OPTIMISED IMPREGNATION PARAMETERS OF SELF-LUBRICATING POWDER METALLURGICAL COMPONENTS FOR COLD BULK FORMING

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Abstract

In order to achieve an economical forming technology production, a well-developed lubrication technology is generally required. Within the scope of this work, further investigations on a novel self-lubricating forming process are presented. Powder metallurgical (PM) components were impregnated with lubricant to store the oil in their process-related porosity. In a subsequent forming process the resulting pressure forces the oil to leak out lubricating the process.

In preliminary works it was found, that the required maximum forming load can be reduced up to 39 % by applying the new lubrication method. In addition, relative densities up to 99 % were reached after deformation. Based on this, in this contribution optimized impregnation parameters regarding the initial porosity and impregnation time are presented. Compression tests were conducted and strain-stress-curves were recorded and analyzed. In addition, friction factors were determined in order to characterize the lubrication behavior. With the optimized parameters significantly higher strains and lower friction factors as compared to dry forming could be achieved.

Keywords: Powder metallurgy, self-lubrication, upsetting, sintering

1. INTRODUCTION

Lubrication is essential in metal forming processes. It has influence on the required forming energy, the material flow, the strain and stress distribution and the resulting workpiece surfaces [1]. Consequently, tool wear and tool life as well as the component quality are affected [2, 3]. In order to increase the tool life different strategies are pursued. Approaches of tool surface modification in order to adjust its properties to the occurring stress situation is scientifically well researched and already applied in industrial practice [4]. Other strategies are aiming at the load reduction during the process by means of optimised cooling and lubrication techniques [5]. Generally the following demands on lubricants are made [6]: a good and constant lubrication film, high oxidation resistance, wear and friction reduction, corrosion protection, and heat removal. Additionally, in cold bulk metal forming conversion layers or coatings are required. These are used as lubrication carrier and are applied on the workpiece in order to compensate the great workpiece surface expansion during forming [7]. Usually, conversion compositions are based on zinc-phosphates and have a negative environmental impact [8]. Besides human health risks and hazardous waste disposal, further process steps are needed in comparison with a tool related lubrication system [9]. I.e., additionally to the actual lubricant deposition, appropriate surface pre- and after-treatments are required, leading to high equipment and energy costs [10]. Many investigations exist on the avoidance of lubricants in metal forming, which confront the above said ecological and economical points of view. Current studies basically focus on three different approaches to reduce friction and wear without using lubricants [11, 12]: ceramic tools [13], self-lubricating coating systems [14, 15] and hard material coating [16].

In this contribution a new lubrication technique for cold metal forming is presented, which allows the usage of conventional lubricating oils without conversion layers by using self-lubricating workpieces. For this, the process-related porosity of PM components is exploited as a lubricant storage similar to self-lubricating bearings. Such bearings were invented in the 1920s by General Motors and are known for their low maintenance requirements and pronounced emergency running characteristics [17]. In operation, the stored oil leaks out due to elevated temperatures, enhanced pressure and elastic deformation. The new lubrication approach uses this effect in cold sinter-forging by means of endogenous workpiece lubrication.

The paper is structured as follows. In Section 2, the investigation methods are presented compromising the used materials, powder metallurgical sample manufacturing including oil impregnation and compression tests. Section 3 is reserved for the evaluation of the proposed lubrication method as well as a critical discussion of the experimental results. Eventually, the paper is closed by the Conclusion section.

2. METHODS

2.1. Materials

For the experimental investigations steel powder with the product name AXD5400 by Rio Tinto Metal Powders Company was used. This press-ready water-atomized powder is particularly designed for sinter-forging applications containing 0.8 wt.-% Graphite and 2.0 wt.-% Copper as alloy elements and 1.0 wt.-% Zinc stearate as pressing lubricate [18]. For the impregnation and compression tests two different oils were used, namely MF155 (Bechem) which is usually employed in cold bulk metal forming, and Turmofluid HPL (Lubcon), a common self-lubricating bearing oil. The major difference is the viscosity, which is ~110 mm²/s for MF155 and ~50 mm²/s for Turmofluid HPL (both at 40 °C). The viscosity influence is studied in order to investigate impregnation and leak-out behaviour during compression. Further characteristics of the used materials (powder and lubricants) are depicted in **Table 1**.

