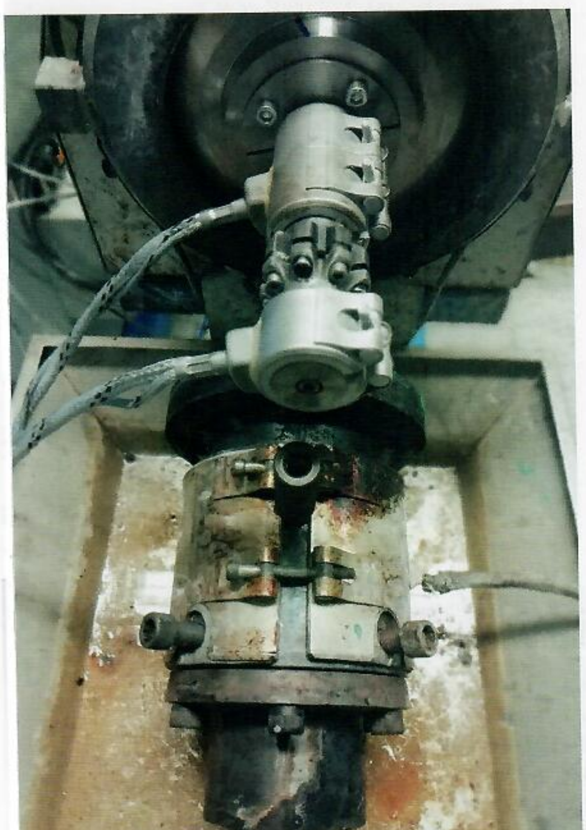
3D-Printed Minimalists

Improved Extrusion Head Designs thanks to Additive Manufacturing

The development of additive manufacturing processes, such as selective laser melting (SLM), has significantly extended the options for manufacturing extrusion heads. Extrusion head designs can now be realized with very slender geometries, which not only have integrated mixer functions, thereby improving the melt homogeneity, but can also be used to attach the mandrel to the head. This allows compact heads to be manufactured with a very high potential for saving operating costs.

The head is the key component for manufacturing pipes, tubes, capillaries or extruding parisons for blow molding, and is substantially responsible for the wall thickness distribution, and thus the quality of the extruded melt tube. The head not only bears the attached mandrel, but also, carries the flange-mounted die, which is movable relative to the head and must be positioned precisely and reproducibly, ideally during operation, in order to optimize the flow channel gap. However, spider-type heads, though advantageous in many fields as they are operating point independent, are unsuitable for many applications, since the spider legs leave unacceptable weld marks on the melt tubes. More complicated, but operating-point dependent designs, such as spiral mandrel systems are necessary in order to extrude melt tubes free of weld marks, with narrow wall-thickness tolerances around the circumference.



Size comparison: the mixer spider-type head mounted on the extruder, which is manufactured by an additive process, without the heating tapes, weighs 480 g; the conventional head lying below it in the catch basin weighs

An Innovative Head Design Avoids Weld Marks and Reduces the Number of Individual Parts

Using selective laser melting (SLM), however, innovative spider-type die heads can be realized in which the mandrel is firmly connected to the head via a large number of mixing elements. Such mixer spider-type dies can be rapidly manufactured directly from CAD data by selective laser melting. Instead of constructing a functioning head from many individual parts as in the past, using additive production, heads are built that only consist of a single part, and therefore avoid critical parting and sealing planes in operation. This thus eliminates assembly work and potentially disruptive production interruptions as a result of leaks at critical seal regions of the head. A movable die, which can be centered relative to the head, however, cannot generally be dispensed with, so that a ready-to-use extrusion head consists of two compact parts.

The advantage of the innovative head designs, in which the mandrel is fixed on the mixer elements, consists in the fact that the mixer elements integrated into the flow channel result in tubes that are free of detectable weld marks. On the other hand, it allows different polymers – despite their strongly divergent flow properties – to be extruded to form melt tubes with identically small wall thickness tolerances around the circumference. Moreover, a mixer spider-type head significantly reduces the residence time of the melt, which leads to significantly shorter purging on material or color exchanges.

