Elastic deflection and tilting effect in a multi-stage micro bulk former

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Abstract

Previous studies have described a high performance transfer press for the application in micro forming. This research extends this finding by conducting a two-stage forming process for the machine tool in order to examine the efficiency of the machine in a real multi-stage process.
In particular the analysis focuses on quantifying the effect the forming force has on the elastic deflection of the machine and the tools by examining the displacement of the moving plate under loaded and unloaded conditions. The results of the measurements were used to describe the tilting effect due to the off-center loading applied to the upper tool plate.

1 Introduction

There are three basic manufacturing concepts: adding, removing or forming material. Forming technology is the art of changing the shape of components maintaining mass preservation. The tools required for forming metal components are custom-made for each application at great cost, so metal forming is often expensive unless used in mass production. Additionally, it is very rare to find a single-step forming process. When manufacturing metallic components in mass production by multi-stage forming, one of the big challenges is the design of the machine tool which is capable of manufacturing with high speed and within desired tolerance. This challenge has been addressed primarily by high performance transfer presses in conventional forming technology [1]. Forming technologies have several notable benefits for manufacturing micro parts such as material saving (0-3% loss compared to 70% in machining), less energy consumption and increased performance by decreasing both the production time and manufacturing cost. Similar to conventional press working, new machine tools must be developed in micro forming which allow micro parts to be formed automatically. The same concept of traditional high performance transfer press is introduced to be used for mass production of micro metal parts. However, the new specifications of micro parts and machine tools such as small tolerances, increased function density of the mechanism and higher cost efficiency require higher static stiffiness of the machine structure, increased dynamic performance of handling system, decreased tool wear and thermal deformations of the tool, mahcine and workpiece. Overcoming these error generation processes, significantly reduces the part error associated with dimensional accuracy, contour precision and surface roughness.

The concept of small forming machines, known as micro presses, was used where the structure of conventional presses were scaled down in drive mechanisms and frames such as horizontal transfer presses for manufacturing cold headed parts [2].

Beginning in 2000, researchers began investigating how to use linear servo motors for small servo presses. As this development has progressed, it has been found that a vast number of press characteristics can be altered using servo drive technology. Linear motors have several potential benefits, such as flexibility for long slide (ram), high speed and position control, availability of maximum force at any position. In 2004, Groche and Schneider published a document demonstrating a newly developed forming press driven by a linear servo motor with maximum force of 20 kN and production rate of 1200 strokes/minute [3]. They also reported on the effects that dynamic load had on the horizontal displacement while introducing a new simulation strategy for optimization of high precision press. In 2008, Niehoff et al. developed a highly dynamic double-axis micro forming press, called MUM [4]. The MUM combined the technology of linear servo and air bearing. The press has maximum force of 15 kN, maximum stroke of 200 mm and stroke number of 1250 spm at 1 mm stroke height. For this production speed, the machine shows 2-3 μm positioning error of the ram (main slide) under unloaded condition. Servo presses with force outputs from 15 kN to 150 kN are now available in the market [5].

Recently, a new high performance transfer press was introduced where the billets are formed in two-stage forming operation with the consistent production speed of 155 strokes per minute [6]. A comprehensive analysis was carried out for the positioning accuracy of the handling system at static and dynamic modes [7, 8]. It was verified that part positioning in a tolerance zone of ±30 μm is achievable with an expanded uncertainty of ±9 μm when transferring the micro parts with the speed of 160 strokes/minute,.

This paper focuses on determining the accuracy of the main slide and the guiding system used in the developed press. The purpose of this research is to explore the effect of loaded condition on the positioning accuracy of the ram while comparing the results to unloaded condition. Moreover, the research discussed herein examines if the efficiency of the machine tool is altered due to the tilting effect and elastic deflection under loaded and unloaded conditions. Under unloaded conditions, the motion of the upper tooling is established with respect to stationary surfaces by clearances in the guiding system, parallelism of the upper and lower plates and perpendicularity of the slide to the lower bed. For instance, in cold forging a slight misalignment of the beds would result in excessive bending moment on the punch causing geometrical errors in the forged part. Under loaded conditions, the tilting effect and elastic deflection when applying forming force and off-center loading are determined for the tooling since they may cause height deviations of the formed part, excessive guiding and tool wear.

In multi-stage forming processes, the tilting and elastic deflection across the upper plate can determine the feasibility of forging for a particular part.The presence of elastic deflection and tilting effect decrease the efficiency of the process and make it impossible to manufacture high precision products regardless of a system’s positioning accuracy.

