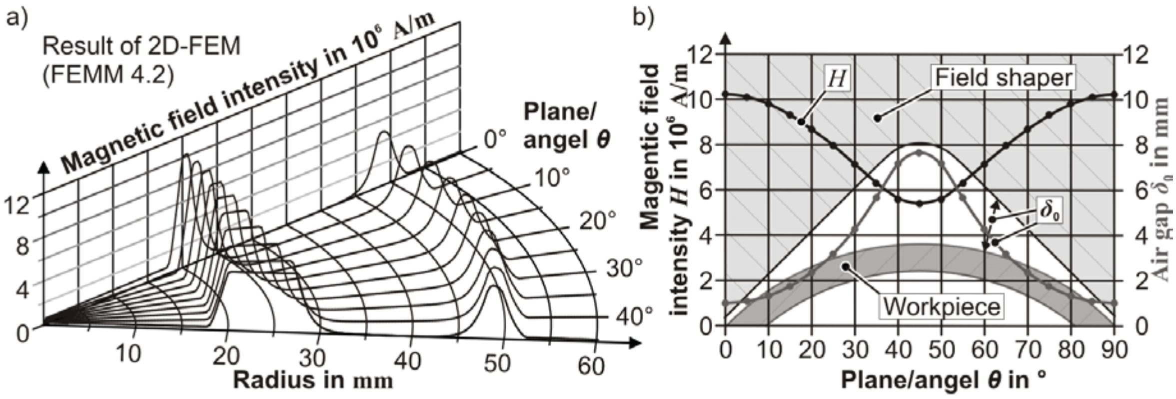

***Figure 4**: a) Radial distribution of the axial magnetic field intensity, b) maximum axial magnetic field intensity between workpiece (round) and field shaper (squared)*

Using an EN AW-6082 aluminum alloy, a porthole extrusion die and a squared field shaper, a round tube (Ø40x2 mm) was extruded with an exit speed of 0.43 m/min while electromagnetic compression was applied periodically in intervals of approximately 10 s. Figure 5 a) shows a locally geometrically graded profile manufactured by the introduced process chain processing of a round tube in combination with a squared mandrel (Figure 5 b)). The distance between the local bulges is determined by the profile's exit speed and the discharging frequency, which is limited by the capacitor charging time of the electromagnetic forming machine. To overcome this limitation the application of two or more banks of capacitors would be possible, in order to allow one or more to be charging while one is releasing energy.

The general feasibility of this technological concept could be proven. Details about the process limits and defects are given in [3]. A possible application is seen in the manufacturing of tubular energy absorbing elements with an adapted force-displacement characteristic as a “crashbox” in a car bumper system, e.g. designed as a telescoping tube or inversion tube. The inversion process involves the turning outside in of a tube under axial compressive load, which is, after initiation of the inversion, characterized by constant load level [6].

