# 세라믹 인서트를 이용한 단조 금형설계

권 혁 홍*

# Forging Die Design using Ceramic Insert

Hyuk-Hong Kwon*

Abstract

The use of ceramic inserts in steel forging tools offers significant technical and economic advantages over other materials of manufacture. These potential benefits can however only be realised by optimal design of the tools so that the ceramic inserts are not subjected to stresses that lead to their premature failure. In this paper the data on the loading of the tools is determined from a commercial forging simulation package as the contact stress distribution on the die-workpiece interface and as temperature distributions in the die. This data can be processed as load input data for a finite-element die-stress analysis. Process simulation and stress analysis are thus combined during the design, and a data exchange program has been developed that enables optimal design of the dies taking into account the elastic deflections generated in shrink fitting the die inserts and that caused by the stresses generated in the forging process. The stress analysis of the dies is used to determine the stress conditions on the ceramic insert by considering contact and interference effects under both mechanical and thermal loads. Simulation results have been validated as a result of experimental investigations. Laboratory tests on ceramic insert dies have verified the superior performance of the Zirconia and Silicon Nitride ceramic insert in order to prolong maintenance life.

**Key Words :** Forging, Die Design, Ceramic Insert

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# 1. INTRODUCTION

As the demands made upon hot and warm forging and extrusion tooling to perform to new levels of productivity continues to grow, the challenge to engineers, and material scientists alike calls for a new approach. Until now, hot working tool steels have been the only cost effective die material option. Recently, the use of ceramic materials as functional materials has increased rapidly in a wide field of industry, since they have many excellent technical properties such as high hardness, high corrosive resistance, high elastic modulus, etc. Clearly they are going to be used increasingly in many engineering fields.[1-2]

Near net shape forging technologies offer the possibilities to produce parts with good mechanical and technological properties combined with economical benefits. To realise precision forging processes of parts, with their demands on the accuracy, some important requirements must be fulfilled. Computer aided design of the tools, especially of the forming dies, FEM simulation of the forging process to determine shrinkage effects and mechanical stresses in the tool system, an exact adjustment of the main influence parameters, and finally the high accuracy of the forging tools.[3] The use of ceramic inserts in steel forging tools offers significant technical and economic advantages over other materials of manufacture. This arises largely due to the very high wear resistance of certain ceramic materials. These potential benefits can however only be realised by optimal design of the tools so that the ceramic inserts are not subjected to stresses which lead to their premature failure. This is now possible since reliable information on the loading conditions in forging tools can now be obtained from process simulation. In some cases dieAs the demands made upon hot and warm forging and extrusion tooling to perform to new levels of productivity continues to grow, the challenge to engineers, and material scientists alike calls for a new approach. Until now, hot working tool steels have been the only cost effective die material option. Recently, the use of ceramic materials as functional materials has increased rapidly in a wide field of industry, since they have many excellent technical properties such as high hardness, high corrosive resistance, high elastic modulus, etc. Clearly they are going to be used increasingly in many engineering fields.[1-4]

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The use of ceramic inserts in steel forging tools offers significant technical and economic advantages over other materials of manufacture. This arises largely due to the very high wear resistance of certain ceramic materials. These potential benefits can however only be realised by optimal design of the tools so that the ceramic inserts are not subjected to stresses which lead to their premature failure. This is now possible since reliable information on the loading conditions in forging tools can now be obtained from process simulation. In some cases die stress calculations can be coupled with the plastic flow analysis. Currently this approach can lead to excessive computing times and has not therefore been adopted in the work described here.

In this paper the data on the loading of the tools is determined from a commercial forging simulation package as the contact stress distribution on the die-workpiece interface and as temperature distributions in the die. This data can be processed as load input data for a finite-element die-stress analysis. Process simulation and stress analysis are thus combined during the design, and a data exchange program has been developed that enables optimal design of the dies taking into account the elastic deflections generated in shrink fitting the die inserts and those caused by the stresses generated in the forging process. The stress analysis of the dies is carried out to determine the stress conditions on the ceramic insert by considering contact and interference effects under both mechanical and thermal loads.

An example is given of the application of this methodology and subsequent experiment trials for the optimal design of a ceramic punch insert in a simple forging configuration.