Design Challenges

Irrespective of the particular design of the head, the homogeneity of the melt is influenced more or less negatively as it flows through extrusion heads produced by conventional methods. The principal aim of the mixer spider-type head design is to avoid undesirable pressure differences around the circumference of the flow channel, as well as disruptive weld marks in the melt tube. Furthermore, it is also advantageous to retain the homogeneity of the melt as it flows through the head, or ideally even to improve it. This can be achieved by means of delicate mixer elements: when the mandrel of the head is fixed on a large number of small mixer elements as "spider legs", an extremely fine-meshed system of very short weld-seam sections forms in the melt in the flow channel of the head. The end result of that is that no weld marks are identifiable in the melt tube that is extruded from the die.

Since the mixer elements, in the ideal case, are distributed uniformly around the circumference of the round slit channel, the pressure differences, which are unavoidable in the case of conventional spider-type heads, can be avoided with mixer spider-type heads. However, designers are inevitably charting new territory when designing the head: the system of mixer spider legs must be very fine-meshed, but on the other hand have adequate mechanical strength so that the mandrel can be firmly fixed in them. It is likewise a new challenge for the designer to represent a fine-meshed and complex web geometry in one of the conventional CAD systems.

Three different head designs produced by adaptive manufacturing are described below.

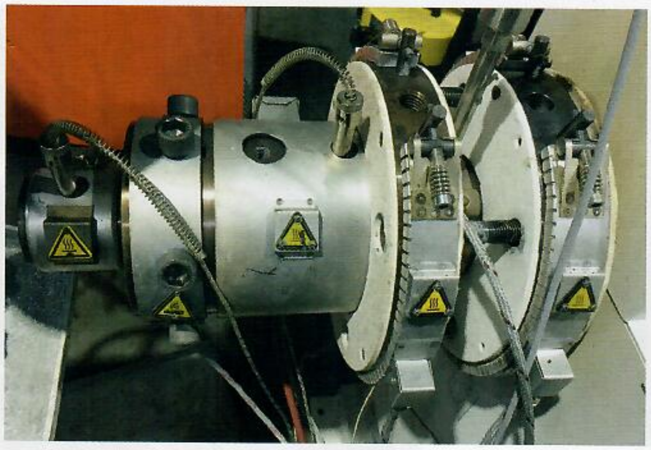


Fig. 1. A spider-type head manufactured conventionally, with radial adjusting screws for centering the die (© H. Gross)

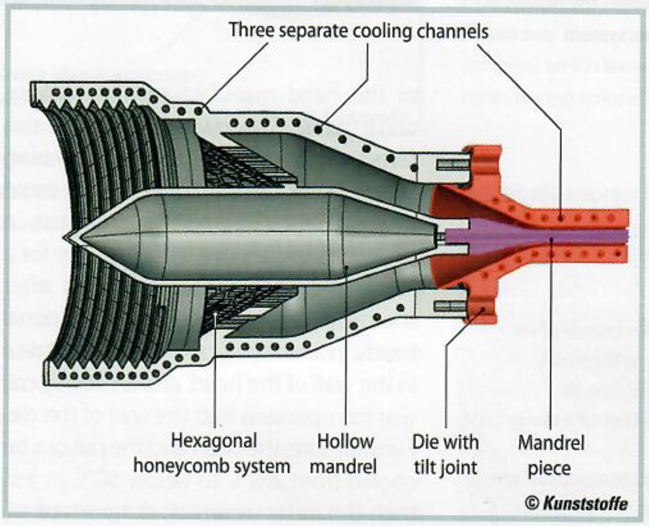


Fig. 2. Section through the innovative pipe head in perspective view (source: H. Gross)

Head for a Small-Diameter Tube

The head for small-diameter tubes produced by additive manufacturing is intended to replace a conventionally manufactured tube head (**Fig. 1**). The SLM head was designed according to the following objectives, which were not adequately satisfied by the existing head:

- Operating-point independent melt distribution in the die head,
- a uniform local melt stream around the circumference of the outlet gap,
- faster and more precise centering of the die,
- further reduction of the wall-thickness tolerances of the tubes,
- faster heating and cooling of the head in order to reduce thermal degradation of the melt that is resident in the head,
- lower energy input for heating the head,
- simple assembly and dismantling of the head,
- fast and easy cleaning of the head, and
- simple and fast dimension change.

