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Published in:
Proceedings of the 11th International Conference on Multi-Material Micro Manufacture (4M2016) : co-organised with 10th International Workshop on Microfactories (IWMF2016)

Link to article, DOI:
10.3850/978-981-11-0749-8 694

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Cannella, E., Nielsen, E. K., & Arentoft, M. (2016). Ejection force analysis of sintered aluminium micro gears using a shrink-fit die principle. In *Proceedings of the 11th International Conference on Multi-Material Micro Manufacture (4M2016) : co-organised with 10th International Workshop on Microfactories (IWMF2016)* (pp. 41-44). 4M Association. https://doi.org/10.3850/978-981-11-0749-8 694

Ejection force analysis of sintered aluminium micro gears using a shrink-fit die principle

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Abstract

This project aims at developing and designing a new die-system capable of reducing the ejection force after in-die compacting and sintering, similar to the functional principle of a Micro-FAST sintering process. The system is based on the shrink-fit principle from cold forging; thus, the die is in a pre-stress condition during sintering. The experimental phase has involved the production of aluminium micro gears either with or without the shrink-fit application. The resulting ejection forces have been compared, showing a reduction with the shrink-fit application. In addition, the influence of several elements on the ejection force has been analysed, such as pressure, time, temperature, and lubrication.

Keywords: Sintering; Micro-FAST; Pre-stress; Die-design; Friction; Ejection.

1. Introduction

Over the last 15 years, there has been an increasing demand on micro-systems and components, e.g., MEMS (Micro Electro-Mechanical Systems), micro-reactors, fuel cell, micro-mechanical devices, micro-medical components, etc., popularly used in vehicles, aircraft, telecommunication, home facilities, medical devices and implant applications. In micro-manufacturing, a large variety of processes can be described [1]. Among the different processes, powder sintering represents a good solution to manufacturing components with complex shape and geometry, especially in mass production. The sintering process mainly consists of two general steps: compacting and heating the powder. The most important result is the possibility of obtaining a net-shape part characterised by high quality and shape accuracy. A secondary process, like machining, is not required in most cases. As a consequence, the loss of material and the manufacturing costs will be reduced. In this field, the Micro-FAST sintering process is a new developing technique, capable of joining the advantages related to the traditional sintering with a reduced lead time of production. The development of this process starts from FAST sintering, defined as Field Assisted Sintering Technology. The aim of Micro-FAST is to take the functional principle of FAST into the micro-scale [2]. This possibility has to be related to the size-effect, which considers the change of the process parameters due to scaling down of components, from macro to micro-domain; some elements such as friction and lubrication, can be more influencing because of micro size. The main characteristic of Micro-FAST sintering, compared to the classical sintering process, consists of the simultaneous application of heat and pressure. As a consequence, a coupled multi-field activated forming process [1] allows the micro part manufacturing in a reduced time, holding the same advantages of a sintering process. Additionally, a better part density can be achieved, with the optimisation of the main process parameters, such as temperature, pressure, and heating rate.

In relation to the Micro-FAST principle, the focus of this paper is on decreasing ejection forces through an optimised tooling design, and possibly avoiding any kind of lubrication; in particular, the effects of lubricants regarding the decreased density and electrical conductivity, because of a higher porosity resulted by residual lubricant inside the part. A tool design has been developed in order to reduce the ejection force and possibly enable unlubricated sintering. A series of experiments have been carried out to examine how the tool design and the process parameters, sintering temperature, compaction pressure and holding time, influence the ejection force.

2. Existing tool designs

Several studies have been involved in the improvement of ejection after forming processes. In sintering, the main problem related to ejection is the friction generated onto the die-wall interface. During powder compaction, the part exerts a radial pressure onto the die-wall interface, as a result of the axially applied pressure. Friction can generate damages and cracks on the lateral surface of the sintered part, with resulting poor quality.

