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Original research article

Benefits of laser beam based additive manufacturing in die production

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ABSTRACT

The aim of this study was to benefit from the novel design and production freedom of laser manufacturing in order to alter the existing design concept of extrusion dies and to resolve the limits in die production.

A two-stage experimental study was carried out to reveal advantages of laser manufacturing on the performance and capabilities of aluminum extrusion dies. In the first stage, geometric forms of hot work tool steel dies used in aluminum extrusion were optimized for Direct Metal Laser Sintering (DMLS) by means of flow dynamics as well as surface quality and mechanical properties of the final part. Simple geometry profiles were extruded to investigate the product quality. In the second stage, dies were tested until failure to determine the performance and lifetime.

Dies were produced using EOS M290 and were not subjected to any conventional finishing and/or surface hardening post processes. Field tests were carried out in an industrial aluminum extrusion facility and high-quality profiles were extruded. Dies and extruded profiles were characterized. Results revealed that DMLS can be a favorable method to produce dies having complex inner sections with high accuracy. Production of high quality extruded profiles was possible using additive manufactured dies directly from production.

1. Introduction

In recent years, owing to the improvements in machinery and materials, additive manufacturing (AM) has begun to be used in the production of extrusion dies. Most of the fundamental studies on this subject are based on hybrid production – production of the important geometrical structure (die matrix) by Selective Laser Melting (SLM) on an existing hot work steel die. AM production and field tests of an entire extrusion die manufactured by AM has not yet been undertaken.

Most extensive work on the production of extrusion dies by additive manufacturing were carried out by Hölker et al. in a number of studies.

Hölker et al. studied the production of an extrusion die with integrated local cooling channels by Selective Laser Melting (SLM). To analyze the effects of this cooling system, hot extrusion trials with different ram speeds (6, 12, 18, 24 m/min) and preheating temperatures were performed. Results of this study revealed that exit temperature of the profile was reduced significantly (41 °C) at low ram speeds. However, at high ram speeds, surface defects in the shape of stripes of high roughness occurred. It was reported that

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these defects could be prevented by internal die cooling [1].

In a similar study, Hölker et al. investigated the influence of local inner cooling in hot aluminum extrusion dies. Conformal cooling channels were manufactured by SLM. Results showed that application of local cooling channels could increase the extrusion speed up to 300% without increasing the exit temperature [2].

Recently, Hölker and Tekkaya studied the hybrid production of aluminum alloys by Selective Laser Melting (SLM). In this study, the die bridge was manufactured conventionally by subtractive methods and the part with the complex geometry was built-up on the conventional die by SLM. An isolated cooling channel for local cooling was produced inside this part. The results indicate that extrusion exit temperature was locally reduced and controlled. It was shown that hybrid tools can withstand the high mechanical and thermal loads that occur during hot extrusion [3].

These studies found in the literature were focused on the improvement of conventional die designs in several contexts by combining SLM method with conventional production concepts.

One of the key requirements in die production is to obtain the exact geometric form and details of the 3-dimensional model in production. Conventional methods require manual operations (machining, polishing etc.) to provide the final form of the die. The human intervention in such operations limits the form and geometry that can be produced and directly effects the quality of extruded profiles. Laser beam based AM methods provide a unique freedom to directly produce the designed geometric forms which cannot be obtained by any conventional method. The aim of this study was to alter the existing design concept of extrusion dies based on a novel 3-dimensional perspective within the geometrical tolerances of DMLS and to resolve the limits in die production which are introduced by conventional linear design perspective.

2. Experimental

A two-stage experimental study was carried out to investigate the manufacturability, performance, and product quality of additively manufactured dies. In each stage, aluminum extrusion dies were produced using EOS MS1 powder and EOS M290 DMLS machine.

2.1. Manufacturability

Aluminum extrusion dies should be resistant to high temperature, fatigue, wear and should have high thermal conductivity. Therefore, dies made of hot work tool steels are generally preferred. Table 1 gives the chemical composition of 1.2344 hot work tool steel commonly used in extrusion. Table 2 gives the mechanical properties of 1.2344 hot work tool steel.

The characteristics of the part produced, as it is in all powder metallurgy methods, depends highly on raw material (powder), production technology and process parameters [5]. Maraging steel, commonly used for the production of plastic injection dies, was chosen for this study because it is commercially available in powder form for DMLS and easy to handle and process. Table 3 gives the chemical composition of 1.2709 maraging steel and Table 4 gives the mechanical properties of DMLS maraging steel powder provided by EOS.

In the first stage of this study, design and production of the porthole die illustrated in Fig. 1 was carried out. The aim of this stage was solely to investigate the manufacturability and the properties of a simple-geometry die and to determine the potential difficulties and necessary precautions.

The conventional design in Fig. 1 was scaled down by 0.5 and optimized for DMLS. Production of the porthole test die was completed in 18 h. The surface hardness of the die was measured after production.

To predict the mechanical properties of maraging steel die at aluminum extrusion operation temperatures, annealing at 550 °C for 3, 6, 9 and 12 h followed by air cooling and hardness measurement was carried out. 550 °C was chosen as the annealing temperature because, in aluminum extrusion operations, the aluminum billet is pre-heated to 440–470 °C, the die is heated to 450–460 °C, the container is heated to 420 °C and the exit temperature of the extruded profiles are approx. 500–550 °C [7].

Following the aforementioned preliminary study, it was decided to perform primary field tests on a simple geometry solid die to be able to observe the flexing behavior of the die under pressure, tribological behavior between the die and the aluminum billet and hardness variations due to operation temperatures as well as the inspection of the extruded profile surfaces and cross sections. A profile cross section with sharp edges and flat surfaces was used to investigate all these effects (Fig. 2). Components of the die set which have no effect on the die geometry and the mechanical and surface properties of the product (backer, bolster, ring) were produced by conventional methods using 1.2344 hot work tool steel and were combined with additive manufactured die matrix to reduce overall cost.

Production of the die was completed in 58 h. Following the DMLS process, the production platform and the die were annealed at 490 °C for 8 h for artificial aging of the MS1 steel as well as reduction of the residual stresses through the die section. The surface hardness of the die was measured both after production and stress relieving. No conventional finishing or surface hardening post-

Table 1
Chemical composition of DIN 1.2344 hot work tool steel [4].

Element	C	Si	Mn	P	S	Cr	Mo	V	Nb
Percent	0,4	1	0,35	< 002	< 0,005	5,2	1,3	1	–