Table 1 Particle size and chemical composition of the powder mix and characteristics of the used lubricants

Chemical composition of AXD5400						
Element	Fe	Cu	C	Mn	O	S
wt.-%	>96.8	2.0	0.8	0.205	0.11	0.0085

Particle size distribution of AXD5400				
Particle size	> 250 µm	> 150 µm	> 45 µm	< 45 µm
wt.-%	Trace	10.0	67.0	23.0

Lubricant characteristics			
Name	Flashpoint (°C)	Density at 20 °C (g/cm³)	Viscosity at 40 °C (mm²/s)
HPL	>250 °C	1.02	50
MF155	>200 °C	0.92	99-121

2.2. Sample manufacturing and impregnation

Cylindrical porous steel samples were compacted using a double-sided tool on a path-controlled hydraulic press (multi-axis powder press, SMS Meer) and were subsequently sintered in a vacuum furnace (HTK 8, Gero) applying the following time-temperature-course. Before heating, the furnace was evacuated for 10 min. In order to burn off the pressing additive a debinding stage at 400 °C was integrated, which is followed by the actual sintering stage at 1120 °C for 30 min. After cooling down to 200 °C furnace temperature, the samples were taken out and cooled at normal air atmosphere.

For a comparative analysis of the compression tests, the dimensions of the samples were set to 30 x 30 mm (diameter x height).

Before and after sintering the relative density was determined by equation (1) using weight and volume measurements. Based on preliminary works the relative sinter density was varied in two steps, approximately 0.85 and 0.9, by adjusting the pressing parameters.

$$\rho_{\text{rel}} = \frac{m / V}{\rho_{theo}} \tag{1}$$

where:

ρ_{rel} - relative density (green or sintered)

m - weight of sintered or green part (g)

V - volume of sintered or green part (cm³)

ρ_{theo} - theoretical pore-free density

The theoretically achievable pore-free density of the powder mix was calculated with equation (2).

$$\rho_{\text{theo}} = 100 / \sum_i \frac{w_i}{\rho_i} \tag{2}$$

where:

ρ_{theo} - theoretical pore-free density

w_i - weight percentages of element i

ρ_i - density of element i (g/cm³)

For the oil impregnation the samples were dipped into a container with the appropriate oil, being completely covered. After impregnation the excess oil was wiped away and the entered oil quantity was determined by measuring the weight gain on a precision scale. The variation of impregnation time was also chosen based on preliminary work to 15 min, 30 min and 45 min. Additionally, the open porosity was determined by impregnating some samples for up to 2 weeks.

2.3. Compression tests

The sintered and impregnated parts were cold upset on a double-acting hydraulic press (Schirmer+Plate, type SOP II) with a maximum pressing force of 12,250 kN using flat dies made of wear resistant tool steel AISI H13 (X40CrMoV511). The active die surfaces were ground to a roughness of Rz = 1.6 µm. The samples were upset to a strain of $\varphi = 1.3$ while the punch force and displacement were recorded using a load cell and a mechanical transducer. The punch speed was constant with v = 1 mm/s. No extra lubrication was used, except for the reference tests. In addition, the experiments were recorded with a high-speed camera for further investigations of the deformation process, i.e. geometry determination for the calculation of the critical strain and bulge factor.

The experimental design is summarised in **Table 2**. It was conducted full-factorial with 4 repetitions for each parameter combination in order to provide an adequate statistical basis for the results.

Table 2 Parameter variation for compression tests

Relative sintered density	Impregnation time (min)	Oil viscosity at 40 °C (mm²/s)
0.85; 0.90	0; 15; 30; 45	~50 (HPL); ~110 (MF155)

3. RESULTS AND DISSCUSSION

3.1. Sample manufacturing and impregnation

In **Figure 1** (left) the mean values and standard deviations of the achieved relative sintered densities of all produced samples are depicted. It can be seen, that the real values are in good agreement with the targeted and the standard deviations for both aimed densities are negligibly small. In addition, the open porosities are listed, which decrease with rising relative density. This behaviour corresponds to the results of [19], where ascending fractions of closed pores with increasing compaction pressure or rather relative density could be observed.