To meet these requirements, a completely new head concept was developed, in which the extended manufacturing opportunities offered by selective laser melting were utilized. **Figure 2** shows a section through the tube head, in which the mandrel is fixed to the head with a fine-meshed hexagonal lattice system. This ensures a low flow resistance and an operating-point independent melt distribution. To this end, the air channel was guided from the outside, through the wall of the hexagonal honeycomb system, into the interior of the mandrel. In **Figure 3**, it can be seen that the air channel follows the profile of the wall of the hexagonal lattice system, and, for integration of the air channel, the wall only had to be made slightly thicker than the other walls.

For faster, more precise, and mainly for reproducible positioning of the die relative to the center axis, the die of the head has a patent protected tilt joint (**Fig. 4**). The relative position between the die and the mandrel can be very sensitively adjusted by means of eight axial setting screws (tilt screws), in order to further reduce the thickness tolerances in the tube. Since, due to the special tilt joint, the die can only be centrically mounted, the precentering of the die before start-up of the system, which is required for a conventional centering solution, is also unnecessary. Once a relative position between the die and the mandrel has been adjusted, it can be precisely reproduced at any time, so that the system can always be started already with the desired die position. Any minimal changes of the process parameters, which can occur from one production run to the next, can be responded to faster and, most important, much more precisely than is possible with conventional centering.

The mass of the head was reduced to save energy for heating and during operation. Whereas the old head manufactured by conventional means weighs 52 kg (**Fig. 1**), the weight of the new head is only 1.8 kg (**Fig. 4**), since the mass that was not necessary for operation of the head was reduced. This reduces the heating time by over 30 min., compared »

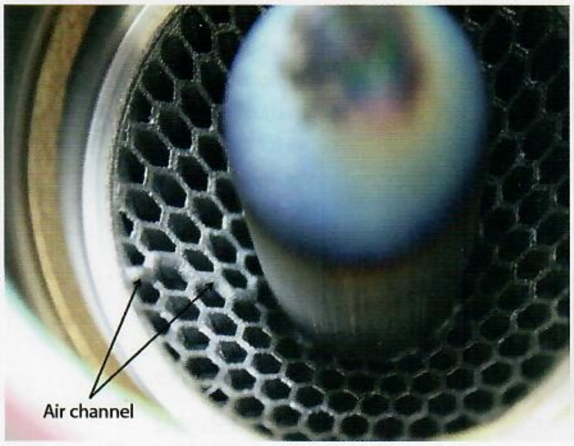


Fig. 3. Air channel that follows the profile of the wall of the honeycomb system (© H. Gross)

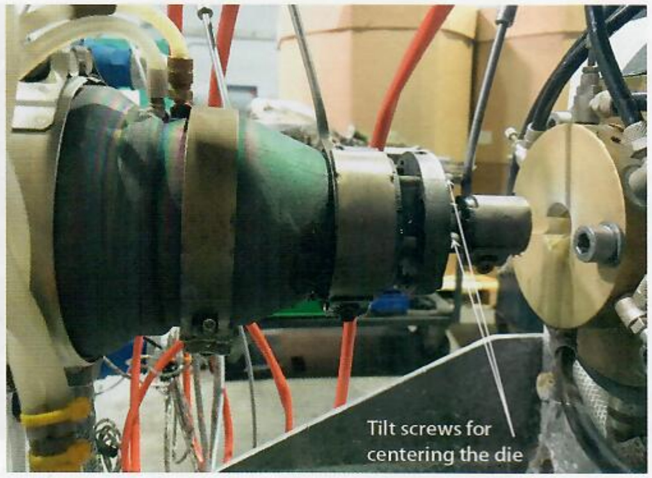


Fig. 4. Tube head with tilt die and axial setting screws during the testing at Siro-Plast GmbH (© H. Gross)

to the head manufactured by conventional means. The low mass naturally also favors a faster cooling of the head during shutdown of the extrusion line. To avoid thermal degradation of the melt that, in all probability, resides in the system for a long time at high temperatures after shutdown of the system in conventional heads, two cooling coils were integrated in the wall of the head, and a cooling coil was incorporated into the wall of the die. Furthermore, the head and the die can be cooled from 285 °C to below 50 °C in less than 10 min by means of compressed air, which is blown through the cooling coils on shutdown of the system. The complete head with the die is simply cleaned in a pyrolysis oven.