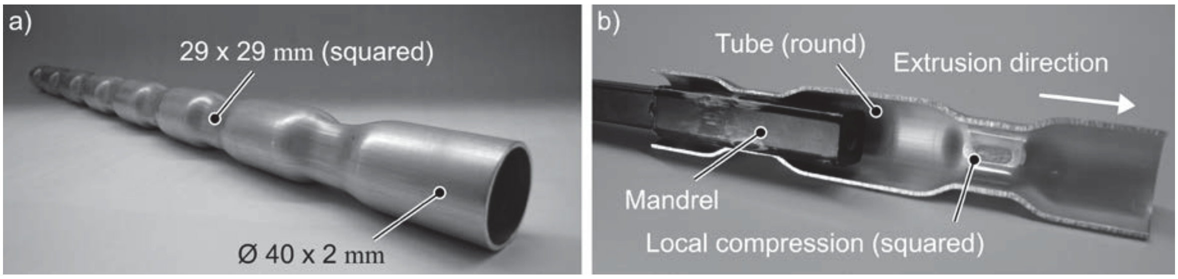

***Figure 5**: a) Tubular product, b) position of the mandrel (longitudinal cut) [5]*

4 Online Measurement of the Radial Workpiece Displacement

For analyzing the deformation behavior of the workpiece in the high speed part within the process chain, the measurement of the displacement of the workpiece is necessary. In the field of “conventional” electromagnetic tube compression, optical measuring concepts are known, where for example the shadowing of a parallel line-shaping laser beam by the workpiece during the forming process is used to detect the radial compression [8] or expansion of a tubular section. Fenton [9] described the usage of a Photon Doppler Velocimetry (PDV) based setup by running a laser beam radially on the surface of the workpiece through a gap between the windings of a tool coil. Alternatively a deflection of the laser beam within the air gap between the tool coil and the work piece, by using a small mirror, is proposed [9]. Due to the tool coil, the field shaper and the combination with the hot extrusion process, the accessibility of the workpiece in the working area of the tool coil is limited and the previously described measuring techniques are not applicable. Because of the mandrel inside the workpiece, an access only from outside of the workpiece seems to be promising. To create the required accessibility, the preparation of a radial hole or a transverse slot in the tool coil and the field-shaper are conceivable or even the use of two similar coils and field shaper which are positioned close behind each other. Both strategies require modifications of the cost intensive tool coil and may result in a measurable inhomogeneity in the distribution of the field and pressure. As a third variant the usage of a special field shaper is proposed, where the concentrator protrudes outside the tool coil and its casing. Schenk [10] compared two different field shapers with a symmetric and an asymmetric positioning of the concentrator in electromagnetic compression. In regard to the magnetic pressure and the final geometry of the workpiece almost the same characteristic could be detected. A further extension of the concentrator was not analyzed.

For testing this concept, corresponding field shapers were manufactured and tested. To prevent an expanding of the slotted field shaper in the area outside of the tool coil, where it is only loaded from the inside, the field shapers are reinforced by laminated rings of a glass fiber reinforced polymer (Figure 6).

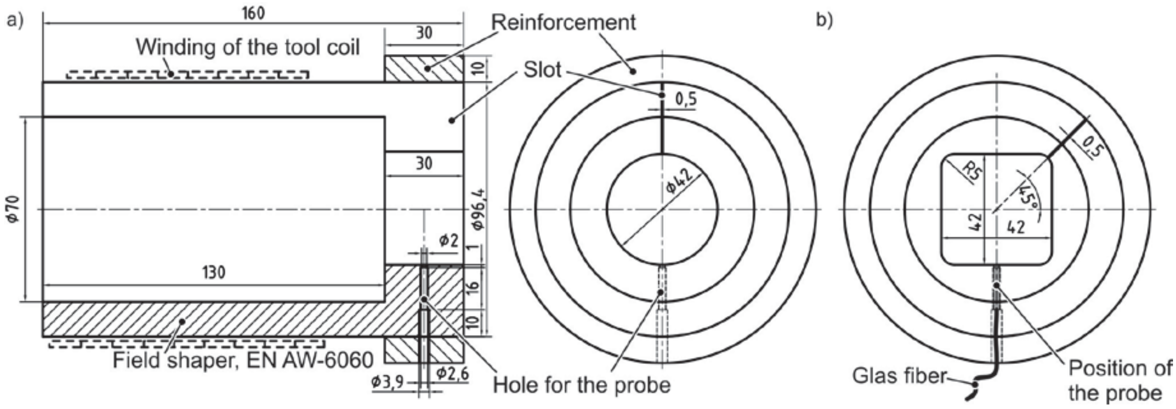

***Figure 6**: Asymmetric field shaper for measuring of the workpiece displacement a) cylindrical and b) squared*

Tests on aluminum tubes made of EN AW-6060 at room temperature revealed, that for achieving the same reduction ratio like in the symmetric reference configuration, the charging energy has to be approximately three times higher. This extensive loss may be connected with the enlarged volume of the slot and has to be taken into account.

In terms of selecting an appropriate measuring technic, optical based systems are preferred, as they are working contactless. Due to the compact design of the probe, a Photon Doppler Velocimetry measuring setup, based on the work of Strand et al. (2005), using a fiber laser source was selected and implemented [11]. The laser source is a 2 W fiber laser with a wavelength of 1550 nm. For the probe a collimator with a case diameter of only 2.5 mm and a measurement range of 10 mm was selected (OZ Optics, LPC-05-1300/1550-9/125-S-0.95-5AS-15-3A-3-3). For integration of the sensor, the field shaper was equipped with a stepped hole according to Figure 5, which was electrical isolated by a polyurethane insulation coating. The sensor itself was wrapped with several layers of polyimide foil to achieve an appropriate diameter for a force fit in the field shaper. The system was tested independently from the extrusion process first (Figure 7 a)).

