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Integrated bottom up and top down approach to optimization of the extrusion process

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ABSTRACT

Boal BV and the University of Twente participate in research projects focused on improvement of die design methods for aluminum extrusion dies. Within this research empirical knowledge is combined with insights gained from numerical process simulations. Design rules for improvements to the geometry and functionality of flat and porthole dies have been defined. For porthole dies this has led to enhanced die stability and significant reduction of scrap. For both flat and porthole dies an increase in production speed and a reduction of wear has been obtained. This paper will describe the scope of this research and present results achieved in industrial practice.

1. Introduction

During the last decades the aluminum extrusion industry had to deal with increasingly demanding customers, heavy competition and uncompromising environmental legislation [1]. Customers demand profile geometries that incorporate progressively more engineering functions and superior mechanical properties. These demands have to be achieved at minimal costs, what among others implies minimal profile wall thickness. On the other hand the annual number of new profiles to extrude increases, whilst the number of repeat order per profile decreases. As a result the reduction of scrap and the increase of the quality of the die become increasingly more important.

From a competitive viewpoint extruders should be able to produce superior products almost instantaneously and at the lowest costs. Scrap production as well as production lead time have to be reduced and production rates have to be enhanced. This results in the need for one-time-right dies, increased die life and optimized process settings [2].

To reduce the environmental impact of the extrusion process worldwide many aspects of the process are investigated. This includes for example the impact of the Mg-content of the aluminum, the type of process (direct or indirect extrusion) and the type of billet-preheating process on the direct energy consumption and CO_2 emission during extrusion of an aluminum bar [3]. When looking at the process as a whole the reduction of scrap has been identified as a key opportunity to reduce environmental impact.

The above depicted views on aluminum extrusion clarify the background against which the research described in this paper was defined. In 1991 Boal BV, a then medium sized Dutch-based aluminum extrusion company decided to improve their ability to deal with above described challenges by deepening their knowledge of the die design and maintenance process. Based on this knowledge the design of better dies and with that increasing competitiveness was looked for. In cooperation with the University of Twente several aspects of the die design and maintenance process have been investigated. Based on this research a view on the design of extrusion dies has emerged that diverges from mainstream die design. This paper will present the outline of the research and also focus on the more distinctive results.

2. Die design and maintenance

2.1. Die correction and maintenance

On extrusion dies the bearing is the area that shapes the aluminum to the desired section (Fig. 1). The length of the bearing is used to guarantee a uniform exit velocity of the aluminum; non-uniformity will lead to deflection of the extruded section or surface defects on the product. One of the main tasks of the die correction and maintenance department is to modify the bearing locally to balance the flow of the aluminum; both the length and the angle of the bearing are changed to balance the flow.

Three cases have been identified that are addressed by die correction and maintenance:

- State of the art die design knowledge does not guarantee a uniform exit velocity of extrusion dies. Based on the results of test-runs the bearing area is modified.
- Die wear induces the need for corrective measures to the bearing area to restore optimal flow conditions.
- Die design and correction are two very distinctive procedures; communication on corrective measures between these procedures is not a straight forward process. As a result repeat orders of proven die concepts often need corrective maintenance also.

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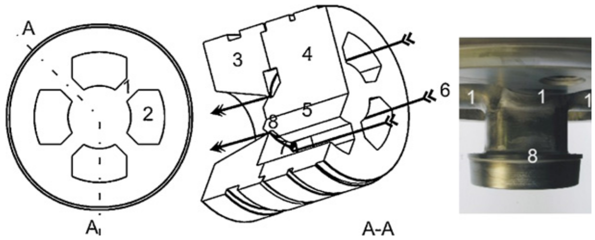

Fig. 1. Left: front view of a porthole die with legs (1) and feeding chambers (2). Middle: cross-sectional view where the aluminum (6) flows around the core (5) via the welding chamber (7) to the bearing area (8). Right: detailed view of the bearing area (8) and the core (5) on the mandrel (4) of a porthole die. (3) Denotes the die plate.