Blow Molding Head for a Parison

To speed up color exchanges, particularly in blow molding, a mixer spider-type head was designed, in which the melt is led by means of special mixer spider legs, on which the mandrel is also fixed, from the flow-channel wall into the center of the flow channel and from the center to the wall, at several points along the circumference. **Figure 5 left** shows a 3D view of the head with the mixer spider legs integrated in the flow channel. In **Figure 5 right**, the head is mounted on an extruder for color exchange trials.

The first mixer geometry, which was based on purely empirical considerations, did not lead to the desired result. Simulations (**Fig. 6**) did show that melt is actually conveyed by means of the mixer spider legs from the center of the flow channel to the wall. The good mixing of the head can be seen, for example, by the fact that, in the case of the mixer spider-type head, no melt distribution can be identified due to the supporting air channel, whereas in the case of the channel systems without spider-type head (right channel sections) a clear difference can be seen between the channel region with, and that without, the supporting air channel. However, there were still regions present in the head in which the melt resides longer than desired. Based on the simulation results, the geometry of the mixer spider-leg system is gradually improved until cross-section samples

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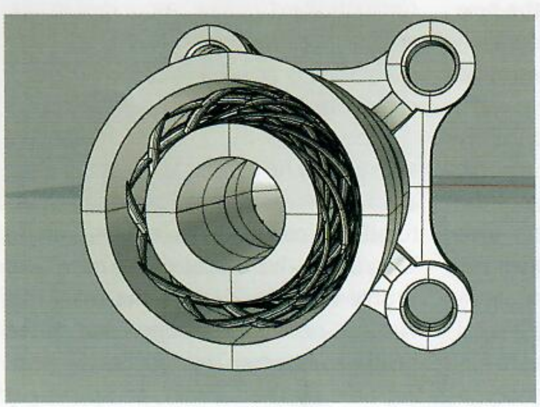

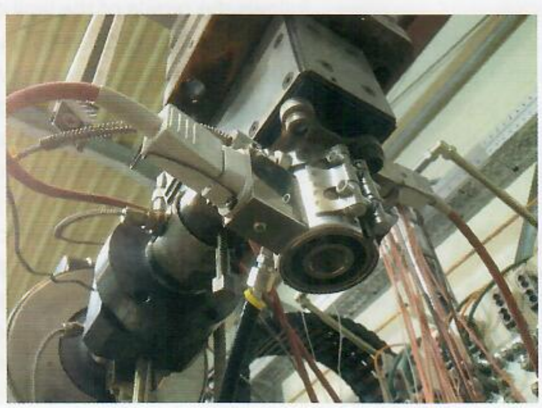

Fig. 5. Mixer-spider-type head with counterrotating spiral mixer spider legs: 3D view (left) and mounted on the trial extruder (right) (© H. Gross)

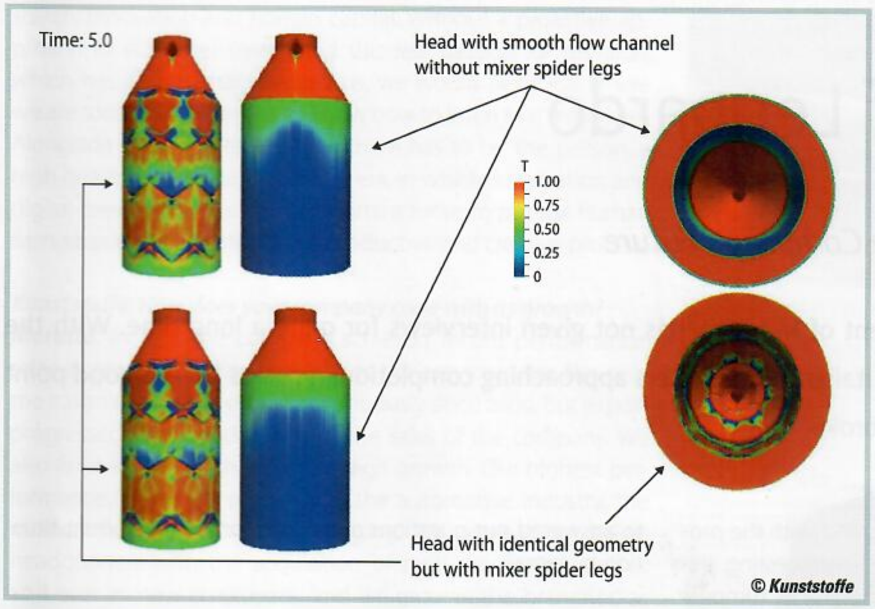

Fig. 6. Simulation results of a color exchange trial after 5 s; figures top left: with supporting air channel; figures bottom left: channel section rotated through 90 degrees without the disruption of the melt stream by the supporting air channel. Blue: original color; red: color purged out of the channel with the blue melt (source: H. Gross)

