Numerical investigation of the effect of friction conditions to increase die life

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Abstract. The standard die materials in aluminium extrusion offer good mechanical properties like high tempering resistance, high strength and ductility. On the other hand, they struggle with the problem of sliding wear. As a result, there is a growing interest in using surface treatment techniques to increase the wear resistance of extrusion dies. In this study, it is aimed to observe the effects of the different friction conditions on material flow and contact pressure in extrusion process. These friction conditions can be obtained with the application of a variety of surface treatment. In this way, it is expected to decrease the friction force on the die bearing area and to increase the homogeneity of the material flow which will result in the increase of the quality of the extrudate as well as the improvement of the process economically by extending die life. For this purpose, an extrusion process is simulated with a finite element software. A die made of 1.2344 hot work tool steel-commonly used die material for aluminium extrusion process- has been modelled and Al 1100 alloy used as billet material. Various friction factor values defined on the die surface under the same process parameters and effects of changing frictional conditions on the die and the extrusion process have been discussed.

1. Introduction
During the extrusion process high pressures and high relative velocity of extrudates are reached. Wear types or wear mechanisms generally depend on the relative sliding velocity, normal contact pressure, materials of rubbing bodies and the environment [1]. As a result of high stresses of the process, tools and especially die and bearing area of the die are exposed to excessive wear and fatigue. Ma et al. states that, in Al extrusion process, friction inside the bearing channel is highly significant to control the surface quality of the final product. Besides, with a high contact pressure, a fully plastic contact is observed between die bearing area and aluminum workpiece, which cause wear [2]. Thus, increasing the tool service life is important for continuity of high quality production by achieving toughness, hardness, wear resistance at elevated temperatures expected from the tool material.

Beyond the good mechanical properties of die materials, nitriding method has been used commonly to increase wear resistance and also complex coatings have been investigated to enhance performance of dies. However, since the most coatings and nitriding forms brittle compounds, and also open to deformation in the substrate, the efficiency varies according to the coating material, the removal rate of the nitrided die material and so on. Therefore, Bakhtiani, Mounayri and Zhang investigated the wear distribution on an extrusion die for two following cases using numerical simulations: without any surface coating and with a bilayer (TiCN + Al2O3) CVD coating. Wear simulations show that the
coated die had a higher resistance to temperature and wear than an uncoated one [3]. Another study of PVD coatings on extrusion dies by Łukaszkowicz et al. presents the research results of CrAlSiN and CrN coatings on an extrusion die. Both coatings showed high potential to extend die life in several orders of magnitude compared to uncoated steel. The lowest wear was obtained with CrN coated dies [4]. In a similar study with various different coatings of Björk T. et al., bearing surfaces of extrusion dies that will work against aluminum under high temperature conditions were coated with TiN, CrN, (Ti,Al)N or TiB₂. The high potential of reducing the extrusion die wear of CrN and especially multilayered-(Ti,Al)N and TiB₂ coatings have been shown [5]. On the other hand, Birol also studied to test the performances of CrN, AlCrN and AlTiN coated hot work tool steel samples under actual aluminum extrusion conditions. It has been stated that the adhesive interaction of the coating with aluminum is the primary wear mechanism in CAPVD coated hot work tools. While CrN coating has shown the most extensive wear damage, AlTiN provided the best performance among CrN and AlCrN in sliding contact against aluminum in terms of friction, resistance against aluminum transfer and wear damage [6]. Also another investigation of Björk et al. concentrating on the wear of the surface treated dies with PVD coatings for aluminum extrusion stated that duplex coatings-plasma nitriding then PVD coating with CrN-can increase tool life at least several orders of magnitude compared to nitriding [7].

As the coating methods have been applied to extend the service life of manufacturing tools used under harsh conditions such as high local stresses, high temperature or cycling loading, the effect of surface roughness and geometric features of the surface has been neglected until recent years. Other than nitriding and surface coating methods, surface texturing and patterning methods have been widely studied these days. In this study, the effect of enhanced friction conditions provided by surface texturing on the extrusion process has been investigated.