Die maintenance itself is seen rather as an art then a science; at the start of the research it had not yet been captured in design rules. For that reason the initial focus of research was directed on defining a body of knowledge on die maintenance. Structured improvement of maintenance could significantly reduce the number of test runs. A research team of die and section designers, die maintenance staff, design support researchers and aluminum flow analysts was set up. The goals of the research were twofold. Firstly, the development of the body of knowledge, both by bottom up knowledge capturing as by top down simulation-based development of knowledge on the processes that define the functionality of the bearing area. Secondly, the knowledge should be used to define and implement a design support tool that would structure die maintenance and would support the exchange of information with die designers. Without focusing on the execution of this research two important results were established. It was concluded that the diversity of successful maintenance formats found between or even within companies showed that a bottom up approach for defining the body of knowledge was not viable. Furthermore, in-depth extrusion simulations indicated that, although the bearing area is used to counteract flow variations, it was not the main cause of these variations. It was concluded that improving the extrusion process and reducing the scrap percentage was best done by upstream improvement of the die design process.

2.2. Extrusion die design

In the next phase of the search for improvement of extrusion productivity several aspects of the design of flat and porthole dies were investigated [4–6]. Research focused on knowledge gathering, knowledge development and die design support.

2.2.1. The bearing and sink in

As was already stated in Section 2.1 the bearing area is used to assure the uniformity of the exit velocity of the aluminum flow. For flat dies flow non-uniformity is caused by flow effects induced by the container and local section width variations [7]. For porthole dies the flow around the legs is another cause for flow non-uniformity. By locally changing the length of the bearing the flow-resistance can be influenced. If extreme die deflection is expected the bearing also can be designed using a bearing angle. In that case the die deflection during extrusion will ensure the bearing becomes parallel again.

Although design rules for parallel bearings are known, the effects of die deflection on the efficiency of the bearing are not well documented. A series of simulations were executed to investigate this effect (Fig. 2). It was found that for small bearing lengths the induced resistance of the bearing is almost constant. Furthermore it became clear that relatively small changes in the bearing angle had large effects on the induced flow resistance, making the bearing very sensitive to die deflection and with that an unstable means to control the exit velocity. These effects also have been observed in a similar process like backward can extrusion [9].

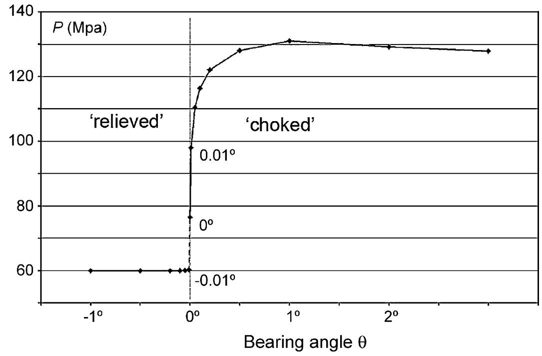

Fig. 2. The effect of the bearing angle on the induced flow resistance of a 5 mm bearing (from Refs. [8,10]).

From literature [7,11] the sink-in (an additional chamber-like feature on the front face of the die; Fig. 3) is also known as a means of controlling the exit velocity. Based on simulations [5] a sink in with a variable offset in combination with a short bearing of constant length was established as a more stable means of controlling the flow (see Section 3). Design rules for the shape of the combined bearing and sink in geometry have been defined.

2.2.2. Feeding chambers and legs on porthole dies

When hollow sections are extruded porthole dies (Fig. 1) are the most common type of die used. On porthole dies the bearing surfaces that define the inner contours are located on the core; the bearing for the outer contour is located on the die plate. Legs secure the position of the core (bearing) while the chambers between the legs are used to feed the aluminum from the front of the die to the bearing area. Legs and feeding chambers are closely related, widening the legs would decrease the feed and the possible production rate. Increasing the size of the chambers would weaken the legs and decrease the stability of the die. For that reason research was started on the optimal geometry of feeding/leg area.

FE-simulations established that even within the die, and also along the legs, dead metal zones are present. The surface along which the aluminum moves is not identical to the surfaces of the die; they are separated by a layer of non-moving aluminum. Based on this observation the hypothesis was postulated that, if the aluminum forms its own flow surfaces within the die, the shape of the legs could be used to optimize die deflection and die life.

Additional simulations were executed on three different leg shapes (Fig. 4). If a die with a uniform leg cross-section (Fig. 4(2)) is loaded with extrusion pressure the leg will deform and the highest values of the stresses will be found at the bottom of the legs. In Fig. 4(1) the classical leg shape is presented. Compared to the other leg shapes the classical leg shape has the least amount of material at the location where the highest stresses are to be expected. From a mechanical viewpoint the best results are to be expected from the third, torpedo-shaped, leg.

