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FE ANALYSIS OF MULTI-CYCLE MICRO-FORMING THROUGH USING CLOSED-DIE UPSETTING MODELS AND FORWARD EXTRUSION MODELS

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ABSTRACT

Research in micro-forming leads to the investigation of the effects of heat generation in the workpiece and temperature changes in the tools during the forming. The results reported in this paper relate to the study of cold micro-forming processes which are usually ignored on its thermal characteristics. Two closed-die upsetting models were used for the simulation of the forming of micro-parts in single forming trial and in mass production (multi-cycle loading) respectively. An elastic–plastic Finite Element simulation was performed for a single forming trial. The heat transferred to the die, computed from the simulation, was then used as an input for the multi-cycle heat loading analysis in the die. Two materials - silver and low carbon steel, were used as the work material respectively. The results show that the die saturation temperature could still go up to 100^{o}C for small size dies, which is significant for the forming of micro-parts. Forming errors due to the die-temperature changes were further computed, which forms a basis for developing considerations on the forming-error compensation. Using the same methods and procedures, forming of a micro-pin via forward extrusion was analysed.

KEYWORDS: Micro-Forming, Multi-Cycle Loading, FEM, Forming Error.

1. INTRODUCTION

Finite Element method has been widely used for the analysis of forming of macro-components, while most of them were focused on the single forming trials. For mass production with cold, bulk material forming, plastic energy dissipation and the friction between the workpiece and the die generate the heat. The heat will transfer to the die, the punch and the ejector. The temperature in the tools will increase gradually but with a cyclic form [1-2]. Due to the heat dissipation to the immediate environment, the temperature in the tools will gradually reach a saturation value. The temperature change will have an effect not only on the die dimensions but also on the interfacial conditions between the workpiece and the die. Long et al. [3] created a finite element model to simulate the influence of thermal and elastic effects on the accuracy of the cold-extruded components. Thermal-displacement coupling finite element analysis was performed and procedures of extrusion, punch retraction, components ejection and cooling were considered. Results showed that the thermal behaviour of the forming material plays an important role on the forming accuracy. There are also many others using either theoretical method or finite element method for the thermal simulation [4-6] for single-cycle forming process. For multi-cycle coupled thermo-mechanical simulation, one direct method is to repeat the finite element simulation. Each new simulation cycle may be based on the previous simulation results such as residual stress, temperature, the deformation, etc. The problem of such a method is the huge computer CPU time requirement, because a moderate finite-element model may need several hours CPU time and more than thousands cycles of iterations may be needed. Some techniques for saving the multi-cycle thermo-mechanical coupling finite element simulations were presented [7,8], but still quite a lot of CPU time required. Qin et al. [9] proposed a method for the analysis of the forming-errors varying with the manufacturing cycles during the forward extrusion of the components. In the simulation, the single forming trial was simulated with the use of a commercial FE code based on elastic and plastic modelling, then the heat flux density generated from the work-material plastic deformation and friction between the workpiece and the die were recorded. A simplified model with the die only was considered for the heat transfer analysis with the heat flux function imposed on the die inner surface. The multi-cycle model was established by the multi-steps heat transfer analysis. Iterations may be needed for the comparison of the temperature fields for the purpose of achieving more accurate results. The results showed that the change of the temperature in the die due to multi-cycle loading causes significant levels of the forming-errors.

Research in micro-forming has attracted significant attention recently. Most of the efforts were focused on the forming processes analysis and optimisation, especially on the material fundamentals. Forming-tool thermal and elastic behaviours and their influences on the dimensional accuracy of the formed micro-components have not been investigated. Differences between the forming of micro-components and the forming of macro-components have been well-documented, and the issues relating to the production precision and efficiency were also raised [10]. From the simulation point of view, due to influences of the size effects to be considered, heat generation and heat transfer during micro-forming, number of manufacturing cycles for the temperature to reach the saturation in the die, as well as effect of the temperature changes on the component-forms, have to be qualified, with consideration of multi-loading characteristics. This paper is focused on these issues.