Features in the applied surface texture on a surface of a substrate can be different in size or shape but the main purpose to apply these features is to create a self-lubricated surface on the die surface by generating micro-traps for wear debris and micro-reservoirs for both solid and liquid lubricants to make them remain within these micro-cavities. In the view of such information, surface texturing methods and various patterns have been investigated to improve the service life of extrusion dies and prevent the possible extrusion defects.

Guleryuz et al. have studied surface texturing of hard coatings for self-lubrication and their applications on machining tools. For this purpose, composite coatings have been developed and surface pattern has been fabricated onto machining tool inserts to sustain lubrication during interaction. In conclusion, it is shown that these surface texturing methods can be applied to manufacturing tools and promising results have been obtained for machining tool inserts [8]. Pettersson et al. developed an original technique to manufacture embossing tool for texturing metallic surfaces. First, silicon etching technology has been used to form surface indentations. A diamond film deposited into these indentations with CVD method and the diamond film was supported by a layer of nickel by electro-deposition. Finally, when the silicon was removed by etching, diamond protrusions were generated. The embossing tool is capable to apply texture on flat and curved steel surfaces [9]. Costa and Hutchings investigated lubrication using surface patterns in drawing process. In this study, circular-shaped pockets and parallel grooves have been used for patterning of the drawing die and the friction forces were compared. It has been observed that the effect on lubrication of the circular pockets is little. However, groove shaped pattern covering a larger area decreased the strip forces and friction relatively, but its performance was dependent on the relative orientation of the grooves, as the grooves parallel to the drawing direction cause to escape of lubricants and result in poorer surface finish on the drawn product [10]. A similar study has been carried out by Suh et al. on the shape of grooves but this time by means of the application of the cross-hatched pattern with different angle orientations and aspect ratios under mixed and elastohydrodynamic lubrication. Their study has showed that decrease of aspect ratio and increase of groove length cause reduction in friction [11]. Tang et al. investigated the effect of different area fractions of dimples with liquid lubrication on friction, wear and load capacity. As a result, an optimum area coverage of 5% of dimples has showed the best performance by providing retention of the lubricant and the generation of hydrodynamic
pressure, also by trapping the wear debris [12]. Jiwang et al. studied a method combining micro-indentation and ultra-precision cutting to manufacture micro dimples on the surface [13]. Jianliang et al. studied tribological properties of laser surface texturing and molybdenizing (duplex treating) of stainless steel at elevated temperatures. Surface pattern has been implemented by laser processing and MoS$_2$ was used as a lubricant. Samples with and without molybdenizing have been compared. After molybdenizing, the hardness of stainless steel increased and the friction coefficient of stainless steel covered with MoS$_2$ powder decreased from 0.4 to 0.1 at elevated temperatures [14]. In their study Basnyat et al. have also used MoS$_2$ as a solid lubricant on surface of textured TiAlCN coated metallic surfaces. Dimples on TiAlCN coating have been introduced using reactive ion etching in a mixed Ar/CF$_4$ plasma. An overlayer of MoS$_2$ or Mo/MoS$_2$/Ag solid lubricants deposited on micro-textured surfaces by magnetron sputtering. The frictional and wear properties are examined for textured and untextured surfaces. As a result, a significant decrease in friction and wear is achieved at both room temperatures and elevated temperatures for textured coatings as the dimples acted as reservoirs which provides a new supply for solid lubricants on the contact surface. [15]. Shipeng Li et al. investigated tribological performance of TiSiN-WS$_2$ composite coatings deposited on WC/TiC/Co cemented carbide. It is shown that the deposition of WS$_2$ layer on top of TiSiN layer significantly improved the tribological performance of the structure providing lower friction coefficient values and smaller wear rates of the steel ball [16].

In this study, it is aimed to investigate the effect of friction conditions on material flow and contact pressure in extrusion process. Here, most of the recently developed or studied surface modification techniques covered above may be exerted to die surfaces. Most of these techniques promise to decrease friction coefficients and/or to improve die life. The finite element simulation was performed for the extrusion process and the numerical analysis around the bearing area have been performed for this purpose.