On the **Figure 1** (right) the impregnated oil volume as a function of impregnation time for both lubricants and relative densities is shown. As expected, the oil quantity increases with rising impregation time. This behaviour conforms to the Lucas-Washburn equation, which says that the capillary flow is proportional to the surface tension and time, but inversely proportional to the viscosity [20]. The latter relation is not evident in this case. This can be either attributed to insufficient impregnation time or strongly divergent viscosities at room temperature. Moreover, a major difference regarding the relative densities can be seen as approximately twice as much oil is impregnated in the samples with lower density, which conforms to the different open porosities.

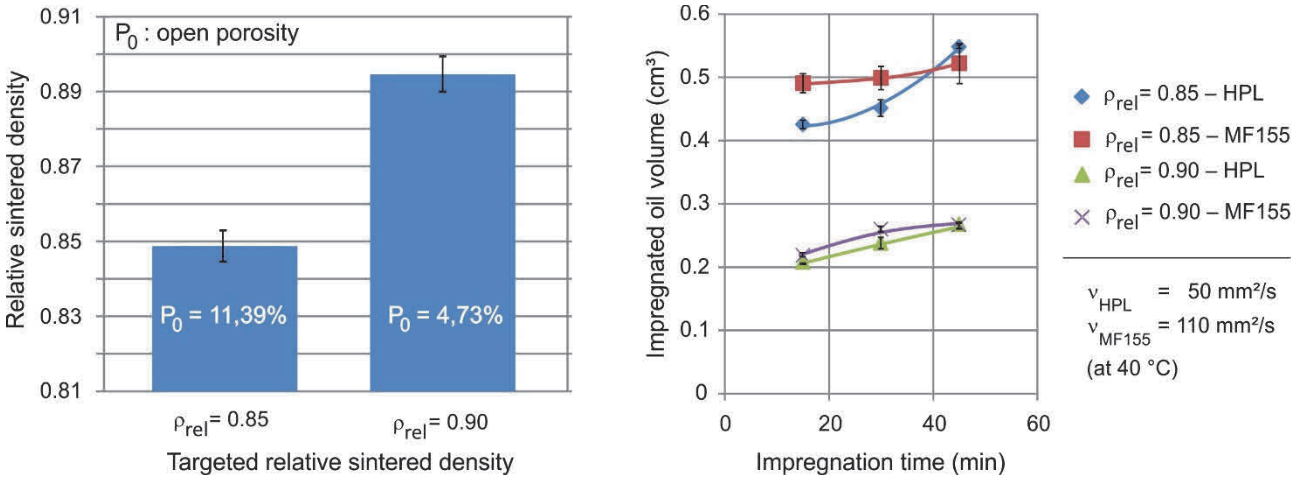

Figure 1 Relative densities of produced samples (left) and impregnated oil volumes (right)

3.2. Compression tests

In **Figure 2** (left) the mean values and standard deviations of the critical strain in dependence of the relative density, used lubricants and impregnation time are shown.

The influence of the impregnation time seems to be insignificant as the critical strain increases only slightly with rising time when using HPL, but decreases the same way when MF155 is applied. This can be attributed to the total impregnated oil volumes, which also differ only slightly in dependence of impregnation time.

By contrast, the relative density has a major effect on the critical strain. For all lubrication configurations the critical strain increases with decreasing relative density. During compression a densification process takes place by closing the residual porosity. The actual deformation begins subsequently, which means that the formability limit of the samples with greater relative density is reached prematurely, which explains the described behavior.