## 2. FORGING DIE DESIGN

Process simulation is now being used routinely in many parts of the forging industry.[6,7] It not only provides information on material flow, die fill and defect formation, but also very detailed information on the contact stress distribution at the die-workpiece interface. The contact stress distributions are far from being uniform in the tooling, an assumption often made in tool stress analysis. But, by combining process simulation and tool stress analysis, more exact stress data can be obtained, and possible failure due to high localised loads in the tooling can be identified and avoided through modifications in the design before the tooling is produced. The general methodology for optimising the design ceramic inserts for forging tools which was taken is shown in Figure 1 and is as follows:

- Process simulation to determine the loads during a forging cycle and the appropriate contact stress distribution at the die workpiece interface. The process simulation software DEFORM-HT was used for the analysis.
- The exchange of data between the different programs is necessary. Reliable information on the loading conditions of a die can only be obtained from process simulation and is given as the contact stress distribution at the die-workpiece interface and as temperature distribution in the die. This data can then be processed as load input data for a die stress analysis. The post-processing of DEFORM-HT results and use of data exchange program of die temperature and contact stress distribution. Preparation of stress analysis in ANSYS by reading in the universal files created by the data exchange program and adding boundary conditions and material data to the models.
- Stress analysis of the tooling using the previously determined contact stress distribution as load input data. ANSYS was used for this task.

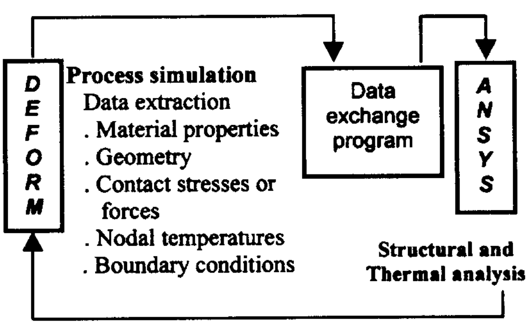



**Fig. 1 Methodology for optimising the design of the ceramic inserts**

### 2.1 Process simulation of forging tools

For non-isothermal processes, such as hot forging, two types of analysis are coupled as follows:

- Large plastic deformation analysis assuming rigid-viscoplastic material behaviour and rigid dies (line and arc representation of dies),
- Transient heat transfer analysis including heat generation in the workpiece due to deformation, and heat flux into the dies (meshed dies).

To demonstrate the applicability of this technique it was applied to the optimal design of a ceramic punch insert in a simple forging configuration as shown in Figure 2. Experimental trials were also performed.

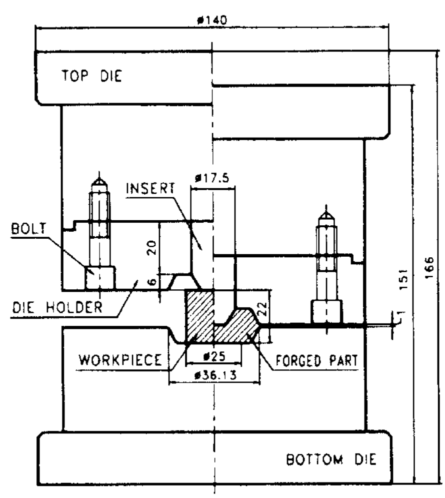



**Fig. 2 Schematic of the forging process and tooling system used in the laboratory tests (units: mm)**

The process conditions of the non-isothermal forging simulation with rigid dies and a rigid-viscoplastic workpiece were as follows: The velocity of the upper die was taken to be 21, friction factor was taken to be 0.3, the initial temperature of the workpiece and the die used in non-isothermal forging simulation were taken to be 1073K and 473K, respectively.

The size of workpiece in this model was 25 in diameter and 22 in height. The mechanical and thermophysical properties are shown in Table 1 and Figure 3. The flow stress and thermophysical properties of AISI 1043 are retrieved from the DEFORM-HT material database and are a function of temperature, strain and strain rate.