2. MODELLING AND ANALYSIS PROCEDURE

Two analysis models are constructed. The first one is about single-cycle forming coupled themo-mechanics finite element simulation and the second one is the heat transfer analysis for multi-cycle forming. For single-cycle forming, the model is based on the simplification of a micro-forming tool design used for micro-forming tests. It is consisted of 4 main parts - punch, ejector, compound die-set and workpiece. Shape of the outer ring of the die was designed with consideration of a heating requirement. The die-insert inner diameter is 1 millimetre and the

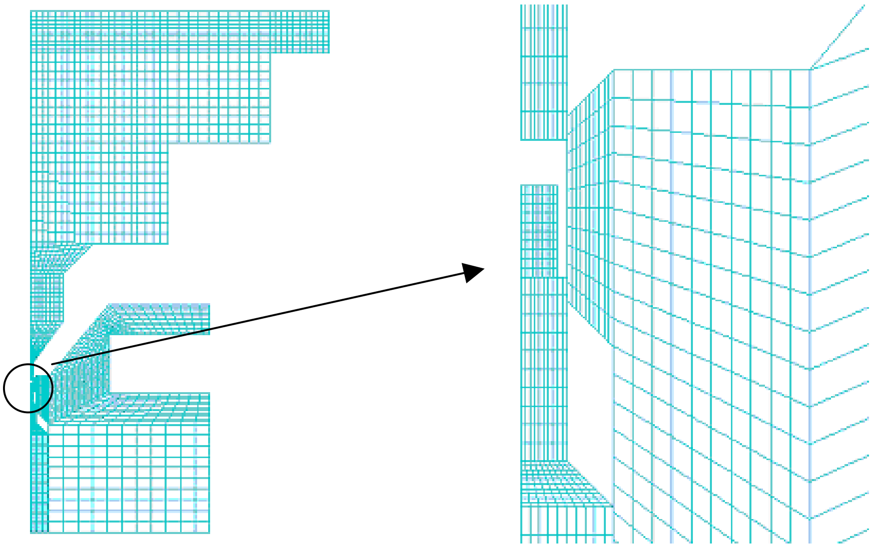

Figure 1 The FE model of the closed-die micro-upsetting

height 2 millimetres. The initial diameter and height of the billet are 0.8 millimetres and 1.0 millimetre respectively. The material for the punch, ejector and die are all tool steel, with Young's modulus, Poisson's ratio and yield stress 193GPa, 0.3 and 2250MPa respectively, elastic-plastic deflection being considered for them. Their heat conductivity and specific heat are 30 W/(m*K) and 460 J/(kg·K) respectively. The density is 7865 kg/m^3 and the thermal expansion coefficient is 1.388*10^{-5} m/m. Silver and low carbon steel are used as the work material respectively, the stress-strain curves of the two materials being at room temperature shown in the Fig. 2 and Fig. 3. The density, Young's modulus and Poisson's ratio for steel work material are 7833 kg/m^3, 193GPa and 0.3 respectively. Thermal properties: expansion coefficient 1.474*10^{-5} m/m, conductivity changing with the temperature. Steel work material's conductivity is 54 W/(m*K) at room temperature, while at 400^{o}C, it is 42 W/(m*K). Its specific heat is 465 J/(kg·K). The data of stress-strain relationship under other temperature is obtained from Ref [11]. For silver work material, the density, Young's modulus and Poisson's ratio are 10500 kg/m^3, 83GPa and 0.37 respectively. Its thermal properties are: conductivity 417.1 W/(m*K) and specific heat 232 J/(kg·K), expansion coefficient 1.98*10^{-5} m/m. Two die-configurations are considered – small die (outer diameter of the die is 6 times larger than that of the workpiece) and large die (40 times larger), for multi-cycle forming loading analysis.

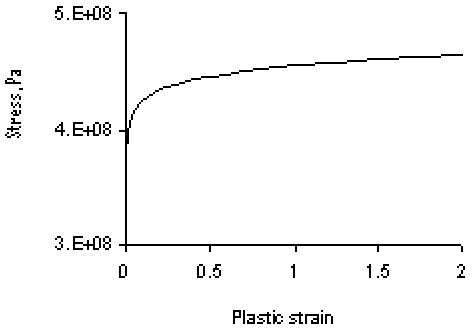

Figure 2 Silver stress vs plastic strain curve at room temperature

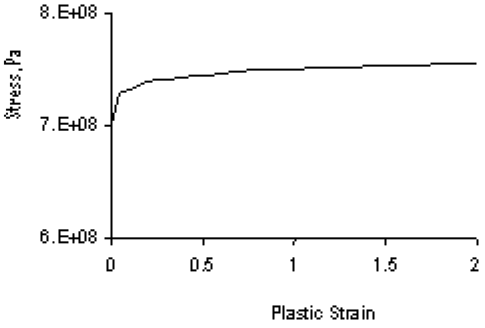

Figure 3 Low carbon steel stress vs plastic strain curve at room temperature

2.1 Single cycle simulation

The simulation includes the following steps:

(1) positioning the billet and forming the workpiece to the full size,
(2) withdrawing the punch,
(3) ejecting the formed part out, and
(4) the formed part cooling down.