Fig. 7. Color exchange trials: the improved mixer spider-leg system results in uniform colors over the entire cross-section of the samples, which were removed at different times during color exchange trials (© H. Gross)

taken under actual color exchange trials at different times no longer showed any colored stripes (**Fig. 7**).

Head for Thin Tubes

The experience gained in the two first projects was utilized in the design of a third mixer spider-type head. With this, thin-walled tubes (4.8 mm diameter, 0.1 mm wall thickness) are produced, which must have extremely low thickness tolerances and a very high degree of straightness. Because, due to the low wall thickness of the tubes, extremely small thickness differences lead to bending of the tubes, special care was taken in design of the head to achieve a high pressure constancy around the circumference of the flow channel. This is achieved by integrating eight spiral mixer elements in the flow channel (**Fig. 8**). The supporting air channel system that is necessary at the high take-off speeds (up to 100 m/min) was guided through the center of each mixing spider to ensure high symmetry around the circumference of the flow channel.

For sensitive and reproducible centering of the die, this head also has a die with a patented tilt joint. Because the mass was reduced from 32 kg (conventional head) to 480 g (**Title figure**), with this head, too, the heating times are extremely short and the energy requirement during operation is low.

Summary

Heads manufactured by selective laser melting and with a sensitive and reproducibly adjustable tilting die, tubes can be extruded with lower thickness tolerances, and with lower production costs than for pipes produced with conventionally produced heads. Because of the drastically shorter heating times, and because of the precise centering of the dies, the system capacity is increased and the material consumption necessary for start-up of the system is reduced. The maintenance costs and the risk of production disturbances, for example due to leaks, are reduced in the head that consists of only two compact parts. Although selective laser melting is still relatively expensive, adaptively manufactured heads are more economical than heads manufactured conventionally, due to the drastic reduction in material use (by an order of magnitude) and the elimination of processing steps, some of which are expensive. ■

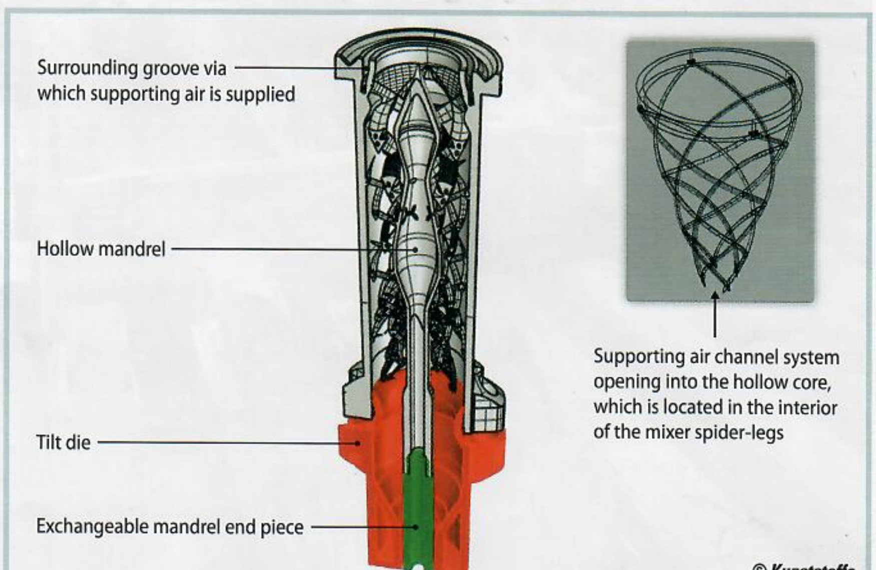

Fig. 8. Cutaway view of a one-piece mixer-spider-type head with an innovative integrated supporting air-channel system and a sensitively adjustable tilt die (source: H. Gross)