**Table 1 Material input data used in the analysis**

| | Dies | Ceramic insert | |
|---|---|---|---|
| Material | H13 | $ZrO_2$ | $Si_3N_4$ |
| Young modulus (GPa) | 190 | 205 | 290 |
| Poisson ratio | 0.3 | 0.31 | 0.24 |
| Thermal conductivity ($N \cdot s^{-1}K^{-1}$) | 28.6 | 2.5 | 25 |
| Heat capacity ($N \cdot mm^{-2}K^{-1}$) | 3.588 | 4 | 8 |
| Emissivity ($N \cdot s^{-1}mm^{-1}K^{-4}$) | 0.7 | 0.7 | 0.7 |
| Interface heat transfer coefficient ($N \cdot s^{-1}mm^{-1}K^{-1}$) | 27.5 | 7.6 | 7.6 |

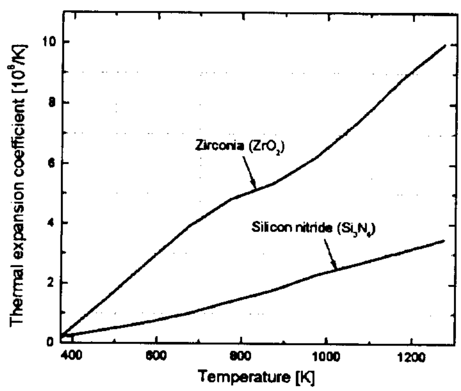



**Fig. 3 Thermal expansion coefficient of ceramic inserts**

The operation steps are shown in Figure 4, which shows the variation of metal flow lines with die stroke. Note that there is no under filling defect in the final product, and Figure 5 shows the deformed shape of workpiece and metal flow lines for both the analysis and experiment at die penetration 15mm.

Temperature gradients of the dies and workpiece are shown in Figure 6. Thermal expansion due to local temperature gradients introduces some stresses. The plastic deformation which is localised near the nose of insert is transformed into heat. The maximum temperature of the die is

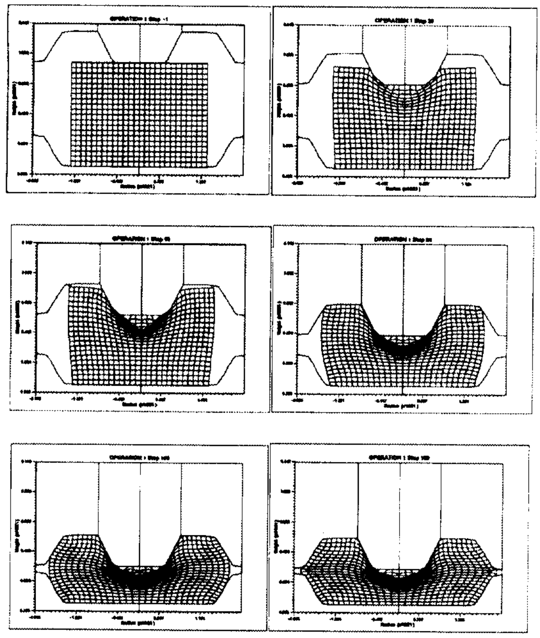


**Fig. 4 Visualisation of metal flow lines of the process**

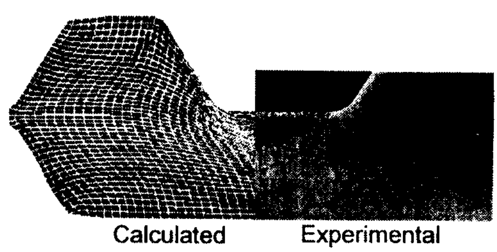


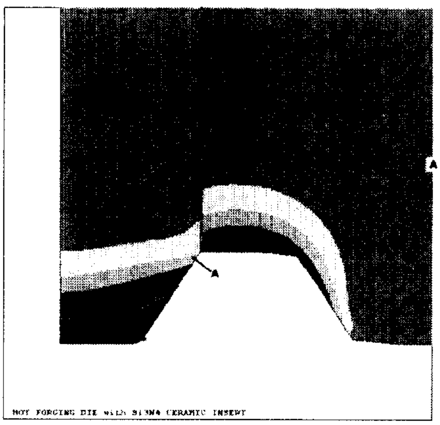

**Fig. 5 The material flow pattern from analysis and experiment (die penetration=15mm)**

located near the insert nose because in this region the contact time is long and the temperature of the workpiece is very high.

