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Application of semi-physical modeling of interface surface roughness in design of pre-stressed microforming dies

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Abstract

Permissible internal pressure in dies for cold extrusion may be increased by the use of one or two shrink rings. The design essentially boils down to defining the diametrical interference fit of the die/ring assembly. There are two methods of design: analytical one based on Lame’s solution and numerical one based on finite element modelling (FEM). None of these methods includes roughness of the interface surfaces of the die insert and the shrink ring. However, when designing the pre-stressed micro-dies, the interface roughness cannot be disregarded and the classical design of the diameter interference must be corrected. In this paper, a semi-physical modelling of interface roughness (SPMIR) is used as novel method which determines the interference correction value. A set of FEM models created on the base of Abbot-Firestone curves, determined from the roughness profile, enables determination of a contact surface stiffness curve and further the interference correction. Relative correction of the die diameter interference increases with the diameter decrease, which might be recognized as a pre-stressed micro-die assembling scale effect. In the experimental part, three miniature dies, with interface diameter 2.8 mm and different levels of interface surface roughness, $Ra=0.16$, $Ra=0.43$, $Ra=0.60$, have been manufactured by WEDM. Relative interference corrections calculated by the SPMIR method reached respectively 17.6, 27.9 and 43.3 %. A practical design advice has been formulated as follows: interference correction based on the interface surface topology is recommended for micro-dies with the interface diameter less than 10, 15 and 25 mm, for the three levels of the surface roughness investigated.

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1. Introduction

Cold extrusion of metals and alloys provides good surface quality and dimensional accuracy comparable even to those obtained by grinding [1]. This technology is particularly useful for manufacturing of micro-parts [2, 3]. For billets of materials with relative high flow stress, the main process limiting factor appears to be the tool's strength. In the case of dies, it is expressed by the maximal inside pressure the die can endure. This pressure might be calculated on the basis of a classical Lame’s theory, which treats a die as a thick cylinder loaded with internal pressure, or using a finite element method (FEM) simulation. The maximum inside pressure is in the range of 1000 MPa, for the tool materials, which are properly chosen and subjected to a right heat treatment. This pressure may be increased by putting the die inside one or two shrink rings [4, 5]. Die pre-stressing creates tensile stresses in the ring and compressive stresses in the die, which increase permissible pressure inside the die cavity. The design essentially comes down to defining the radial/diametrical interference fit of the die/ring assembly. When designing such a die one should be extremely careful. Too small interference does not provide enough pre-stressing to protect the die from fracture because of circumferential tension during the process. On the other hand too big interference might cause the ring cracking during the assembly.

The problem is exacerbated when dealing with micro-dies used for microforming. Here, the additional factor is die/ring interface roughness, which becomes comparable with the theoretical interference fit and, therefore, has influence on the real interference and the stresses produced. This paper introduces a new approach to designing pre-stressed micro-dies, which takes into account die/ring interface roughness. It is based on measuring interface surface roughness profile together with its bearing ratio expressed by an Abbot-Firestone curve. Based on this curve a contact surface stiffness curve is established and the interference correction calculated.

2. Pre-stressed micro-dies

Three cylindrical pre-stressed micro-dies with inside diameter \( d = 1 \) mm and interface diameter \( d_{\text{int}} = 2.8 \) mm were designed, Fig.1a. It was decided to use conical assembling as the pre-stressing method, Fig.1b. Vancrone 40 and Orvar Supreme steels were chosen for dies and rings respectively.

Fig. 1. (a) Die design; (b) assembling procedure controlled by the initial height \( h_0 \); (c) dies before assembling.

The pre-stressed dies (die inserts and rings), labeled as die a, die b, and die c have been manufactured by WEDM in accordance with three different settings of the WEDM machine, Fig. 1c. The technological regime was the same for each pair of the die and the ring. This resulted in the same surface topology for both tool elements. On the other hand an important parameter that is a mean spacing of profile irregularities \( R_s \) was found to be the same (with about 5% accuracy) for all investigated surfaces. Surfaces profiles and their Abbot-Firestone curves are presented in Fig. 2. The measured values of the roughness parameter \( R_a \) for die a, die b and die c appeared to be: \( R_a = 0.16 \), \( R_a = 0.43 \) and \( R_a = 0.60 \) \( \mu \)m respectively.
The value of the diameter interference $N_m = 0.02034\ mm$ was obtained by an FEM (Marc Mentat 2015.0.0) analysis; that meant radial interference $N_r=0.01017\ mm$. It implied an interface pressure $p = 740\ MPa$. Flattening of asperities of the interface surfaces, either a die or a ring, is expected as shown in Fig. 2c. This causes a reduction of the calculated interference $N_r$ to the real value $N_{r\text{-real}}$ (1).