2 Elastic deflection and tilting effect

When a machine tool is under loaded condition, workpiece, tools and machine are elastically deformed while varying the force during forging. When the process is finished, the load is removed and the elastic deflection disappears. The concept of uncompensated and compensated change of force on the tools with respect to elastic deflection is schematically shown in Figure 1. In examining the graphs, it is apparent that the geometry of the forged part deviates from the final dimensions due to the elastic deflection.

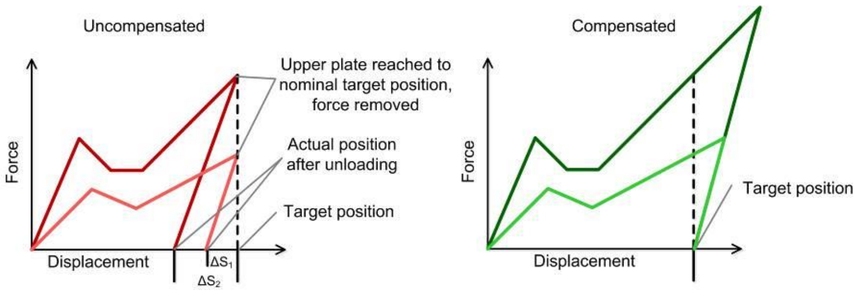


Figure 1: Concept of uncompensated and compensated elastic deflection error

When manufacturing metal parts in a multi-stage forming process, forming force varies from one stage to another causing uneven load distribution on the upper plate which introduces an unwanted moment to the upper tooling resulting in displacement error or tilting effect. The time-displacement data at the different points of the upper tooling has the advantage to determine the effect of off-center loading on the upper tool plate under loaded condition.

As previously mentioned, the tooling is a two-stage cold forging with a force of 4kN applied in the second stage and 1kN in the first stage according to the FEA (Figure 2). For the testing described herein, the representative forged parts of the forming tests applying the conditions associated with uncompensated and compensated stroke position, are shown in Figure 3 (a) and (b) respectively.

When comparing the deformed shape of the specimens, while inspecting the geometry of the parts, incomplete cavity filling is observed in Figure 3 (a).

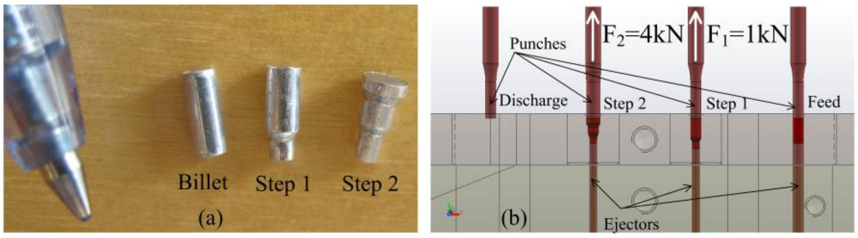


Figure 2: Forming stages; (a) Samples for billet, first and second forming stages; (b) Tooling layout and off-center loading on upper plate

(a) Not completely formed (b) completely formed

Figure 3: Effect of elastic deflection of the machine tool on the forged parts

3 Main slide error

The working accuracy of a press ram is mainly characterized by two features: the tilting effect of the main slide under off-center loading and total deflection under load. For the testing described in this work, the layout of the machine tool is one-point configuration for the slide when transmitting the force from the linear servo motor to the upper tooling. The guiding system is a two-pillar system with ball-guide bushes. The analysis of errors considered time-displacement curves under loaded and unloaded state at the center and side edge of the upper plate where the measurements occurred.

3.1 Elastic deflection error

To observe real time displacement of the main slide, a built-in facility (controller of the linear motor) continuously monitored and captured the position (of the center) at 2 milliseconds time intervals for 254 milliseconds (a complete cycle time: 350 milliseconds) due to the limitations in data acquisition. To verify the repeatability, 25 measurements were tested under loaded and unloaded condition for the same stroke. In order to provide a means of reference for checking the controller measurements, laser interferometry measurements were conducted for the same conditions to verify repeatability between the two measuring methods. The laser interferometry measurements were performed on the side edge of the upper tooling as shown in Figure 4.