2. 3D modeling

A circular die cavity is relatively easy to create and it is sufficient to observe the effect of the different friction conditions by eliminating other effects that would interfere with our results when complex part cross-sections used. Due to these reasons, an extrusion die with a circular die opening was selected.

The main objective of this research is to observe the effects of the different friction conditions. These friction conditions can be obtained with the application of a variety of surface modification methods covered above used together with liquid and/or solid lubricants. Most critical section of an extrusion die is the bearing area, therefore we have concentrated our research on this area.

The finite element software, SimuFact forming, developed by MSC Software Company, has been used to numerically model the extrusion process. Extrusion and die cavity are shown in figure 1 given below. Since friction at the bearing area is important for the research, a simple extrusion die tooling has been designed with a 6-mm-length-bearing-area. In the numerical simulation, the pressure is considered constant during the process like in the case of the real process using an hydraulic press. Simulation model consists of a container, a billet and a support to fix the extrusion die as shown in figure 1 (a). Extrusion profile is chosen circular to model under the condition of axisymmetrical modeling. By means of axisymmetrical model, the computation time is decreased significantly.

The billet has been defined as a deformable body whereas other setup parts were defined as rigid objects. Die material defined as 1.2344 hot work tool steel with a hardness of 50 HRC as it is generally used in industry in Al extrusion process. Billet material used was Al coded as 1100 with a diameter of 25 mm and a length of 40 mm. This material was selected due to its sticky behavior during the extrusion process. Table 1. shows the mechanical and physical properties of the tool material (1.2344 hot work tool steel) and billet material (Al 1100) of the simulations.
To define the die interface correctly, quadtree elements used in the die model. Because of the intense deformation during the extrusion process, finer advancing front quadrilateral elements used in billet model as shown in Figure 2. Friction behavior of billet material, Al 1100, was simulated with friction factors (coefficient of friction values) of 0.05, 0.2, 0.4, 0.7 corresponding various possible friction conditions. In metal forming, well-lubricated processes such as wire-drawing and deep-drawing, a friction coefficient (friction factor) in a range of 0.05 to 0.15 is very common and severe processes such as hot rolling and forging may have friction factor values up to 0.4 [17]. Also, lowest end of this friction factor value range may be represented application of a lamellar solid lubricant such as MoS$_2$ or graphite [18]. Highest end of the friction factor range shows the surface coverage of the liquid and/or solid lubricant has been mostly lost and partial-sticking conditions may be observed. In order to observe effects of different possible friction factors of the die bearing area on extrusion process, billet interface friction was assumed 1 as pure sticking condition (no lubrication assumed) in all scenarios. In the numerical simulation, the pressure is considered constant during the process like in the case of the real process using an hydraulic press and ram speed was defined 2 mm/s with a maximum stroke of 30 mm. Initial temperatures of the container, the billet and the extrusion die were defined as 25 °C.

**Table 1.** Material data used in simulations.

| Mechanical/physical property          | Unit     | 1.2344 hot work steel | Al 1100 |
|--------------------------------------|----------|-----------------------|---------|
| Young’s modulus                      | GPa      | 215                   | 70      |
| Poisson’s ratio                      |          | 0,30                  | 0,33    |
| Thermal expansion coefficient        | 1/°C     | 10.4 x 10$^{-6}$      | 23.6 x 10$^{-6}$ |
| Thermal conductivity                 | W/(m.K)  | 28,6                  | 218     |
| Density                              | kg/dm$^3$ | 7,80                  | 2,71    |
4. Results and Discussions

Axisymmetric model of deformed billet during extrusion process is shown in figure 3 and figure 4 given below. The thick section is the initial billet that is still preserved in the extrusion container and the thin section of it is the extruded part of the Al 1100 billet.