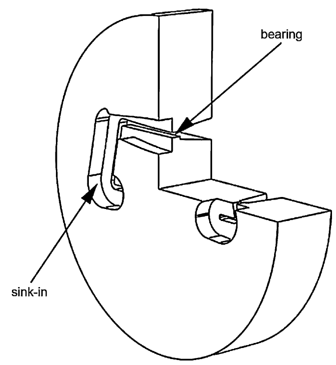

Fig. 3. Bearing and variable sink-in layout on a flat die (from Ref. [12]).

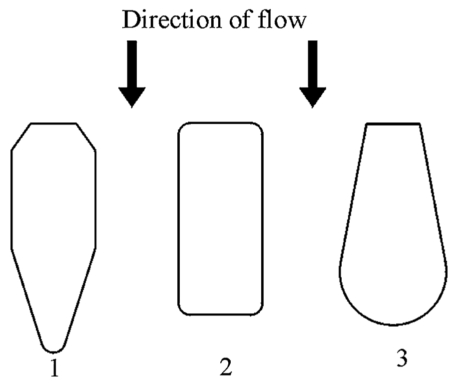

Fig. 4. Leg shapes investigated: (1) classical (2) uniform (3) torpedo shaped.

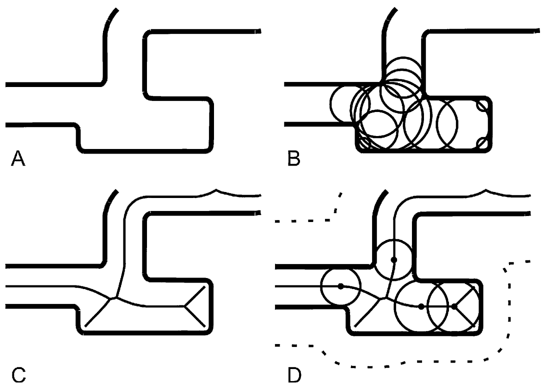

Fig. 5. Transforming the boundary representation of a section into a medial axis or skeleton representation.

All three leg shapes have been simulated [13] and results have been compared, both on flow and on mechanical behavior. As can be expected the dies with torpedo shaped legs required higher welding chambers, but the simulations showed no indications against using torpedo shaped legs. Data obtained during commercial production on the effects of the leg-type can be found in Section 3.

2.3. Die design support

Within this research computer support tools are seen as one of the building blocks when substantial advances towards a more efficient extrusion process are sought after. Based on the knowledge developed on the bearing and the sink in area these features have to be designed simultaneously. A CAD-module ([4,8]) has been developed that supports the designer in defining the geometry of this region of the die. In Fig. 5A a boundary representation of part of a profile is given. The boundary representation does not describe the width of the profile but the location of its borders. When all inscribing circles of the profile (Fig. 5B) are connected, the skeleton of the profile emerges (Fig. 5C). On this skeleton the local thickness (the radius of the inscribing circle) is defined. This is then used to generate the sink in geometry (Fig. 5D).

To increase the repeatability of both the die design as the die manufacturing process an additional general die design support tool is being developed that guides the designer through the design process. Both empirical and design knowledge developed within this research will be incorporated and will be used to standardize the development of 3D models of extrusion dies. Expected benefits include progress in the direction of companywide best design practice, the possibility to compare the results of different design scenarios, increase of design rate, avoidance of knowledge drain, increased repeatability, etc.

Finite element simulations discussed until now were used to develop generic die design knowledge. For individual dies that do not perform satisfactory finite element simulations can be used to look for possible causes. If this approach is used for the in process optimization of dies the calculation as well as the pre- and post-processing thereof has to be executed efficiently. Within this project the finite element formulation DiekA is used and optimized for simulations on the extrusion process [14]. Modules have been developed that support the time-efficient simulations of die deflection, die load, die filling, particle tracking, etc. Furthermore modules are being developed to directly associate the finite element simulations to the generic die design support tool.