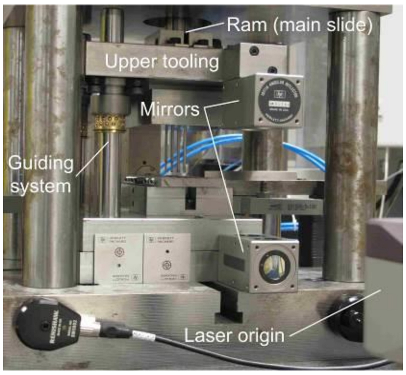
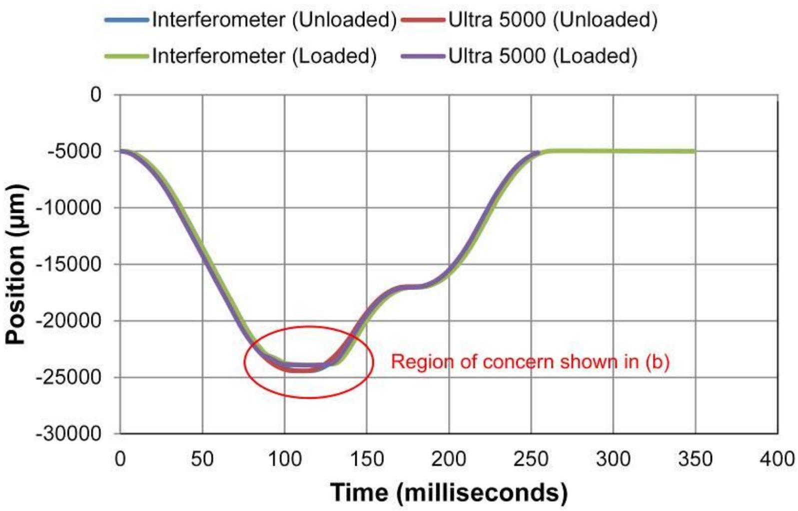
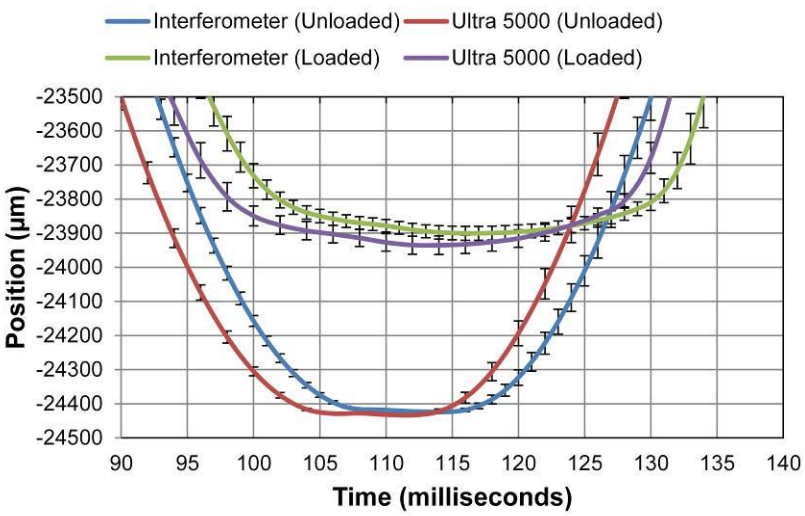


Figure 4: Experimental setup for displacement measurements under loaded and unloaded conditions

The curves of the motion versus time for the main slide associated to the loaded and unloaded conditions are shown in Figure 5a. It should be noted that, the testing region is one cycle time due to the repetition. As can be observed in the figure , the displacement at the bottom dead center (BDC) is very important since this determines the elastic deflection of the machine tool causing geometrical errors at the forged part. Relatively good agreement between controller output and interferometer was found, although a constant delay of 2.5 milliseconds was observed between the two curves at the same loading condition.



(a) Once cycle time



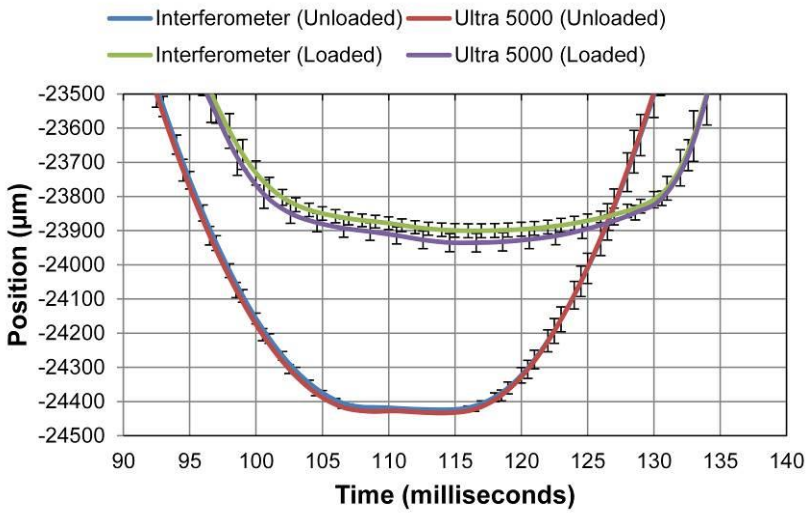
(b) Region of concern

Figure 5: Displacement-time curve connected to the load conditions; Error bars indicate ±1 standard deviations