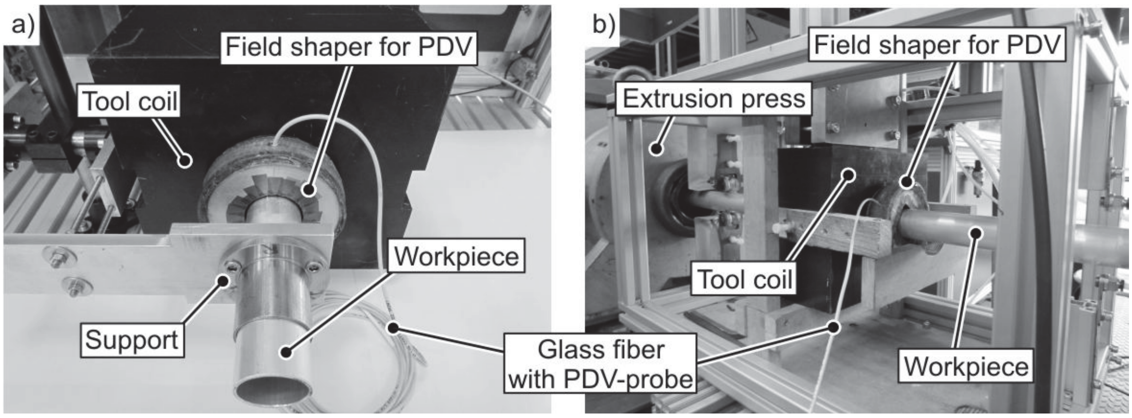

***Figure 7**: Setup for measuring the radial workpiece displacement in electromagnetic compression using an asymmetric field shaper, a) test setup, b) integrated into the extrusion process*

The signals for determining the velocity of the workpiece and for the current (detected by a Rogowski-coil) are detected and recorded parallel on an oscilloscope (LeCroy waveRunner 104MXi 1GHz Oscilloscope 10 GS/s). For analyzing the velocity signal, represented by the beat frequency as the difference between the emitted light and the Doppler-shifted light reflected from the specimens' surface [11], a Fourier transformation in Matlab using the implemented "spectrogram"-function is run. It results in a plot of a time variant frequency distribution. In Figure 8 a) an example of a determined spectrogram is given. Due to multiple reflections between the specimen and the probe, beside the intrinsic signal integer multiple ones of it can appear which complicates the automatic compilation. The radial workpiece velocity is calculated by multiplying the beat frequency by the half of the frequency of the laser wavelength (Figure 8 b)).

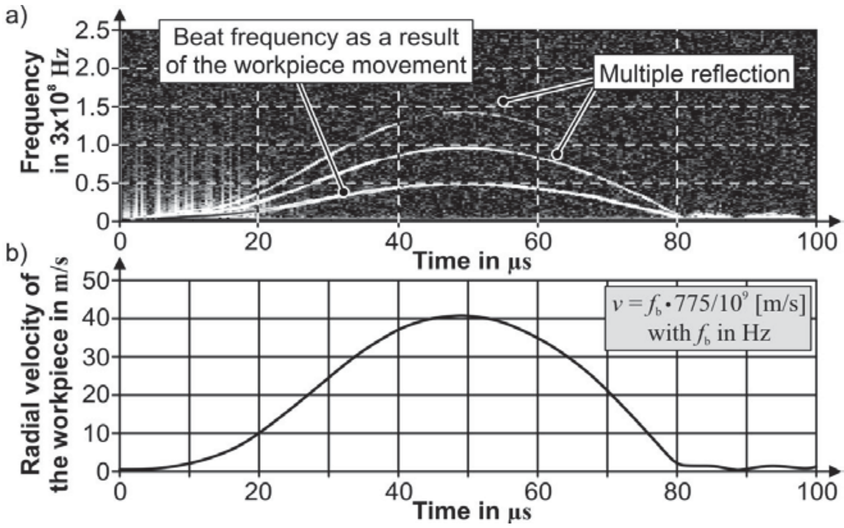

***Figure 8**: Example for the analysis of the Photon Doppler Velocimetry (PDV) a) spectrogram of the beat frequency, b) absolute value of the radial workpiece velocity*

The developed measuring setup was tested within the process chain. While in applying the cylindrical field shaper in combination with a cylindrical mandrel (Ø29.2 mm) adequate forming results could be achieved, the squared version worked insufficient. In Figure 9 the results of the velocity measurements and details of the parameter in processing of a round tube (Ø40x2 mm) subsequent to hot extrusion by using the asymmetric field shaper with a squared cross section (Figure 5 b)) in combination with a squared mandrel are summarized. Limited by the insulation of the used tool coil, even at the highest applicable charging energy of 11 kJ, the workpiece touches the mandrel only locally, while the side faces are not getting into contact. In comparison: By using a symmetrical field shaper, a charging energy of only 8 kJ is sufficient to achieve a full contact between the workpiece and the mandrel.