The comparison of different lubricants for a relative density of 0.9 leads to no clear findings. However, a greater effect of the applied lubricant can be seen at the samples with lower relative density. Here, using HPL leads to considerably higher critical strains compared to MF155. This can be ascribed to the different viscosities of the oils. Viscosity is a measure for a fluid's resistance to deformation by shear or tensile stress and depends strongly on pressure and temperature. As the viscosity of HPL is considerably low compared to MF155, it can leak out more easily, which can also be seen in equation (3).

$$\tau = \nu \frac{du}{dy} \tag{3}$$

where:

τ - Shear stress

$\frac{du}{dy}\nu$ - Viscosity

- Local shear velocity

Assuming the same local shear velocity, a greater shear stress or rather force is required to initiate the movement of MF155 compared to HPL. Taking into account the exponential increase of viscosity with rising pressure, the leakage of the oil becomes even more difficult. In summary, MF155 is not able to leak out as fast as HPL. As a result, the forming process is less lubricated, and oil residuals are enclosed in the pores, which in turn leads to premature material failure as the enhanced oil pressure burst the pores. This behavior is confirmed by the photographs of the samples, shown in **Figure 2** (right).

As expected, the dryly formed samples reach lower critical strains due to higher tensile stresses in the outer shell. The results of conventionally lubricated samples are comparable to the new lubrication method.

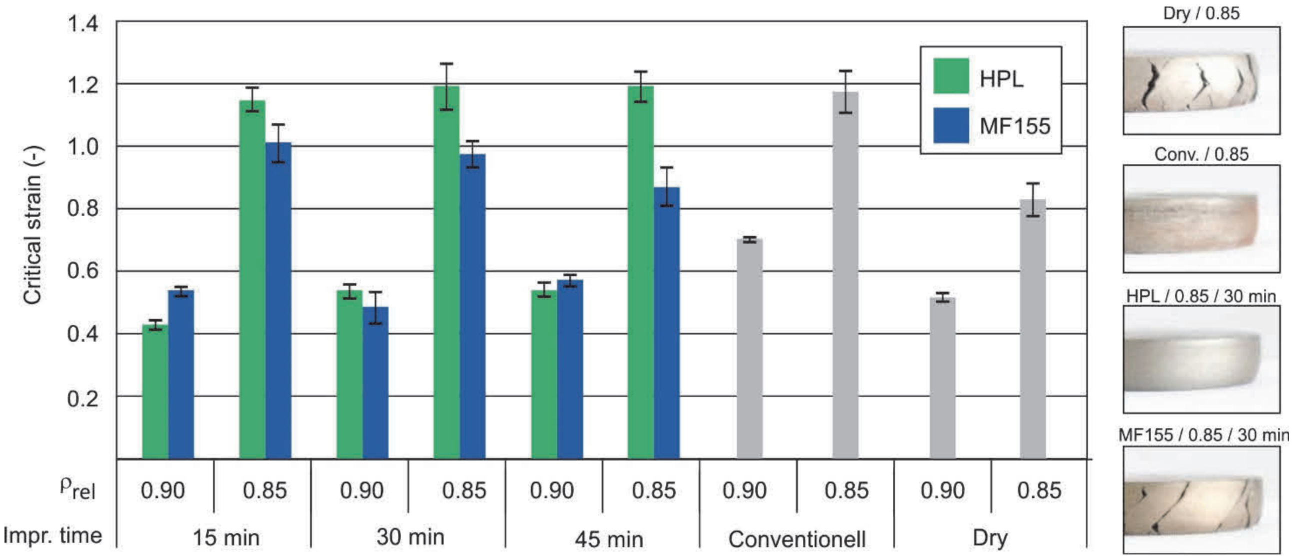

Figure 2 Critical strain in dependence of relative density, used lubricants and impregnation time (left) and corresponding photographs of the compressed samples at max. strain (right)

4. CONCLUSION

In this work, a new lubrication approach for cold bulk metal forming was presented. By infiltrating PM steel components with oil, the process-related porosity was used as a lubricant storage. During the subsequent forming process the resulting pressure forces the stored oil to leak out lubricating the process.

The described method was tested on cylindrical PM steel components with two different porosities (ρ = 0.85 and ρ = 0.9). Impregnation studies were carried out by varying the impregnation time (t = [15, 30, 45] min) and using two oil types. Subsequently, the deformation behavior by means of compression tests was investigated.

The presented endogenous workpiece lubrication shows high potential as an alternative lubrication technique in cold bulk metal forming. The best results could be reached using HPL with a relative density of 0.85 and an impregnation time of 45 min. For future work, a lubricant with a low viscosity should be investigated to enable an easier leak out behavior.

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