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Controlling Heat Balance in Hot Aluminum Extrusion by Additive Manufactured Extrusion Dies with Conformal Cooling Channels

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To prevent overheating of the workpiece material, an extrusion die with integrated local cooling was designed and manufactured by selective laser melting (SLM) as an additive manufacturing technology. The major advantage of SLM is the geometric freedom of the components that can be manufactured, which has been used to produce a die with integrated multidirectional channels for a cooling medium and the integration of thermocouples for temperature measurement. To analyze the influence of the die cooling on the heat balance in hot extrusion, extrusion trials at different ram speeds and billet preheating temperatures with and without applying die cooling were performed. Compressed air was used as coolant. At lower ram speeds, a significant reduction of the profile's exit temperature in hot aluminum extrusion was achieved without causing an excessive rising of the extrusion force. At higher production speeds, surface defects in the shape of stripes of rough surfaces occurred but could be prevented by applying internal die cooling. Due to focusing of the heat exchange on the area of the die bearings, only a little influence of the cooling on the microstructure can be observed.

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NOMENCLATURE

HRC = Rockwell hardness
R_a = surface roughness
T_{die} = die temperature
$T_{extr.}$ = exit temperature extrudate
TC = thermocouple
v_{ex} = profile exit speed

1. Introduction

To improve the productivity in hot metal extrusion, an increase of the extrusion speed is desired. However, the exit temperature of the extrudate increases due to the forming heat and the heat generated by friction and shear in the peripheral zone of the billet.[1] This can result in surface defects, like hot cracks and grain coarsening after extrusion.[2] Especially in extrusion of high strength alloys, a compensation by lowering the billet temperature is not possible due to a limited capacity of the used extrusion press. The application of a local inner die cooling is a promising method to control the heat balance in hot extrusion in order to extend the working range of the process. By concentrating the heat dissipation at the end of the forming zone, the extrusion force will increase only slightly. In addition, it is possible to cool critical die areas directly by sizing and positioning cooling channels or cooling nozzles adequately to prevent hot cracking.[3] However, inserting conformal cooling channels close to the die bearings, which would ensure the shortest heat conduction path from the forming zone to the cooling zone, in the die cap as well as in the mandrel, is difficult or even impossible for profiles and dies with highly complex geometries. The use of additive manufacturing technologies is a promising approach to allow a conformal cooling while the structure of the die is not weakened. This concept is already established in the tooling for polymer injection molding[4,5] but has not yet been applied to dies for hot metal extrusion. This work aims at the integration of conformal cooling channels in extrusion dies by a powder based additive manufacturing method to avoid surface defects as well as grain coarsening with the aim to raise the productivity in aluminum extrusion processes.

2. State of the art

2.1 Die cooling in hot metal extrusion

The heat balance in hot extrusion can be controlled by the initial temperature of the billet, for example by reducing its preheating temperature, which leads to higher press forces, or by applying tapered heating.[6] However, a reduction of the billet temperature leads to a higher material flow stress that requires a higher press load and results in a higher tool stress. Other options for controlling the heat balance or the exit temperature are lowering the ram speed (isothermal extrusion[7]), which results in a lower productivity, or increasing the heat dissipation by cooling the container.[8] However, cooling of the container reacts slowly due to its high mass.[9] Cooling the die is a promising option to dissipate the heat locally and controlled. One reason for the heat dissipation by the die is the short heat conduction path from the forming zone, where the heat is mainly generated, to the cooling source. By concentrating the heat dissipation at the end of the forming zone, the extrusion force will increase only slightly.[3] It is a common procedure to dissipate forming heat by spraying a liquid cooling medium on the exit face of the die via nozzles[10] or by feeding liquid nitrogen through circular channels between the die and backer.[11,12] Less commonly, a heat exchange can also be accomplished by channels within the die or the mandrel itself,[3] but due to the extreme thermal shock stresses, cracks can occur in such dies.[13] Fiorentino et al. developed a two-stage die concept consisting of a cooled die in combination with a cooled pre-chamber with an elongated contact zone to raise the contact time between the workpiece and the cooled die.[14,15] By applying this cooling concept, on the one hand, the risk of inducing hot cracks can be reduced, on the other hand, the flow stress and the ram force increase. Ward et al. detected that by using bridge dies, the inner surface of the profiles fails first.[11] This demonstrates the usefulness of the cooling of the mandrel.