Proceedings of the 4M/IWMF2016 Conference
Edited by Guido Tosello, Hans Nørgaard Hansen, Kornel Ehmann and Stefan Dimov

ISBN: 978-981-11-0749-8 :: doi:10.3850/978-981-11-0749-8_694

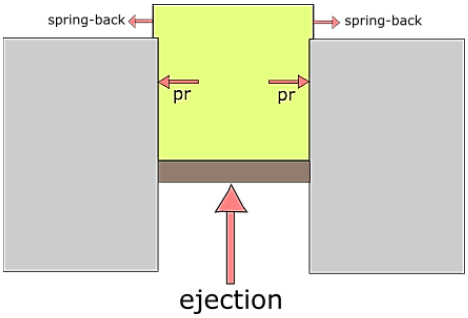

Fig. 1: Spring-back effect during ejecting phase.

During ejection, when the part starts to leave the die (see Fig. 1), two different pressure conditions are involved: loaded and unloaded. This phenomenon is a consequence of the spring-back effect, because of elastic releasing of the sintered component in unloaded condition. The two simultaneous conditions can lead to cracks over the departure corners.

Several solutions have been focused on a split-die principle. Before starting the process, all the components are assembled in order to close the die and sinter the workpiece. After the manufacturing process, the die is disassembled and the part ejected [3].

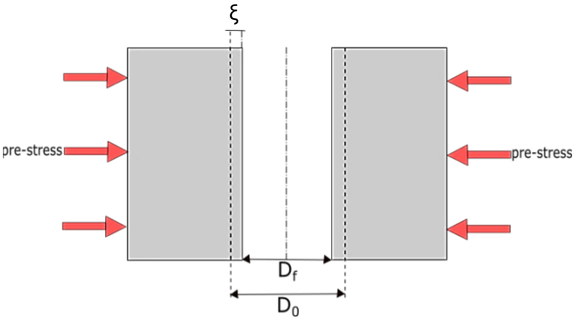

Fig. 2: Diameter reduction due to a pre-stressed condition.

A different approach to overcome the problem related to friction consists in using a pre-stressed die during sintering. The functional principle related to pre-stress consists in reducing the inner diameter of the die through a compression tool applied on the outer diameter (see Fig. 2). After the sintering process, the die will be released from pre-stress and it will expand to its starting size, at last. Simultaneously, the sintered part starts to expand due to elastic releasing. If the die expansion is higher than the workpiece expansion, a clearance between the two parts will be generated. Different tool solutions have been inspired by the shrink-fit principle. The most widespread concept is based on a stress-ring application. The functional principle is based on assembling one or two rings on the external diameter of the die [4]. A fit pressure is generated among the different components, related to the interference value. A conical-interference solution has previously been used, in order to ensure the assembling and releasing of components [5]. A stress-pin application represents a good solution to obtain localized stress-fields. They are placed in critical areas of the die depending on the part complexity [6]. Shape-memory alloys (SMAs) have a particular property based on recovery capability when they are heated over certain temperatures (austenitic temperatures). After heating the SMAs over their proper austenitic temperature, they start to apply pressure over the die, similar to a stress-ring [7]. From cold forging, strip-wound containers produced by STRECON® represent the industrial solution to pre-stressing of dies. The stress distribution can be optimised by varying the wind tension to the optimal value [8]. The use of chamfered dies could be an alternative solution to obtain an easier ejection; chamfers allow a gradual elastic releasing of the sintered part, resulting in a decreased friction throughout the ejection stroke.

3. Experimental set

Based on the shrink-fit principle, a conical-die-ring solution has been adopted. The main components are: die, sleeve, and ring.

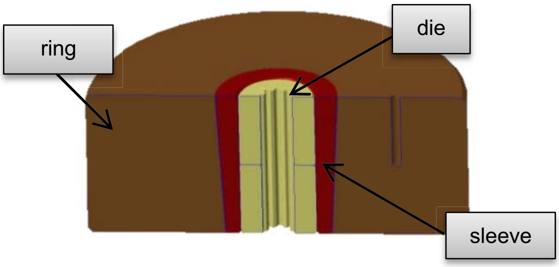

Fig. 3: Conical-die system.

The conical-interference shape (see Fig. 3) should be seen in the assembling/releasing capability of this system. According to thick-walled hollow cylinder theory [9], the expected diameter reduction due to a pre-stress has been estimated. In this design an interference fit of 40 μm has been realised, resulting in a theoretical-internal radius reduction of 6 μm.