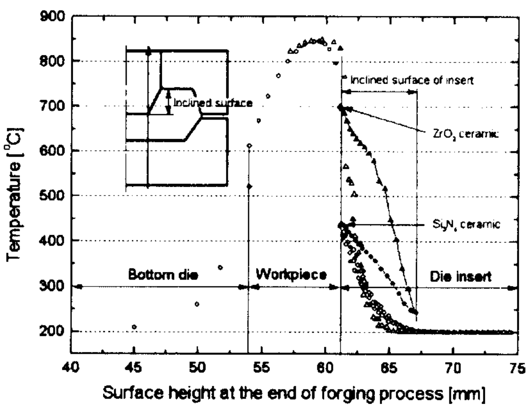
### 2.2 Structural and thermal analysis

In forging die design, pre-stressing is useful in preventing excessive tensile hoop stresses which may cause die failure during metal forming.[8-9] It is therefore necessary to determine accurately the interference value between the die insert and die holder for pre-stressing. Also, the thermal stress analysis is focused on the insert. The mechanical and thermal stresses are calculated with ANSYS software by modelling the interference using contact elements between insert and die holder. Figure 7 shows hoop stress distribution each of ceramic-insert under the mechanical and thermal load with interference value 0.1 mm/dia.. For a thermal analysis, transient heat transfer analysis is performed based on temperature-time profiles during forging being derived from the process simulation.

The von Mises stress distributions on the Zirconia insert under mechanical and thermal loads with different interference values (0.1 and 0.04mm/dia.) were analysed by ANSYS and are shown in Figure 8. The stresses are compressive on the inclined surface of the insert and the ther-

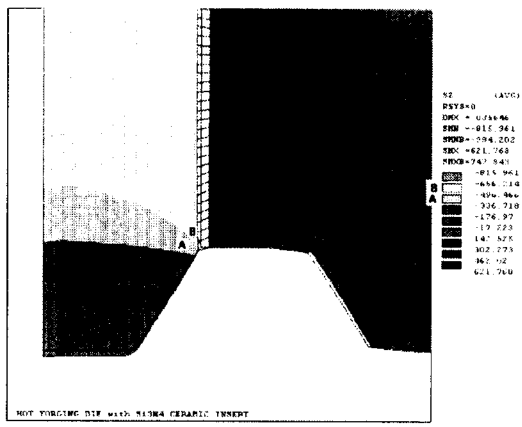


(a) Temperature distribution of theceramic-insert die after forging

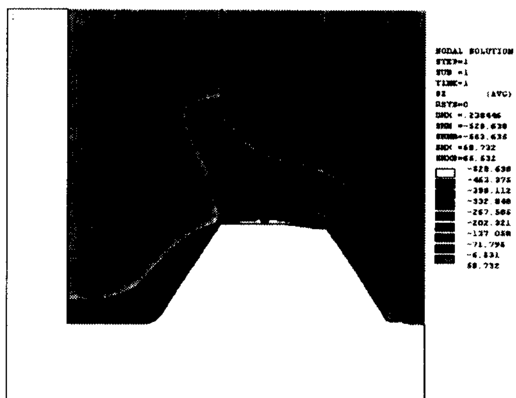



(b) Temperature distribution of die and workpiece

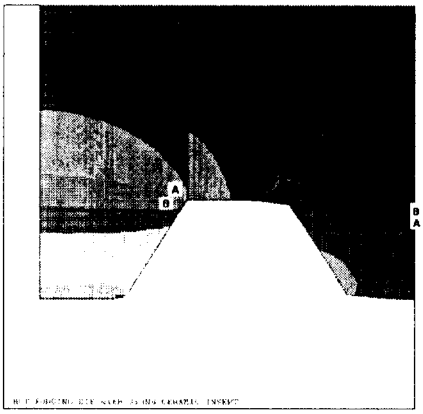
**Fig. 6 Temperature gradients in the die and workpiece at the end of forging process**