Indicated by the previously presented state of the art, die cooling is a promising tool to control the heat balance in hot extrusion, but it is limited by technological restrictions and has been investigated only partially. Improvements in the die concept, the design of cooling channels and the die manufacturing are required which will allow a precise and well-directed control of the heat balance in hot extrusion.

2.2 Rapid tooling for metal forming applications

In contrary to the conventional subtractive methods like turning, drilling, milling and eroding, where the shape forming results from the removal of material, parts in rapid prototyping processes are generated successively layer by layer, that means additively. The major advantage of additive manufacturing is the geometrical freedom of the components/dies produced[16] as e.g. the manufacturing of shapes with undercut and the manufacturing of conformal cooling channels.[17] The technological basic principle of metal additive manufacturing is mostly identical. The information of the geometry of the component that shall be manufactured is provided by a volume model (3D CAD model). This CAD file of the component is the input information for the slice process, in which a special software slices the component into several layers with defined layer thickness. In the powder-based methods of rapid tooling, the basic material, provided as a powder or granulate, is deposited and locally melted and solidified layer by layer by using an energy source. In the field of metal forming technology, the use of laser sintering processes is limited to small dies. Levy et al. investigated dies for a scaled deep drawing process.[18] Die, punch and blank holder were manufactured additively. Chea et al. used a punch and a die, which was generated by selective laser sintering for a hollow stamping process.[19] Investigations on selective laser sintered dies with integrated cooling channels for the extrusion of starch-based polymers were carried out by ÓDonnchadha und Tansey.[20] In the field of bulk metal forming, Müller and Neugebauer proved the applicability of laser melted dies for die forging.[21] The authors of the present work have introduced dies manufactured by laser melting for hot aluminum extrusion applications.[22]

3. Die design and manufacturing

While the cooling channels have been inserted up to now only in the die cap of the extrusion die,[23] in the present work conformal cooling channels are introduced in the mandrel (with external dimensions Ø 84 × 42 mm) for the manufacturing of a squared hollow aluminum profile (18 × 18 × 1 mm) and experimentally tested. For manufacturing the mandrel of the porthole extrusion die, powder laser melting was applied. The design is presented in Figure 1.

Due to the design of the extrusion press and the die holder, a supply of the cooling medium and the measuring setup are only possible from the exit end face of the die. To supply the coolant, holes for the inlet and the outlet of the cooling medium were inserted into the die, to which two small brass tubes with flanges were attached. For feeding the coolant medium into the mandrel and close to the die bearings, a multidirectional course of the cooling channel through the mandrel part of the die was designed. Two opposite bridges of the four bridges carrying the mandrel include the cooling channel (Fig. 1(a)) while in the other two, a channel for thermocouples is positioned (Fig. 1(b)).

According to the recommendations of Hofmann (2007) for the design and dimensioning of cooling channels and the limitations of the

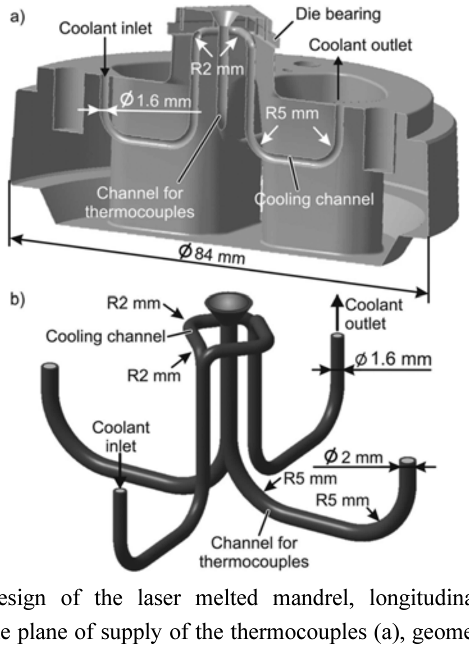


Fig. 1 Design of the laser melted mandrel, longitudinal section through the plane of supply of the thermocouples (a), geometry of the channels (b)