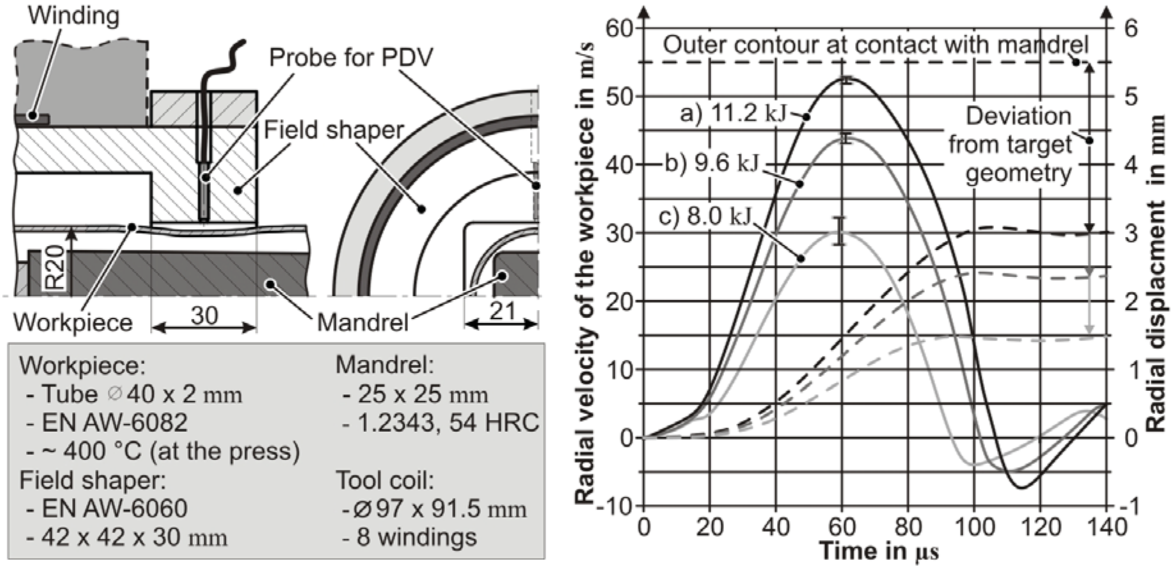

Figure 9*: Results of the PDV-measurement within the process chain by using an asymmetric field shaper*

As the asymmetric configuration of the concentrator leads to considerable losses in the efficiency of the process and insufficient compressions of the workpiece, the measuring concept was redesigned. The aim was to integrate a collimator probe into a symmetric field shaper. For doing this, a stepped hole for the integration of the probe was attached radial in the center of field shapers' concentration area. Due to the surrounding tool coil, only a lateral supply of the signal-carrying glass fiber seemed to be feasible. Consequently a channel was axial drilled through the field shaper approximately 5 mm below its outer surface as far as it crosses the hole for the probe (Figure 10 a)). To install the rigid sensor together with the fixed installed glass fiber, a pocket was milled in the field shaper which provides access to the junction of the drilled holes. To restore the electric conductivity in this area, after inserting of the probe, the pocket was closed by impressing a cap made out of the field shaper material. The final setup is presented in Figure 10 b).

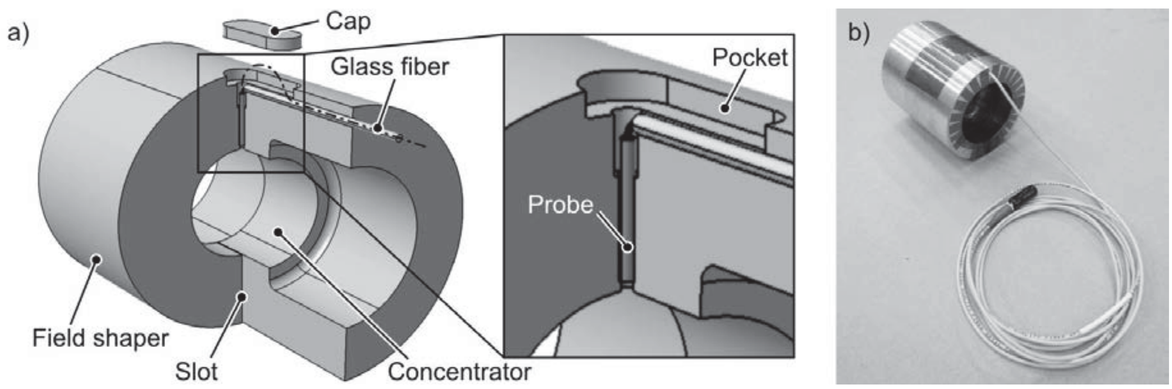

Figure 10*: Symmetric field shaper prepared for PDV, a) schematically, b) final setup*