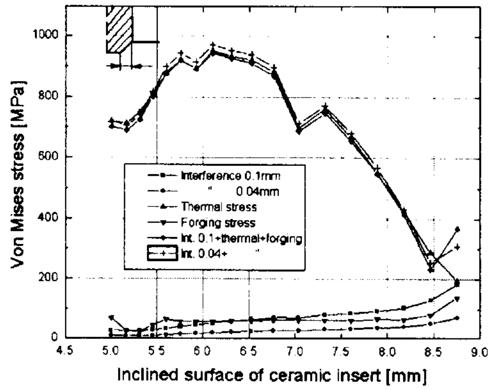
(a) Hoop stress distribution with shrink fit only



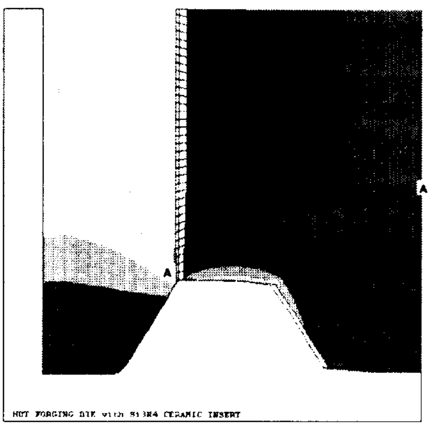
(b) Hoop stress distribution with thermal load only



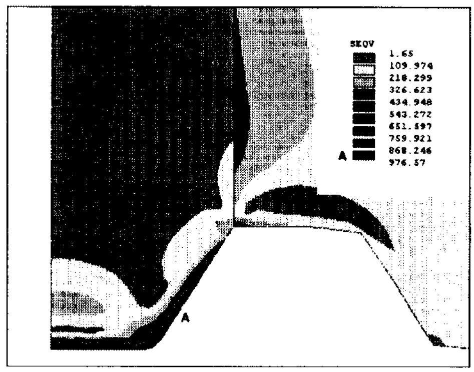
(c) Hoop stress distribution with forging load only




(a) Von Mises stress

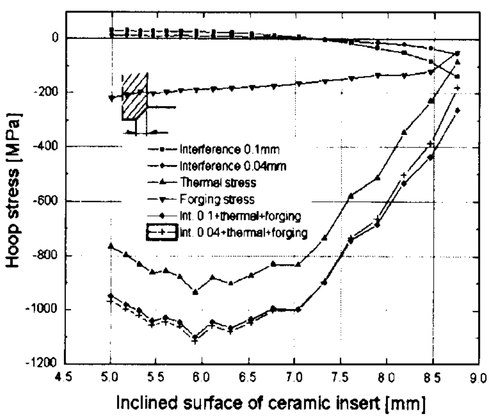


(d) Hoop stress distribution of total load



(b) Von Mises stress distributions under the mechanical -and thermal loads with interference value 0.04mm

**Fig. 7 Hoop stress distribution each of ceramic-insert under the mechanical and thermal load with interference value 0.1 mm/dia**

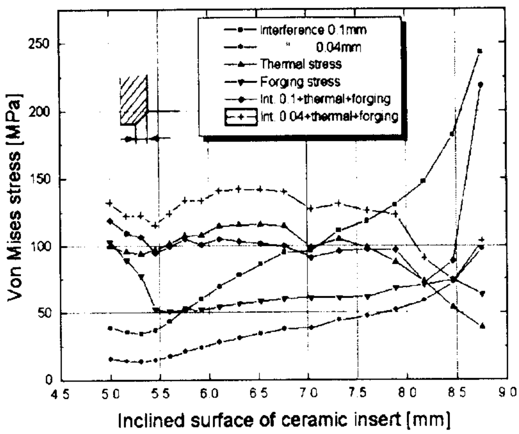



(c) Hoop stress

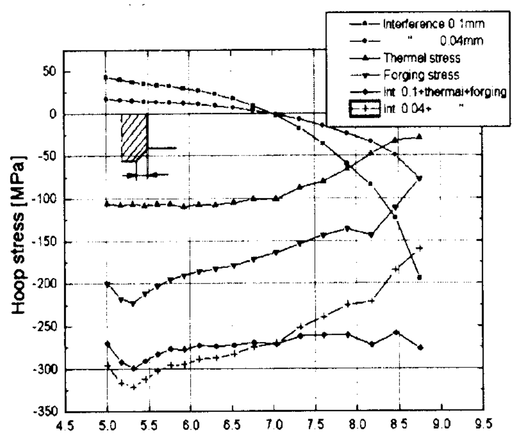
**Fig. 8 Von Mises and hoop stresses on the Zirconia insert due to mechanical and thermal loads**

mal stresses are as high as the total stresses in the inclined areas of the insert. The maximum equivalent stress reaches a value of 977MPa at the point A.