powder based manufacturing technology, a round cross-section and smooth rounded turns were considered.[24] The cooling channel has a diameter of 1.6 mm, two radii with 5 mm in the lower part and a radius of 2 mm in the upper part where the channel is splitted into two parts with an included angle of 90° on the level of the die bearing (Fig. 1). The inner cooling channel follows in a squared shape the geometry of the die bearings and merges together in the opposite direction, where the coolant is dissipated. To achieve a short heat conduction path, the distance between the die bearing and the cooling channel is less than 5 mm. To measure the effect of cooling, two channels with a diameter of 2 mm for introducing thermocouples are inserted in the bridges that merge into one single central channel through the squared mandrel. On top of the mandrel, up to 8 thermocouples with a diameter of 0.5 mm can be guided into 8 holes (Ø 0.6 × 4 mm) near to the die bearings to measure the temperature on the level of and along the die bearings.

The mandrel was manufactured in a powder bed of CL50WS (similar to hot working steel 1.2709) in a nitrogen atmosphere by using a laser cusing machine m^3 linear (by Conept Laser GmbH). The fabrication of the die, with a volume of 116 cm³ and a deposition rate of 3,8 cm^3/h, took around 30 h. 1580 layers with a thickness of each of 30 µm were printed. To reduce thermally induced residual stresses in the component, a stochastic exposure strategy of the laser was applied, leading to a segmented structure at the surface (Fig. 2).

In order to avoid any boundary effects and to achieve the required surface quality of the die bearings, an allowance of 0.3 to 0.5 mm was added to the geometry to be printed. After 30 minutes of wire eroding (cutting the part from the mounting plate) the final geometry was achieved by mechanical finishing, which took 1 hour of milling (the whole geometry, the holes, the threads etc.). The manufacturing of the mandrel was finished by a heat treatment (ageing 500 °C, 8 h) to a final hardness of around 55 HRC. An accessory die cap made of different steel sheet layers with the corresponding adaption of the tube for the coolant inlet and outlet was designed and produced and the tool set was assembled (Fig. 3).

The tool was tested on a 2.5 MN direct extrusion press (Collin PLA250t) with a container diameter of 66 mm using EN AW-6060 billets. The billet temperature was set to 540°C and the die and container temperature to 450°C. In extrusion of four billets with a ram speed of 1 mm/s, an increasing thinning of the wall thickness of the profile was observed, which resulted in a collapse of the extrudate (Fig. 4(a)).

The reason for this collapse was a deflection of the layered die cap due to insufficient support of the lamellas. Additionally, the deflection of the die cap resulted in an insufficient support of the laser melted mandrel. After etching the tool in caustic soda, cracks initiating at the transient area between the bridge and the mandrel became visible (Fig. 4(b), 4(c)).

The increase of the protruding length of the bridges, due to the deflection of the layerd die cap, raises the stress in the corner between the bridge and the mandrel on a critical level for the tool steel (Fig. 5).

Besides the damage of the die, a second problem of the configuration exists in the attachment of the thermocouples. The rough surface, caused by the printing process, in combination with the multiple redirection of the channel in the bridge complicates the feeding of the thermocouples. Beyond that, the deflection of the