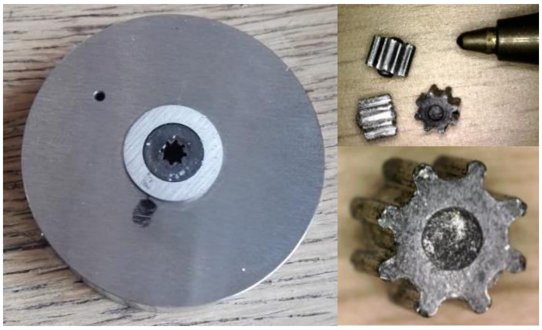

Fig. 4: On the left, manufactured components in H13 steel. On the right, samples of sintered gears and a pen tip.

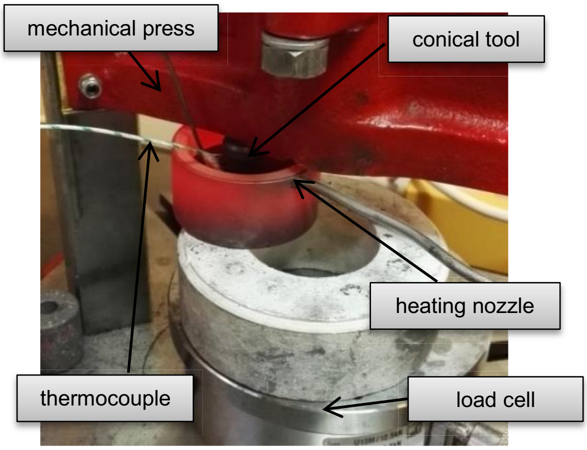

Fig. 5: Sintering phase.

H13 steel has been chosen as die and sleeve material (see Fig. 4), because of its good properties in hot-working condition. The experimental workpiece is a micro gear, characterised by a circumscribed-diameter of 3.5 mm, an inscribed-diameter of 2.55 mm, and 3-4 mm thickness (see Fig. 3). After assembling die, sleeve, and ring, the micro aluminium gears have been sintered by using a mechanical press and a radial nozzle heater (see Fig. 5).

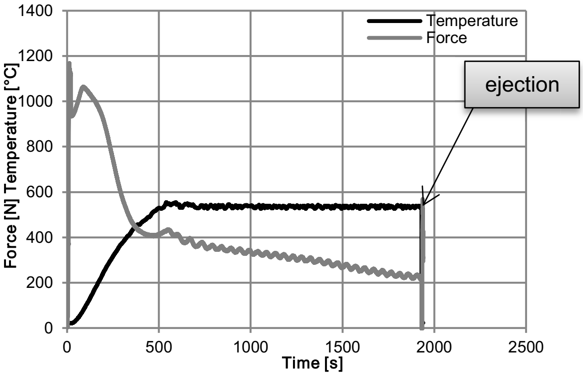

Fig. 6: Diagram used for controlling process parameters.

Typical sintering parameters have been 80-150 MPa in compaction pressure, 450-550 °C in sintering temperature, and 15-25 minutes of sintering time. Temperature has been controlled by using a thermocouple connected to a digital interface (Allen-Bradley TC-32). Pressure has been monitored by using a load cell. The instantaneous values have been acquired by using an electronic system (DataTranslation DT-9800) (see Fig. 6). During the sintering process, pressure and heating have been applied simultaneously, according to the Micro-FAST principle.

4. Results

The experiments have been focused on a comparison between parts sintered either with or without pre-stress; this has been done in order to understand the effectiveness of pre-stressing between the two tool configurations. In total, 32 micro gears have been sintered. All the experiments have been carried out under lubricated condition. A single comparison has been made in unlubricated condition.

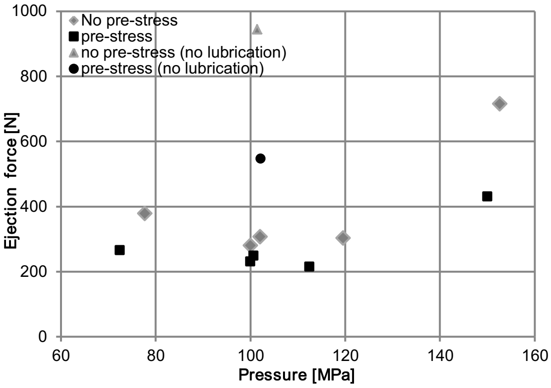

Fig. 7: Experimental results as a function of pressure (T: 550 °C; holding time: 20 min).