Figure 9(a) shows von Mises stress distributions of the Silicon Nitride insert, which the peak of von Mises stress is smaller than the flexural strength in the insert case with interference value 0.1mm. Figure 9(b) shows hoop stresses under the mechanical and thermal loads on the Silicon Nitride insert. The hoop stresses are largely compressive, with a small tensile value in the central region of the insert.




(a) Von Mises stress




(b) Hoop stress

**Fig. 9 Von Mises and hoop stresses on the Silicon Nitride insert due to mechanical and thermal loads**

This does not however exceed the flexural stress 450MPa (at 1073K) or the maximum compressive stress 2000MPa of the Silicon Nitride. Ceramic inserts have very high compressive stress capabilities, but low tensile stress and low thermal shock capabilities. These aspects have to be accommodated in the design of the insert.

## 3. EXPERIMENTAL INVESTIGATIONS

The forging dies were made from H13 tool steel and hardened and tempered to HRC 55-56, the tool was preheated up to 723K and pre-stressed by shrink fitting with two different interference values. Forging tests conducted in the laboratory have verified this assessment on a RHODES 1000 kN hydraulic press were shown in Figure 10.

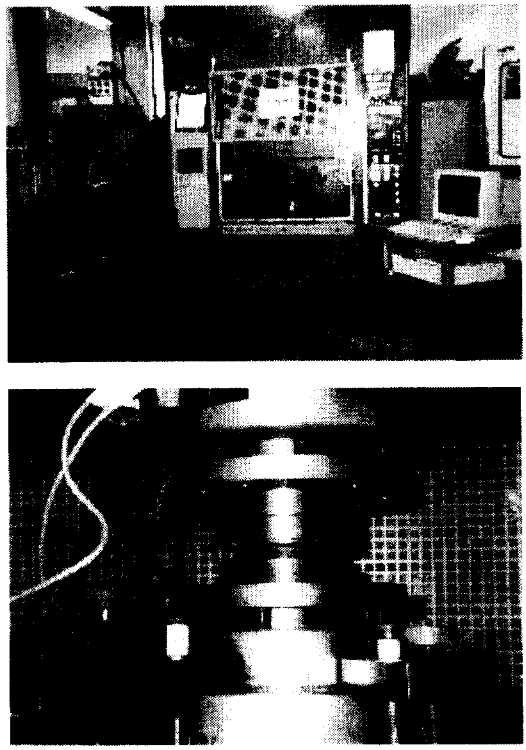
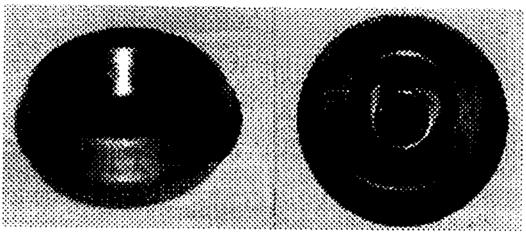


**Fig. 10 Tooling system used in the laboratory tests**

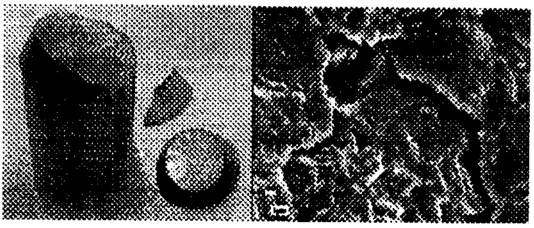
Ceramic inserts accept a high polish and provide excellent surface finish to the forged part as shown in Figure 11(a). Figure 11(b) shows the fractured pieces and scanning electron microscope of the Zirconia insert with interference 0.04mm after 50 forging strokes.