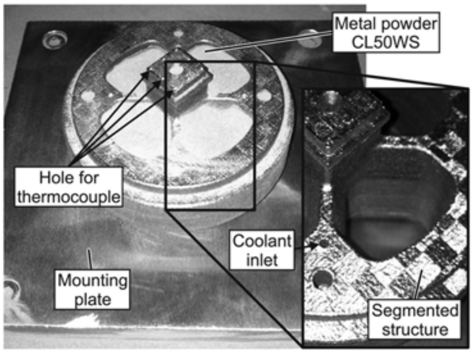


Fig. 2 Mandrel part of the extrusion die manufactured by selective laser melting

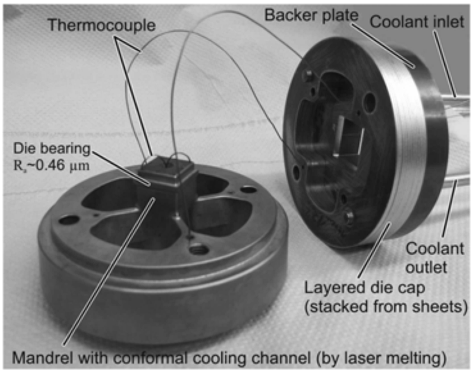


Fig. 3 Tool setup with two thermocouples and coolant supply

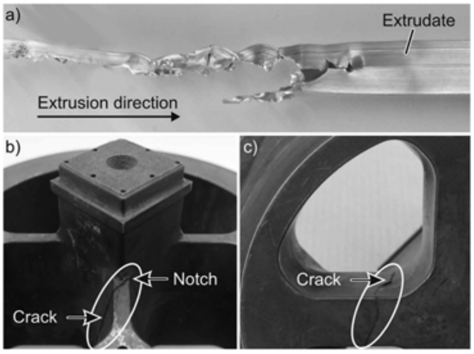


Fig. 4 Thinned profile (a), top (b) and back (c) view of the cracked laser melted mandrel of the extrusion die

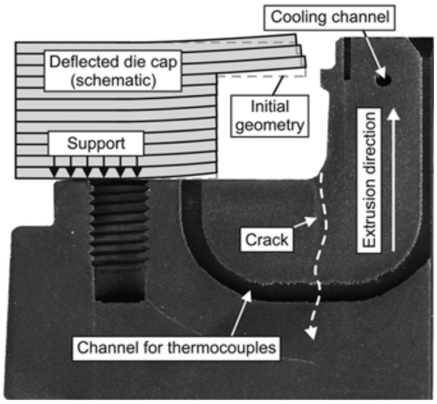


Fig. 5 Insufficient support of the mandrel due to the deflected lamella die cap (quarter section, longitudinal cut)

extrudate during the beginning of the extrusion process implies the risk to generate a contact between the extrudate and the thermocouples at the front tip of the mandrel, which might cause a pull out of them. To avoid the reported problems, a conventionally manufactured die cap and a slightly redesigned mandrel were manufactured and tested experimentally (Fig. 6).

The following modifications were performed (Fig. 6).

- Enlargement of the diameter of the channels for the thermocouples.
- Simplification of the geometry of the channels in the bridges to a constant and enlarged radius.
- Attachment of a deflector in the shape of small noses at the front tip of the mandrel to prevent a contact between the extrudate and the thermocouples.

To test the new setup, initially 9 billets of the softer alloy EN AW-6060 were extruded successfully.

4. Extrusion trials with die cooling

By applying different cooling strategies, eight extrusion trials were carried out (Table 1) at 2 mm/s up to 8 mm/s ram speed at an extrusion ratio of 50 : 1, resulting in exit speeds between 6 m/min and 24 m/min. EN AW-6082 was used as billet material and compressed air (8 bar) as coolant. The exit temperature of the extrudate was measured approximately 300 mm behind the die exit by a multiwavelength pyrometer (Williamson 100 pro 120-20). The billet temperature was set to 540°C and the die and container temperature to 450°C. On each extrusion speed level (Table 1), one billet was extruded without and one with applying cooling of the mandrel. To prevent excessive cooling of the die, the cooling was initiated after the stop mark at the profile of the previous billet has passed the measuring position of the pyrometer, and stopped a few seconds before the end of the billet was reached. To ensure the comparability between each separate trial, the following trial was carried out when the whole system has reached the same initial temperature level.