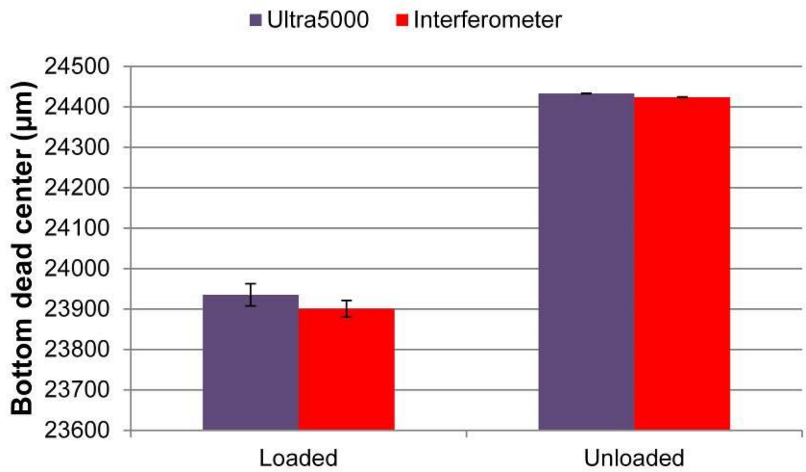
Fluctuations with overshoots, undershoots and a steady state error are present at the region of concern with respect to the final placement of the upper tooling. The curve has several potential benefits, such as determining time-dependent characteristics and characterizing the accuracy of the machine tool. The time-dependent variables include number of strokes per minute, contact time under pressure and velocity under pressure. The testing leads to evaluation of the elastic deflection by comparing the position of the upper tooling at the bottom dead center when applying the loaded and unloaded conditions (Figure 5b). It is observed that the BDC is reached after 115 milliseconds. In examining the two deflection measurements, it is apparent that good agreement between controller output and interferometer was found, since the difference between the values was only 5% maximum at the same loading state.

To examinet the BDC, a correction of 2.5 milliseconds was performed in the curves in order to remove the drift (Figure 6a). More consistent measurements (less position variation between the repetitions) in the unloaded than the loaded condition, for both measuring methods can be seen from Figure 6b.

The positions for bottom dead center are listed in Table 1. When comparing the average positions of the upper tool at the bottom dead center while applying loaded and unloaded conditions, a large elastic deflection (~0.5 mm) in the machine tool is observed.



(a) Drift correction in the displacement curves



(b) Comparison of positions at BDC

Figure 6: Analysis of elastic deflection of the press associated with loaded and unloaded conditions. Error bars indicate ± 1 standard deviation.

To this end, the elastic deflection is too large for precision manufacturing of micro forged parts. This leads to the conclusion that the static deformation of the machine tool due to the elastic deflection is considerable and must be compensated in order to achieve a satisfactory production accuracy.

Table 1: Position of upper tooling at the bottom dead center

	Loaded (STDV) A	Unloaded (STDV) B	Elastic deflection C=|B-A|
Ultra5000 (µm)	23935.2 (27.4)	24433.1 (0.8)	497.9
Interferometer (µm)	23900.3 (20.3)	24423.9 (0.6)	523.6
Deviation (µm)	34.9 (14.4)	9.2 (0.6)	25.7

To provide a more detailed analysis of the forming force effect on the elastic deflection, an explanation was made based on the previous observations. When comparing the records for the nominal and actual position of the press ram at the bottom dead center, it can be seen that the position error increases almost linearly for longer spindle travel (Figure 7, Left).

Furthermore, in another test the spindle was programmed for higher nominal value (>24400 µm) and the result showed almost completely formed part (Figure 7, Right). This occurred due to the fact that the engine is not at maximum force (>5200 N) when performing elastic deflection testing (Refferring to Figure 6). One possible reason for this large deflection is that several parameters decrease the performance of the tubular linear servo motor such as damaged coil system, magnets not in the right position, air gap between magnets changed and abrupt change in the current which applies excessive stress to the coil system. For the purpose of safety, the maximum allowable current had been set to 95 A to avoid over current problem in the testing (Figure 6).