$$N_{r\text{-real}} = N_r - \Delta N_{r1} - \Delta N_{r2}$$  

(1)

where: $N_r$ - calculated radial interference, $N_{r\text{-real}}$ - real radial interference, $\Delta N_{r1}$ - flattening of die asperities, $\Delta N_{r2}$ - flattening of ring asperities. The proper design of a pre-stressed micro-die must then take the interference correction $\Delta N_r$ into account because of already mentioned flattening. It leads to the right value of the interference.

$$N_{r\text{-cor}} = N_r + \Delta N_r$$  

(2)

$$\Delta N_r = \Delta N_{r1} + \Delta N_{r2}$$  

(3)

3. Determination of interference corrections by the SPMIR method

The semi-physical modeling of interface roughness (SPMIR) method introduced in [6] is based on a set of FEM analysis of deformation of models of single die and ring representative asperities. The starting point is a surface profile represented by an Abbot-Firestone curve [7], which describes the surface texture. This curve may be found from profile trace by drawing lines parallel to the datum and measuring the fraction of the line which lies within the profile. For the analyzed micro-die it can be noticed that the surface profile was taken in the direction of its axis using a non-contact 3D Alicona Infinite Focus G4 system. Representative asperities for each die (a, b and c) were then determined (Fig. 3a), according to the Abbot-Firestone curve and standard roughness parameters $R_s$ (Fig. 2a).
The most important aspect of this idea is the fact that these asperities - because of their shape - provide the same Abbot-Firestone curves as examined surfaces. It means that they are statistical representations of all asperities. Further, it is believed that the reaction to deformation under pressure of such a model is equal to the reaction of a real surface consisting of multiple asperities. What remains to be done is finding a difference between stiffness of a perfectly smooth contact (assumed in most computational methods of die design) and a rough real contact. The rough contact stiffness might be determined by pressing together FEM models of two asperities representing contact surfaces of a die and a ring. The contact stiffness of perfectly smooth bodies might be found by pressing models of smooth bodies, see appendix A. However, in a real contact situation, some asperities of the die may go directly to the valleys of a ring profile. Other asperities may take any of the non-symmetrical mutual positions. Such misalignment of asperities decreases the contact stiffness and should not be neglected.

Let us assume that there exist \( n+1 \) relative positions of die and ring asperities, Fig 3b, that are described by the parameter \( e_i \).

\[
e_i = \frac{RS}{2n}, \quad i = 0,1,\ldots,n
\]

(4)

It is suggested that the set of \( n+1 \) mutual positions of model single asperities represents the initial situation at the contact zone between rough real surfaces. The behaviour of such a contact might be found as a result of \( n+1 \) experiments carried out on \( n+1 \) physical models created with the help of FEM modelling. It has been proposed [6] that the mean pressure evolution function \( a(x) \) that is treated as a contact stiffness of a pair of real rough bodies might be obtained as an arithmetic mean value of contact stiffness, \( Q_i(x) \), for all \( n+1 \) cases (5).

\[
a(x) = \frac{1}{n+1} \sum_{i=0}^{n} Q_i(x)
\]

where \( a(x) \) - contact stiffness of model; \( n \) - number of segments.

Three times (for each of three dies) \( n+1 \) FEM simulations, see Appendix 1, are conducted for each of the relative positions \( e_i \) of asperities. Each contact stiffness \( Q_{ia}(x) \), \( Q_{ib}(x) \) and \( Q_{ic}(x) \) of a model pair of asperities as well as resulting functions \( a_{ia}(x) \), \( a_{ib}(x) \) and \( a_{ic}(x) \), (also in Fig. 5a) and a contact stiffness of a model pair of perfectly smooth bodies \( Q_s(x) \) are shown in Fig. 4.