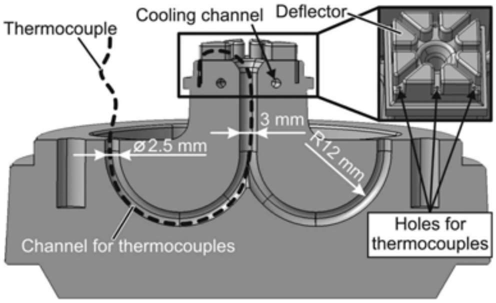


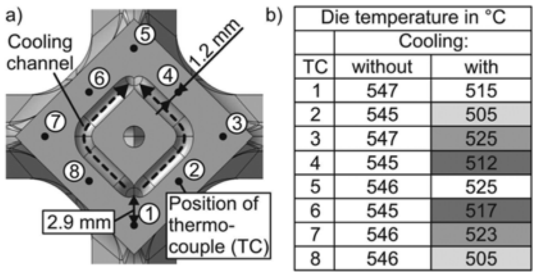
Fig. 6 Redesigned laser melted mandrel (schematic)

Table 1 Overview extrusion trials EN AW-6082, billet preheating temperature 540°C

Billet	1	2	3	4	5	6	7	8
Exit speed	6 m/min		12 m/min		18 m/min		24 m/min	
Cooling	-	x	-	x	-	x	-	x

For each trial, the tool temperature near the die bearings of the mandrel, the exit temperature of the profile as well as the extrusion force were recorded. While, without cooling, the temperature at the eight measuring points around the die bearing is quite the same, with cooling, a gradient between the thermocouples close to the coolant inlet (TC 1) and outlet (TC 5) of 10°C appears ($v_{ex} = 6$ m/min) (Fig. 7).

The temperatures in both branches are similar at the corresponding positions, which indicate that the fluent is equally divided between both channels. Due to different distances between the cooling channels and the measuring position (2.9 mm in the corners and 1.2 mm at the faces), the measured temperatures in the corners (TC 1, 3, 5, 7) are



Die temperature in °C		
	Cooling:	
TC	without	with
1	547	515
2	545	505
3	547	525
4	545	512
5	546	525
6	545	517
7	546	523
8	546	505

Fig. 7 Arrangement of the thermocouples in the mandrel (a), die temperature at the end of the extrusion process at $v_{ex} = 6$ m/min (b)

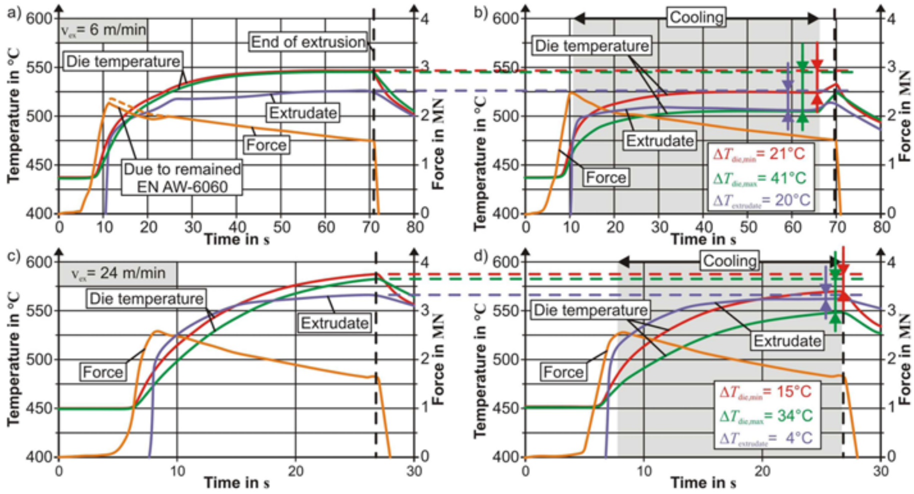


Fig. 8 Plots of the die temperature, the extrudates' exit temperature and the extrusion force: a) exit speed 6 m/min, without cooling, b) exit speed 6 m/min, with applying cooling, c) exit speed 24 m/min, without cooling, d) exit speed 24 m/min, with applying cooling

lower than at the neighboring positions at the faces of the mandrel (TC 2, 4, 6, 8). The different lengths of the heat conduction paths, as a result of the design of the cooling channels, might cause different cooling effects around the circumference of the profile.