The analysis of cooling-down of the workpiece was not performed with FE simulation, considering that the workpiece was so small that it may not have significant influence on the contraction of the formed part. As for the single forming-cycle analysis, the first step is the most important one as major heat-generation and transfer take place within this step. Due to the pressure acting on the die inner-surface, the die will also be expanded. This is another source of forming-error generation. During the step (2), after the punch withdraws, the die will contract, this may cause a new plastic deformation in the deformed workpiece. After the step (3) (the part is ejected), the deformed workpiece will go under elastic recovery (springback). During the final step, the deformed workpiece will contract due to the cooling of the material. The time-duration of each step is assumed to be 0.1 second. A fully coupled displacement and temperature analysis was performed with the use of ABAQUS [12].

2.2 Multi-cycle loading analysis

For reducing the CPU requirement of the analysis, the punch, ejector and workpiece were not considered in every cycle, in the multi-cycle loading analysis, and only the die itself was considered for thermal loading. Instead, the heat fluxes generated from the plastic deformation of the workpiece and the friction between the die inner surface and the workpiece were imported into a separated die-model. The heat flux density values (as functions to the time) recorded from the output file of the single cycle full-scale FE simulation. For the die-analysis, only heat transfer analysis was performed for the given number of the cycles. During the forming the state of the contact between the material and tool-surfaces change from time to time. As a result, FORTRAN source codes were developed to obtain the values of the heat transferred to the die-surface as a function of the time.

3. RESULTS AND DISCUSSION

3.1 Single-cycle forming analysis

Meshes of the workpiece and tools at different forming stages are shown in Figs. 4(a) to 4(c).

The temperature distribution at the final stage is shown in Fig. 4(d). The temperature in the workpiece reached as high as 80°C for the steel workpiece, while for silver workpiece it is relatively low (60 °C), for the forming-rate examined. For both cases temperature in the die increases insignificantly for a single cycle