The new setup was used within the process chain of hot extrusion of a tube (Ø40x2 mm) and subsequent hot electromagnetic compression in combination with a cylindrical mandrel (Ø29,2 mm). The tool coil (center) was positioned 470 mm behind the die exit. As workpiece material an EN AW-6082 alloy was used. The extrudade entered the working area of the tool coil with an axial speed of 0.5 m/min and a temperature of approximately 415 °C. Trials with charging energies between 3.2 kJ and 6.4 kJ were run. The results are presented in Figure 10. The movement of the workpiece starts with a delay of approximately 5 µs after initiation of the damped oscillating current through the tool coil. In applying charging energies of 3.2 kJ and 4.0 kJ only a free forming operation takes place. At the higher investigated levels, a contact between the compressed tube and the mandrel can be detected by sudden drops in the workpiece velocities (area A, B and C in Figure 11 b)). The development of the radial workpiece displacement was calculated by integration (Figure 11 b)). For the charging energies of 4.8 kJ, 5.6 kJ and 6.4 kJ, a final radial displacement in the range of 3.7 mm to 3.8 mm which correlates with the theoretical one of 3.4 mm, calculated on basis of the constant-volume law, by assuming that the axial length stays constant.

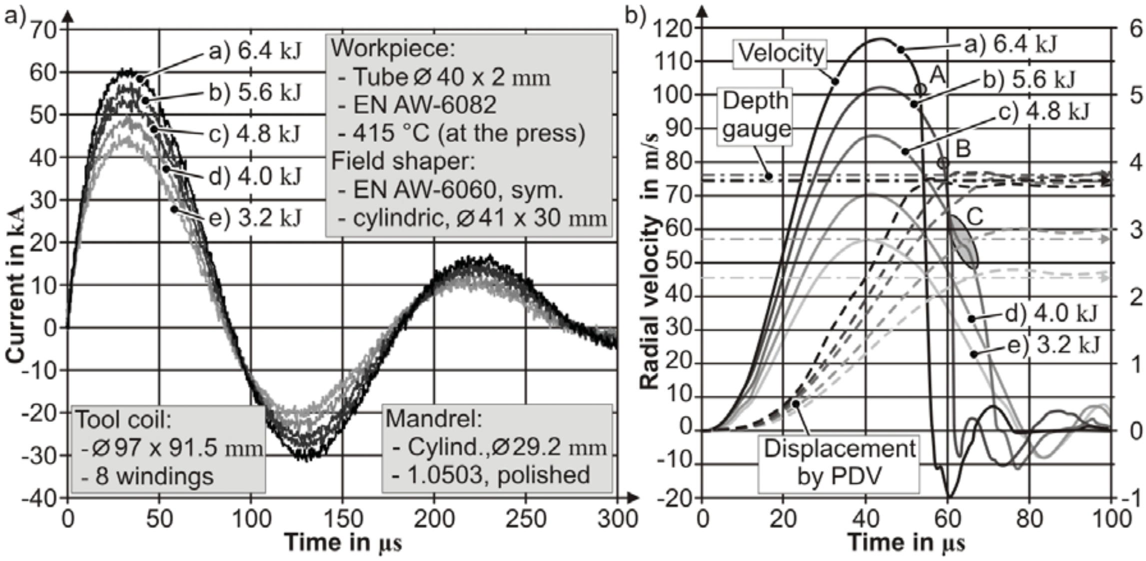

__Figure 11__: Results of the PDV-measurement within the process chain by using a symmetric field shaper, a) coil current, b) radial velocity and displacement

Indicated by these results a powerful tool for the analysis of the workpiece displacement under the special conditions of the proposed process combination has been developed. In future it will be applied for the detection of the interaction between the pressure impulse and the workpiece deformation within the process chain. Beside the characterization of the special hot forming process the application of the setup can be used for the characterization of the processed material at high strain rates and hot forming conditions.

5 Conclusions

Electromagnetic compression was integrated into the process chain of hot metal extrusion in order to reduce the cross section of the workpiece locally. Experiments were conducted on hollow profiles which were compressed by electromagnetic forming subsequent to extrusion. By applying a counter die in combination with an adapted field shaper, a more defined geometry can be achieved and the geometrical complexity of locally compressed areas can be increased. For analyzing the deformation behavior of the workpiece in the electromagnetic forming part of the process chain, specially designed field shapers for the online measurement of the radial velocity of the workpiece on the basis of the Photon Doppler Velocimetry were developed and tested successfully. A tool for the analysis of the workpiece displacement under the special conditions of the proposed process chain has been developed. This offers the potential to analyze the interaction between the pressure impulse and the workpiece deformation within the process chain in future.

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