Nominal position (µm)	Actual position (µm)
24000	23740
24250	23880
24400	23935

Figure 7: Position error of press ram under loaded condition; Left: nominal and actual position records also from other tests; Right: comparison of formed part for higher ram travel than the elastic deflection test

3.2 Guiding error (off-center loading)

The connecting rod applies a total force at the center of the upper tool plate (Front view) where the forming forces are applied at a distance of 10 mm away from the center, as can be seen in Figure 8. In the previous section, it was shown that the controller output measures the displacement of the linear motor's piston rod while the interferometer gives the position of the upper tool plate's side (Figure 8). To examine guiding accuracy, the variation between the two measurement methods was used for positioning error at the same loading condition. This information are listed in Table 1.

As can be seen, the table shows 9 µm deviation under unloaded condition for both measuring points. It was previously mentioned that the measurements at unloaded condition establishes the clearance of the guiding system. The results also was confirmed by the manufacturer's specifications. The total play of a two-pillar die set when using guide bearings for 20 mm pillar's diameter is expected to be in the range of 4-11 µm (according to the manufacturer) .

Likewise, under loaded condition, an increase to 25.7 µm in the overall deviation of measurements is observed due to the tilting effect and rod's elastic deflection (Assuming the layout of positioning sensors shown in Figure 8). FEA (not shown) also predicted 11 µm elastic deflection for the connectiong rod under 5 kN. Therfore, the pure deviation due to the tilting effect results in 14.7 µm. When assuming a linear deviation from zero at the center to 14.7 µm at the measuring point of interferometer, the deviation of 1.5 µm can be estimated at the distance 10 mm away from the center where 4 kN is applied for the total length 196 mm of the upper tool plate. While slight position deviation was noted due to the tilting effect, this variation was deemed negligible for the purpose of this research.

To reduce the effect of off-center loading and ram tilting in a multi-stage forming operation, the center of loading of the upper tool plate, i.e., the point where the resultant total forming load vector of all forming operations is applied, must be moved to the center of loading of the main slide (Linear motor's connecting rod). Another solution is to change the shape of cross section of the connecting rod from a cricle to rectangle.

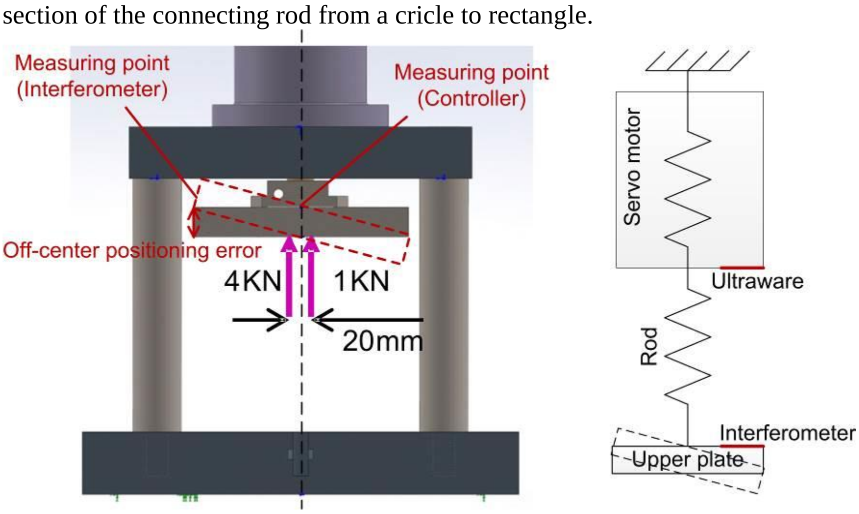


Figure 8: Measuring points on upper plate and linear servo motor for displacement

4 Conclusion

The paper introduces an analysis of the positioning precision of the machine tool with respect to the drive mechanism and frame structure for micro cold forging.

The proposed method includes the analysis of the tilting effect due to the off-center loading as well as exploration of the elastic deflection induced by the forming force. The machine tool is analyzed using loaded and unloaded conditions for one complete cycle of the main slide. The tests under unloaded condition showes 10 µm clearance in the guiding system and parallelism of the upper and lower plates. The analysis under loaded condition illustrates the tilting effect and elastic deflection. A notable elastic deflection error is observed at the bottom dead center due to the forming force when a deviation of 15 µm occurres at the side edge of the upper plate due to the tilting effect.

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