Contact pressures at the billet-container interface and billet-die interface can be seen in Figure 3. \( f \) is the friction factor and it is defined in the range of 0.05-0.7. The highest pressure values have been observed on the container wall, then on the die surface, and on the entering section of the bearing area respectively. As the process quality is especially bound to the die bearing area, the highest pressure values concentrated on the entrance of the die bearing area has been considered. In Figure 3 (a), at the entrance of the bearing area, contact pressure starts from a mean value of 730 MPa and it decreases to around 500 MPa further along the bearing area. In figure 3 (b), with a friction factor of 0.4, contact pressure on the die bearing area starts from a mean value of 610 MPa and it decreases to around 280 MPa, for figure 3 (c), with a friction factor of 0.2, it varies from 500 MPa to 280 MPa through the bearing area and pressure drops earlier than figure 3 (b) in start of bearing area, for figure 3 (d) with a friction factor of 0.05, the contact pressure for the entrance is 400 MPa and it quickly decreases to 270 MPa.

Björk et.al. have mentioned in their study on the wear surface treated dies for aluminum extrusion that wear reaches critical rates especially in entrance of the bearing area [19]. This comment is consistent with the simulation results given in figure 3, showing that high pressure values concentrated at this area of the bearing. Also Bomback et al. has stated in their study that wear occurs at the exit of the bearing area due to high contact pressures at this area [20]. As seen in figure 3, contact pressure is concentrated towards to exit edge of the bearing area in (b), (c) and (d) given for a friction factor of 0.7, 0.4, 0.2 and 0.05 respectively. And for these simulations, pressure values at this area decreased by decreasing friction. With decreasing friction factor values, contact pressure decreases, too, and therefore, wear rates of extrusion die are expected to decrease as wear is also related to the load values on surface.

Recent studies show that hard coatings with micro-reservoirs filled with solid or liquid lubricants can provide decreases in friction factor values. The increased effectiveness of the solid lubricants when applied with micro-reservoirs in the hard coatings have been shown in various studies [15,21]. In their work, Zimmerman et.al. have applied carbon coating on the hard coating with micro-reservoirs and achieved friction coefficient values of about 0.1 against aluminum counterface for about 8,000 cycles in pin-on-disk tests. It is observed that no such decrease is possible without surface texture [21].
Figure 3. Contact pressure distribution at the interface material-die of the FE simulations of directly extruded Al part with friction factors of: (a) $f=0.7$; (b) $f=0.4$; (c) $f=0.2$ and (d) $f=0.05$.

Figure 4 shows flow rate of the 1100 Al alloy during the extrusion process. Dead metal zone is validated in the simulations as mentioned in Ouwerkerk’s study [22]. As seen from the flow rates of material in figure 4, the maximum flow rate of material decreases as the friction decreases. This happens because the friction at the walls that holds the material locally. As a result, the material in the center section of extrudate have higher flow rate. As the friction value on the die section decreases, material flow rate difference between the interface and the center section of the material decreases. So decrease of friction reduce sticking effect of the material on the die bearing surface locally, extrude material flows more homogeneously and this decreases the possible defects in the extruded profile.
3. Conclusions
An extrusion process has been modeled for a product with a simple geometry using a die with a circular cross-section. In the model, die-workpiece surface interaction has been taken into account using different friction factor values. Contact pressure especially at the bearing area is important because high contact pressures increase die wear.

In this study, contact pressure change has been investigated for various friction factor values in the range of 0.05-0.7. As the friction decreases, contact pressure values around the die section decreases substantially. Also extrusion process has been investigated by observing the material flow change with respect to the friction values within the same range. With the decreasing friction factor values, material flow rate difference between the surface and the center section decreased. Minimum flow rate difference will decrease possible defects that may occur in the extrudate as the material flow is more homogeneous. According to the results of the finite element simulations performed in the scope of this study, the most appropriate surface condition of the die is the one with a friction factor of 0.05 for 1100 aluminum alloy. It is the optimum value among the other friction values that will prevent inhomogeneous deformation and provide the minimum die wear.

Figure 4. Material Flow rate distribution with respect to friction factors: (a) $f=0.7$; (b) $f=0.4$; (c) $f=0.2$ and (d) $f=0.05$. 
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