3. Results

The influence of the developed design rules on extrusion results can best be illustrated with an example. For the extrusion of round AA6063 tube from 1999 until 2006 8 repeat orders of the die have been manufactured (Fig. 6 and Table 1). Based on the low maximal die height this die type was denoted as critical. Repeats 1–5 have been designed with classical leg shapes, 6–8 are designed with variants of the torpedo shaped leg. Table 1 presents extrusion results of these 8 repeat orders; columns CLS and TS contain average values for rows 1–5 and 6–8. As can be seen in this table after transition to the torpedo shaped leg the average gross production per die increased with 550% whilst the total scrap produced dropped with 15%. The gross production rate increased

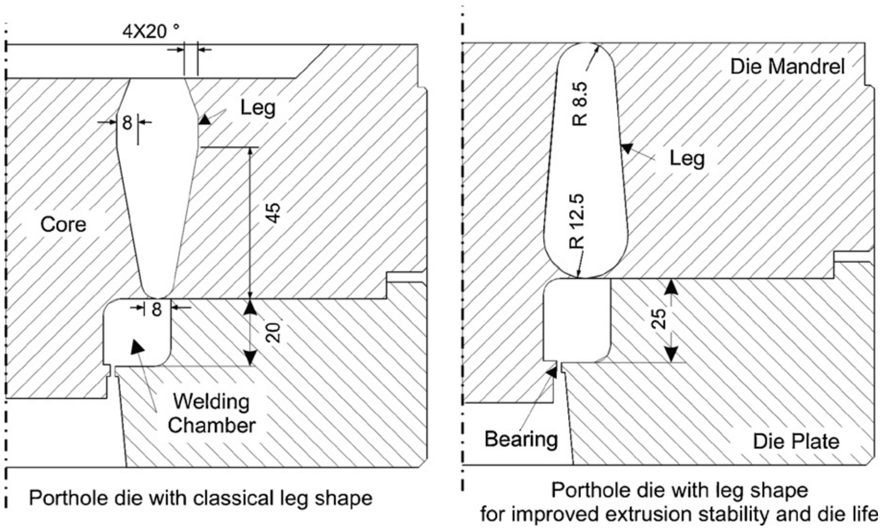

Fig. 6. Leg shape variations on the design of a porthole die for the extrusion of round tube. The cross-sections of the legs face towards the reader for illustrative purposes (see Table 1).

Table 1
Extrusion results for repeat order for porthole dies

Repeat die number	1	2	3	4	5	6	7	8	CLS	TS
Production gross (kg)	3811	3596	1155	4625	3323	17,719	19,296	17,771	3302	18,262
Production net (kg)	2535	2753	598	2856	1551	13,409	14,666	13,671	2059	13,915
Scrap percentage (%)	33	23	48	38	53	24	24	23	39	24
Production rate gross (kg/h)	949	1233	1308	1084	968	1,193	1,249	1,580	1108	1,340
Production rate net (kg/h)	631	944	677	669	452	903	949	1,215	675	1,022

Repeats 1–5 are constructed with a classical leg shape, 6–8 are constructed with torpedo shaped legs. Columns CLS and TS contain average values for rows 1–5 and 6–8.

with 21% but due to the lower scrap rate the net production rate increased with 51%.

Based on observation during production these excellent results are contributed to the increased stability of the die over it life span. The stability also has been improved by better balancing the pressures that are induced by the feeding chambers. For both porthole and flat dies the decreased length of the newly designed bearing also allows for higher production rates. Finally a reduction of wear has been observed both on porthole as on flat dies. This has been contributed to the reduction of the heat generated in the bearing area. In general 70% of the dies designed based on the new set of design rules showed significant improved extrusion results.

On a company level these new insights into the design process have had an impact also. At the start of the research dies were designed and manufactured externally. Today's company goals among others include that all dies will be designed by the in-house die design department. Expected benefits of this new position include among others lower die costs, independence of external die manufacturers and the ability to use and maintain the developed die design strategy. As a concluding remark it can be said that in the last years a 10% dematerialization has been realized within the company.

4. Conclusions

Research into empirically based every day extrusion practice combined with intensive extrusion simulations has lead to a new and distinctive set of design rules for flat and porthole dies. Dies designed based on these rules have been used in an industrial setting for some years now. For the extrusion of a round tube the significant improvement of extrusion results have been discussed in detail. Among others a 550% increase in die life was obtained for this die. Statistical analysis of long-term extrusion performance showed in 70% of the cases an improvement of extrusion performance.

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