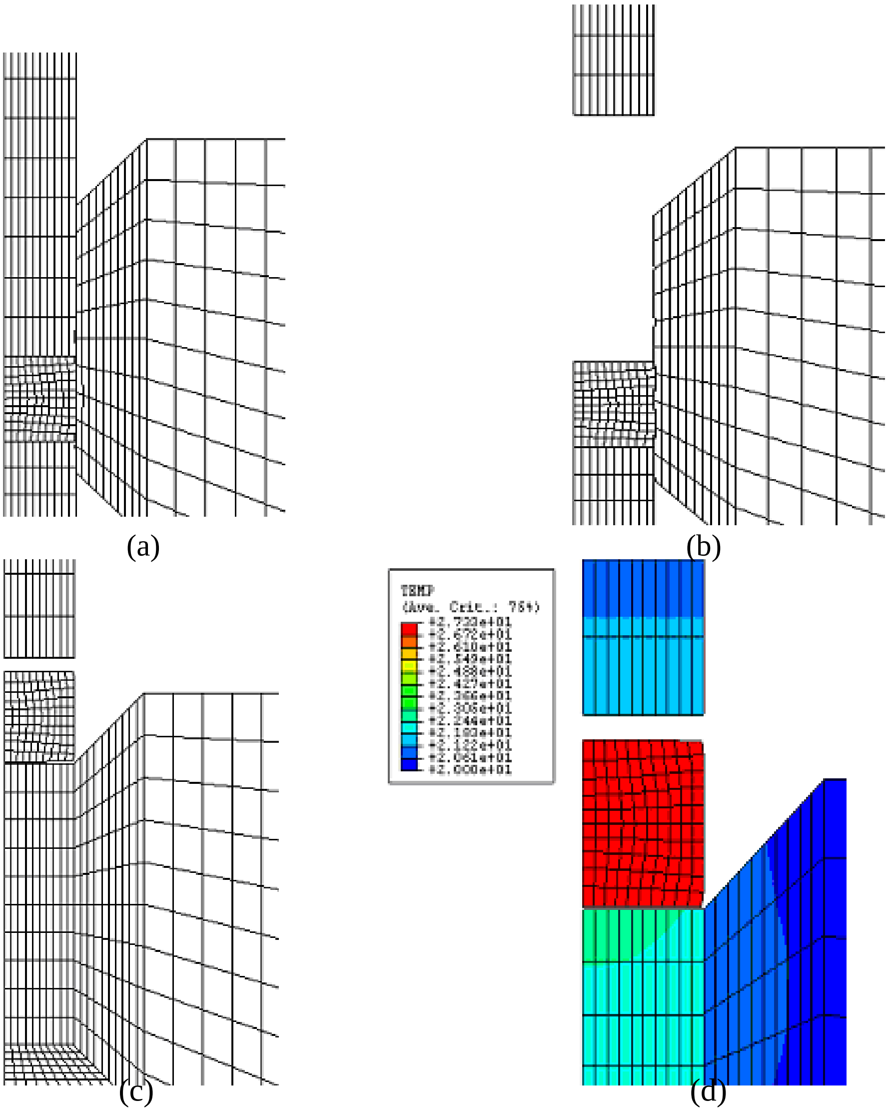

Figure 4 Closed-die upsetting: (a) fully formed, (b) punch withdrawn, (c) part ejected, and (d) temperature distribution

loading. Contact pressures between the die and the workpiece vary from stage to stage. During the forming stage, the high pressure causes the die expansion, and when it is released, the die contracts. The residual die-deflection leads to a forming error. Due to overall temperature increase is not significant, the temperature effect on the forming die may be neglected for the single-cycle forming of micro-parts, or for a slow forming process, but with the repeated forming processes, the temperature could accumulate to a significant level. It may result in the considerable forming errors.

Influences of the friction at the material/die interface were also investigated, based on the model described above. Three values of coefficient of friction were assumed (0.05, 0.1 and 0.2 respectively). Table.1 shows the maximum temperature within the formed part and the temperature in the die after the component is fully formed and then ejected. Slight increase of temperature due to the increase of the friction will still have significant effect on the overall temperature in the die after many forming cycles. Before the component is nearly fully formed, the component contacts with the die inner surface, and at this moment, the heat flows from the component to the die and then the die temperature increases. For one forming-cycle, the die inner-surface temperature only increases slightly, but with the repeated forming cycles, the die temperature will gradually increase. The die temperature may not be important for the error analysis if only a single cycle is looked, but it may influence the forming-error generation significantly if multi-cycle forming is considered. The deformation rate is another factor which needs to be considered since it influences plastic energy dissipation.

Table.1 The maximum temperature of component and die inner surface

Friction coefficient	$T_{component}$(^oC) (when fully formed)	$T_{die\ inner\ surface}$(^oC) (when fully formed)	$T_{die\ inner\ surface}$(^oC) (when ejected)
0.05	71.26	21.87	20.33
0.10	75.19	22.25	20.50
0.20	80.61	22.62	21.17