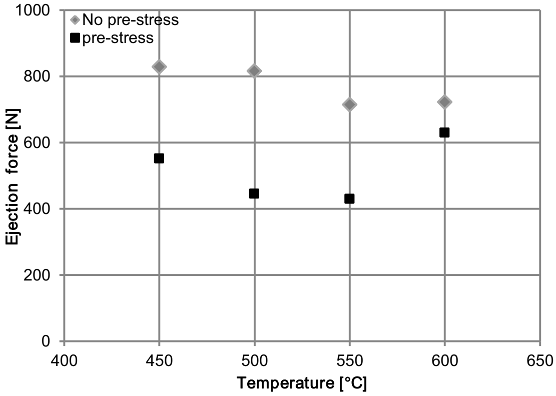

Fig. 8: Experimental results as a function of temperature (holding time: 20 min ; pressure: 150-160 MPa).

The purpose of reducing the ejection force has been obtained in all the samples sintered with pre-stress. The results obtained have been compared as a function of the main process parameters, which are compaction pressure (see Fig. 7), temperature (see Fig. 8), and holding time (see Fig. 9).

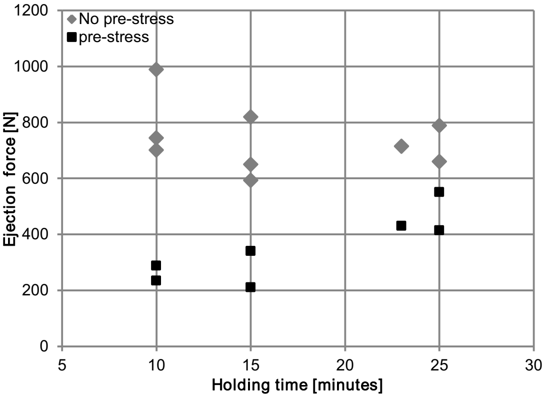

Fig. 9: Experimental results as a function of holding time (temperature: 550 °C ; pressure: 150-160 MPa).

Table 1
Percentage reduction of the ejection force as a function of the process parameters.

	Pressure	Temperature	Time	Unlubricated
Reduction	30 %	31 %	53 %	42 %

Average data have been presented on Table 1. If considering the variation of temperature and pressure, the percentage reduction of the force has been similar. By contrast, the same percentage as a function of time has been higher; with decreasing of the sintering time, the force difference between the two configurations has been increased. The percentage reduction of the ejection force in unlubricated condition shows the possibility of sintering and ejecting the sintered part without using any lubricants. Problems related to residual aluminium particles stuck to the die and punch after ejection have limited the number of experiments under these conditions. An accurate relation between the ejection force and process parameters has not been possible due to high scattering of results. This is a consequence of several influencing elements, such as variable amount of powder and lubricant, contamination, and residual aluminium particles on the tools.

5. Conclusion

This paper has shown the results obtained for improved ejection condition after sintering of a micro gear. According to thick-walled hollow cylinder theory, the functional principle of a pre-stressed die has been tested on a simplified ring-sleeve concept, with a conical interference of 40 µm and a resulting inner-diameter reduction of 6 µm. The conical design has been used for obtaining an elastic system capable of assembling/releasing for several manufacturing cycles. The maximum reduction of the inner tool diameter is limited by the yield strength of tool components.

Experimental comparisons show how all the samples obtained in a pre-stressed die are in accordance with the purpose of decreasing the ejection force. Compared to a non-pre-stressed configuration, the ejection force has been reduced by 30-50 %, depending on the process parameters. Firstly, an increase of the compaction pressure has generated a higher value of the ejection force, according to the radial pressure generated during powder compacting. Secondly, the analysis of forces as a function of sintering time has produced a larger scattering of results; a shorter sintering process duration has produced a higher difference in force values between the two tool configurations. Finally, due to several influencing elements during sintering and scattering of results, no theoretical relations have been made between the process parameters and the ejection force. Part ejection after unlubricated sintering has been proven possible, as the pre-stressed tool has shown a high reduction of the ejection force; although new critical conditions arise, because of material sticking and contamination problems. In order to investigate the quality of the sintered gears, future works could be focused on geometry, surface, and strength measurements.

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