![Fig.4. Results of FEM simulations of interface contact models: (a) for die a, (b) for die c, (c) for die b.](image)

Function \( a_{ia,b,c}(x) \), (5) expresses a contact stiffness of a model pair of rough bodies and depends on the height of a model. Both FEM models had the same height that enabled obtaining the contact surface stiffness of the examined assemblies as function of \( c(x) \), respectively \( c_{ia}(x) \), \( c_{ib}(x) \) and \( c_{ic}(x) \), that satisfies equation (6).

\[
c^{-1}(x) = a^{-1}(x) - Q_s^{-1}(x)
\]

(6)

The results of FEM simulations might also be presented as the diameter interference corrections for considered dies a, b and c, as a function of the assembling pressure \( \Delta N_m(p) \), see Fig 5b. For the applied assembling pressure
p=740 [MPa], dotted lines in Fig. 5b enable establishing the interference corrections $\Delta N_{m(a)} = 3.40 \mu m$, $\Delta N_{m(b)} = 5.38 \mu m$, $\Delta N_{m(c)} = 8.36 \mu m$. Finally the corrected interference for dies a, b and c follow equation (7).

$$N_{m-corr} = N_m + \Delta N_m$$  \hspace{1cm} (7)

Fig. 5. (a) contact surface stiffness functions $c(x)$ of examined micro-dies a, b and c obtained by FEM simulation; (b) diameter interference correction as a function of the assembling pressure for dies a, b and c.

4. Analysis of results

The above corrections of the shrink fit interference calculated by the SPMIR method, which took into account geometrical features of the die/ring interface surface for a micro-die with 2.8 mm interface diameter, constitute a relative change of 17.6% for die a, 27.9% for die b and 43.3% for die c accordingly to the level of accuracy of surface manufacture. The interface surfaces have been made by WEDM with different productivity depending on the rate of erosion and the number of passes. The surface roughness obtained was $R_a(a)=0.16$, $R_a(b)=0.43$ and $R_a(c)=0.60 \mu m$. The achieved surface finish of die a was at the limit of WEDM capability. The worst finish of die c was comparable to what can be achieved by grinding. In that case, 43% correction of the vital die prestressing parameter shows the scale of danger, which could be avoided by taking into account the roughness profile of the surfaces in contact.

Due to the current miniaturisation trend in metal forming, smaller and smaller dies will be required. Following this way of thinking, Fig. 6 displays a relative interference correction as a function of the die interface diameter. This relationship has a hyperbolic character, which means that reducing the interface diameter to, for example, 2 mm increases the required correction to 25%. On the other hand corrections smaller than 5% are required for the interface diameter greater than 10, 15 and 25 mm for $Ra=016$, $Ra=0.46$ and $Ra=0.60$ respectively.

Fig. 6. Relative correction of diameter interference as a function of interface diameter due to contact surface roughness: type a, type b, type c.
5. Conclusions

The SPMIR method of determining correction of diameter interference due to roughness parameters was applied for design of three micro-dies manufactured with different levels of interface surface roughness quality. For the analyzed micro-dies with an interface diameter 2.8 mm the relative corrections of diameter interference were 17.6%, 27.9% and 43.3% respectively for roughness parameters Ra = 0.16 μm, Ra=0.46 μm and Ra=0.6 μm. The extended results show that the relative interference correction depends on the roughness of the interface surface and is hyperbolically increasing with decreasing the interface diameter. Thus, for average surface finish, it is strongly recommended to take into account the topology of the interference surface when designing pre-stressed dies with the interface diameter lower than 25 mm. This threshold might be decreased due to fine surface finish, but not below 10 mm. Increase of the relative correction of the die interface diameter interference with decreasing of this diameter might be recognized as a pre-stressed micro-die assembling scale effect.

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Appendix A.

Each FEM model consists of four deformable bodies: 1,2,3,4, Fig 7a. Body 1 is defined by boundary conditions - no lateral movement of both side nodes. Bodies 2 and 3 are added on both sides of body 1 since they have an influence on its deformation through side deformations of body 4. Lateral movements of the left side nodes of body 2 and both side nodes of body 3 are eliminated. The wall 8 additionally limits deformation of body 3. Bottom nodes of body 4 are fixed and both side nodes cannot move laterally. There are additionally two side walls 9 and 10. During the simulation three rigid bodies, 5, 6 and 7, move down together. Force on body 5 is recorded and used to calculate mean pressure on body 5 – function Q(x). Model for perfectly smooth contact is shown in figure 7b.

Fig. 7. (a) Example of FEM model representing rough contact; (b) FEM model of perfectly smooth contact.

References