The recorded parameters are presented in figure 8, exemplarily for the minimum and the maximum extrusion speed. To improve the transparency of the illustration, only the curves of the maximum (green curve) and the minimum (red curve) die temperature are shown. At an exit speed of 6 m/min and without cooling, the temperature of the die as well as of the profile increases until a stationary level is reached approximately after extrusion of the first half of the billet (Fig. 8(a)). With cooling (Fig. 8(b)), a similar tendency can be observed, while the temperature increase and the maximum temperature level are lower. A maximum temperature gradient in the die of 20°C can be detected, while by cooling a reduction of the die temperature of 21°C to 41°C can be achieved. This results in a reduction of the profiles' temperature of 20°C (measured at the profiles' surface opposite to TC 8). Comparing the extrusion forces, only a difference at the beginning of the process is visible, because in extrusion of billet 1 the prechamber of the die is initially filled with the softer alloy EN AW-6060. After extruding this, the extrusion force between applying and not applying cooling is the same. This means that by concentrating the heat dissipation at the end of the forming zone, the extrusion force increases only slightly.

At an exit speed of 24 m/min, the temperatures increase continuously without attaining a stationary level (Fig. 8(c)). Even with applying cooling, the generated heat is higher than the dissipated one (Fig. 8(d)). By cooling, the die temperature can be reduced by a comparable amount like at the lowest exit speed ($\Delta T_{\mathrm{die,min}} = 15^{\circ}\mathrm{C}$, $\Delta T_{\mathrm{die,max}} = 34^{\circ}\mathrm{C}$) while the extrudates' temperature is reduced only slightly ($\Delta T_{\mathrm{extr.}} = 4^{\circ}\mathrm{C}$).

The temperature reduction within the series of tests is summarized in table 2. In general, with increasing production speed, the temperature reduction by cooling decreases.

The results indicate that even with a further decrease of the die temperature, due to the short heat exchange zone and exposure time, concentrated on the die bearings, a remarkable reduction of the product temperature is limited. The influence of accumulated heat will be investigated in the future in detail. Where required, a higher flow rate of the cooling medium or even a substitution of the medium (e.g. by water or nitrogen) can be applied. A combination with an internal cooling of the die cap might be helpful.

Table 2 Temperature reduction at the end of the extrusion process

v_{ex}	Billet	Cooling:	$T_{\mathrm{die,min}}$	$T_{\mathrm{die,max}}$	$T_{\mathrm{extr.}}$
6 m/min	1	without	21°C	41°C	20°C
	2	with			
12 m/min	3	without	19°C	39°C	10°C
	4	with			
18 m/min	5	without	17°C	35°C	4°C
	6	with			
24 m/min	7	without	15°C	34°C	4°C
	8	with			

Table 3 Overview extrusion trials EN AW-6082, billet preheating temperature 565°C

v_{ex}	Billet	Cooling	$T_{die,max}$	$\Delta T_{\mathrm{die,min}}$	$\Delta T_{\mathrm{die,max}}$	$\Delta T_{\mathrm{extr.}}$
12 m/min	9	without	570°C	20°C	38°C	6°C
	10	with	550°C			

In the previously described experiments, the maximum profile temperature did not reach the solidus temperature of the processed alloy EN AW-6082 of 575°C.[25] No surface defects like hot cracks occurred. To allow a proof of the die cooling concept that overheating of the workpiece material can be reduced or even be avoided, a reference trial, which results in temperature related surface defects, is required. As the generation of additional heat by increasing the extrusion speed is limited by the used extrusion press, trials with a higher billet preheating temperature of 565°C were performed (Table 3) and the surfaces of the profiles were examined (Fig. 9).

Inside both profiles, no surface defects occurred. Without cooling, the die temperature reaches 570°C, which is close to the level of the solidus temperature of the alloy. Although the measured value of the profile temperature reaches a maximum of 550°C only, defects in the shape of stripes of rough surface occur (Fig. 9(b)). This indicates an overheating of the material in the die.

With a cooling of the mandrel, the maximum die temperature is reduced by 20°C to 550°C. The previously observed defects are remarkably reduced (Fig. 9(c)).