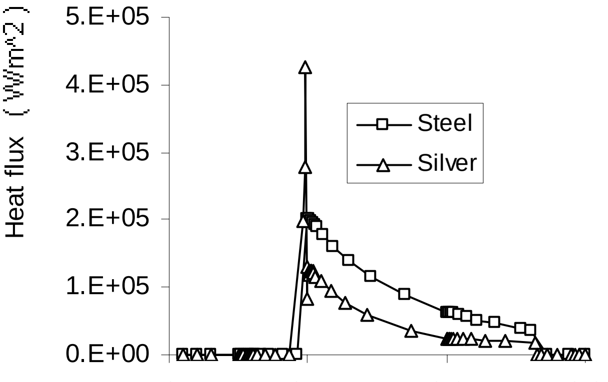

Figure 5 Heat flux (at the top of workpiece surface) changes with time

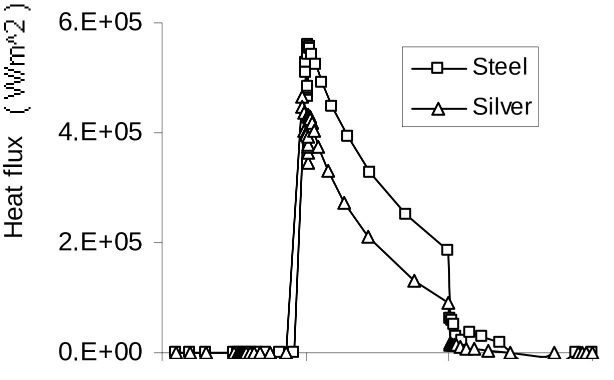

Figure 6 Heat flux (at the middle of workpiece surface) changes with time

3.2 Multi-cycle forming analysis

The heat generated from the plastic deformation and the friction during the forming of the Silver and Steel parts are show in Figs. 5 and 6 respectively. Obviously the heat flowing into the die for forming the steel part is higher than that forming silver part. During the first step (time less than 0.1 second) during which the workpiece is not in contact with the die, the heat flux is zero. As soon as the contact occurs, the heat flux rapidly increases to the highest value and then gradually decreases, as the workpiece is nearly formed, and also due to the heat lose to the environment. At the end of the second step (time at 0.2 seconds), the heat flux continues to decrease to zero. Fig. 5 shows values referring to the top corner of the workpiece surface, while the Fig. 6 shows the values at the centre of the workpiece surface. The average temperature increases from 20°C to 100°C after about 3,000 cycles (Fig.7), the forming error at saturation state increasing from 0.5 to 1.7 microns. The saturation temperature for silver workpiece is lower than that for lower carbon steel workpiece, this value being only about 60 °C. Similar forming errors were also found for silver workpiece, the initial forming error being also about 0.5 microns and the forming error at saturation temperature about 1.8 microns. The forming-errors change from cycle to cycle which indicates the challenges in controlling dimensional accuracy of the formed parts. For larger die, although the heat generated from the work material plastic deformation and friction between work material and die inner surface doesn't change much by comparing with that of smaller die, due to the large volume of die material, the heat will increase inside the die very slowly.

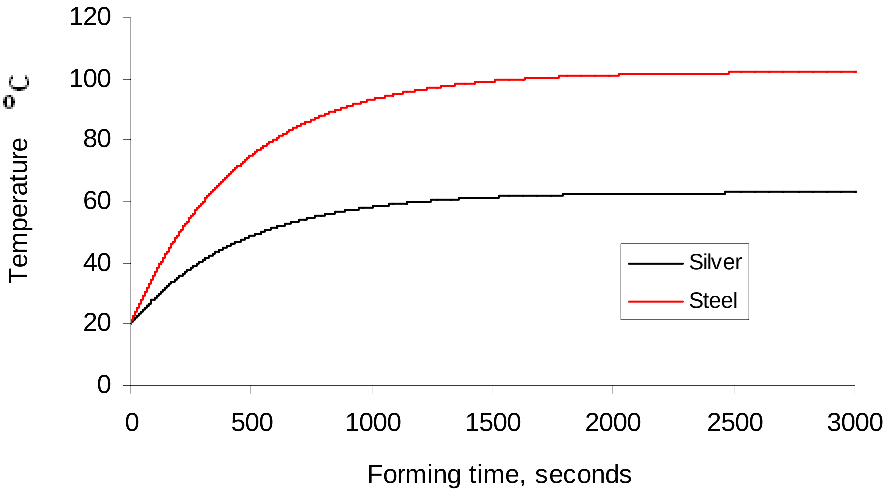

Figure 7 Comparison of the temperature increase at the die-inner surface for two work materials, (3000 seconds for 10,000 cycles)

4. DISCUSSION

There are many challenges for design, manufacture and simulation in micro-forming. The size effect has overall influences as the part size decreases to hundreds or tens microns. The size effect may be considered, in the simulation, in the forms of the inclusion of size-dependent stress strain relationships and friction behaviours between the surfaces of the formed parts and the die, as well as the thermal behaviour between these contact surfaces, etc. These were not a focus of the study reported in this paper. In this paper, for the case of small die, the saturation temperature can reach 100°C. By comparing with that of the macro-forming[13], the same work-piece and die material are used, with the die outer diameter being about six times of the die inner diameter.

Due to the forming speed of macro-forming[13] is 22.15mm/s, while the micro-forming in this paper is only 3.6mm/s, the number of forming cycles when die temperature reaches to saturation temperature is much less than that of micro-forming. Although the temperature of die increases much quick than that in micro-forming, finally about the same saturation temperature is predicted. The nearly the same relative forming error can be expected because this depends only on the temperature increment. Obviously, larger absolute forming error happens for the macro-forming.

5. CONCLUSIONS

For cold forming of micro-parts with materials such as silver and steel, temperature changes in the die are still significant, when multi-cycle loading is considered. The die inner-surface temperature could reach as high as 60^{o}C and 100 ^{0}C respectively, for the models examined. The thermal and mechanical properties of the workpiece materials play important roles in prescribing the temperature saturation in the die. Considering the characteristics of multi-cycle loading in mass-forming, effects of the temperature changes with manufacturing cycles on the tools, and hence, the workpiece, will have to be qualified, if higher dimensional accuracy of the formed parts is to be achieved.

Since only small amount of the heat is generated during a cycle of cold micro-forming, it takes much longer time for the temperature in the die to reach the saturation state, compared to that for the forming of macro-parts, which reflects the needs of performing “in-process” forming-error compensation.

The methods and procedures described in this paper are applicable to the analysis of thermal forming processes, such as warm forming processes and laser-assisted micro-forming processes.

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