The location of the fracture is consistent with the point of maximum equivalent stress, point A in Figure 8(b). This exceeds the flexural stress 354MPa (at 1073K), but does not exceed the maximum compressive stress 1700MPa of Zirconia. Silicon Nitride insert dies survived more than 30 forges per die without showing excessive wear or improper finish to the forged product.

EDS(Energy Dispersive X-ray Spectrometer, Model:



(a) Forged part



(b) Fractured pieces and SEM of Zirconia insert

Fig. 11 Photos of the forged part and Fractured pieces and SEM of Zirconia insert

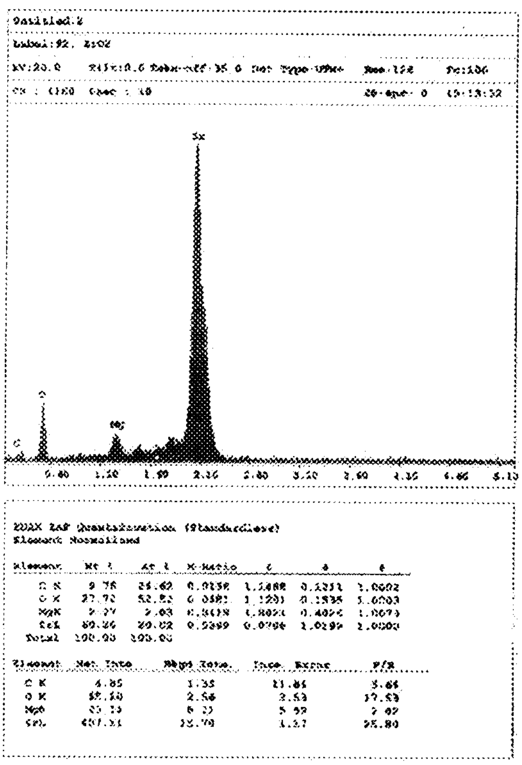


Fig. 12 The EDS of of Zirconia ceramic insert

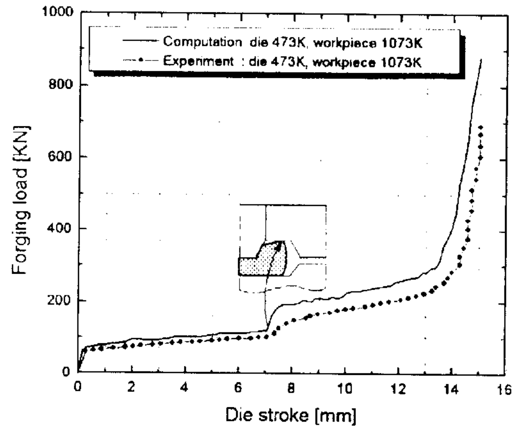



Fig. 13 The comparison of computer simulations with experiments in load-stroke curves(workpiece:BS 080M4

EDAX Falcon Imaging system 60 SEM) of the Zirconia ceramic insert composes chemical composition Zr 60.26 wt%, Oxigen 27.72 wt% etc. was shown in Figure 12.

Figure 13 represents the load-stroke curves obtained from the simulation and the experiments. In both the simulation and the experiment, the forging loads of the simulation are slightly higher load than those of the experiment until material flow reaches the upper part of the die but two curves are good agreement.

## 4. CONCLUSION

This paper described a computer aided die design procedure for incorporating ceramic inserts in hot forging tools. Forging simulation results provided useful information such as metal flow, temperature distribution, stress state etc. A linked elastic analysis of the dies was carried out to obtain the stress state of the ceramic insert. In the die stress analysis, thermal effects and the shape of the loading pressure were found to be very important. The analysis also incorporated the mechanical loads due to shrink fitting and thermal loads from the forging process. The use of shrink fitting in assembling the die and holder can provide substantial residual compression, which adds to the inherent strength of the insert and permits the ceramic insert die to withstand forging stresses.

Laboratory tests on ceramic insert dies have indicated the potentially superior performance of the Zirconia and Silicon Nitride ceramic insert in order to prolong maintenance life. Low wear and dimensional stability of ceramic insert result in forged product with good dimensional control and obviate the necessity for frequent refinishing, thereby minimising downtime and increasing the efficiency of forging operation.

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