To investigate the origin of the surface defects and to analyze the the influence of the applied inner die cooling on the microstructure of the extrudate, metallographic preparations of the two profiles listed in Table 3 were performed. Specimens of the upper side wall of the profiles have been cut out and prepared in the cross section transverse to the extrusion direction. The samples were grinded and polished

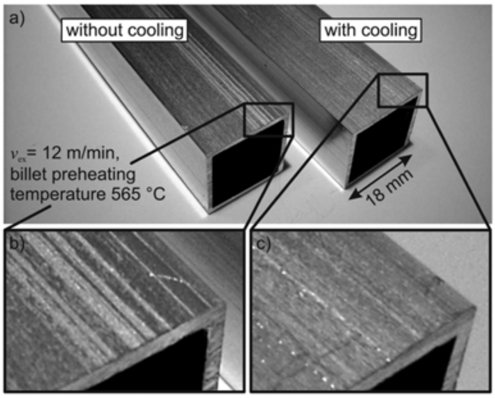


Fig. 9 Extruded specimen (a) of EN AW-6082, with (b) and without (c) surface defects

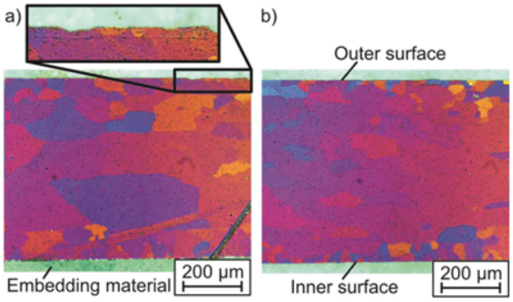


Fig. 10 Micrograph of the extruded specimens of EN AW-6082, without (a) and with (b) applying die cooling

mechanically and the grain structure was prepared for light optical microscopy by polarized light by electrolytical etching with Barker reagent (0.85 vol.% HBF_4 + 99.15 vol.% H_20, 25 V, 60 s) (Fig. 10).

In the not cooled condition, grooves on the outer surface of the profile can be observed (Fig. 10(a)), probably resulting from pick-up on the die bearings. Both microstructures are characterized by a predominantly static recrystallized coarse grain structure, while the grains in the cooled profile are, in general, smaller, but only slightly, which corresponds likewise to the small reduction of the profile's exit temperature of 6°C. To achieve a more remarkable effect of the inner die cooling on the microstructure, an intensification of the cooling is necessary. One of the next steps in this project will be to use water or even nitrogen to achieve a stronger cooling effect.

5. Conclusion

The manufacturing of components of an extrusion die by selective laser melting provides the possibility to integrate multidirectional channels for supplying a cooling medium and to integrate thermocouples for temperature measurement into hot extrusion tools. By applying die cooling by internal conformal cooling channels close to the die bearings, using compressed air as a coolant, a reduction of the temperature of the tool as well as of the extrudate is possible. In extrusion trials of a thin walled squared hollow profile (R = 50 : 1) of EN AW-6082 at an extrudate's exit speed of 6 m/min, a significant reduction of the die (41°C) and profile exit temperature (20°C) was achieved without causing an increase of the extrusion force. For higher extrusion speeds (24 m/min), by applying cooling, the exit temperature of the extrudate can only be slightly reduced (4°C), while the reduction of the die temperature is on the same level (34°C).

Regarding the surface quality, it can be detected that, at higher production speeds and billet preheating temperatures, surface defects in the shape of stripes of rough surface occurred, which could be prevented by applying internal die cooling. Due to focusing the heat exchange on the area of the die bearings, only a little influence of the cooling on the microstructure can be observed. The capability of the proposed die cooling strategy is seen in the avoidance of temperature peaks of the processed material at higher production rates, which might lead to thermally induced surface defects. However, this is currently restricted to lower ram speeds. The full advantage of the die cooling is seen especially in the extrusion of high strength heat treatable alloys, with a small temperature gap between solvus and solidus temperature, where even a little reduction of the tool and extrudate temperatures will lead to a big rise in the productivity. This is the main goal of the work and will be tested in future. Additionally, the efficiency of the cooling has to be improved by a redesign of the cooling channels and/or applying different cooling media like water or even liquid nitrogen. Also a combination with an internal cooling of the die cap might be helpful.

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