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Advanced Metalworking using **Electro-machin** able Ceramic Extrusion Dies.

Synthesis Report

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Housing of Ceramic Die Inserts for Aluminium Extrusion

by

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ABSTRACT

This work was undertaken as an European Union programme and aims at greater utilisation of ceramic extrusion dies, to take advantage of their potential for long maintenance free life and production of good surface finish. However more extensive use of ceramics is handicapped because of machining difficulties and the low toughness of these materials.

As part of this programme electro-conductive silicon nitride and zirconia have been developed facilitating die manufacture using EDM methods.

Stress concentration at aperture corners during extrusion can lead to failure by cracking. Finite Element simulations show that this problem can be overcome by applying pressure to the outside of the insert producing a compressive stress concentration at corners of the aperture to offset the tensile stress due to extrusion pressure which would otherwise cause cracks. External pressure on an insert is produced by shrink-fitting. Problems with this process have been identified and addressed. These include the loss of shrunk-in stress at the operating temperature of the die and the development of unfavorable stresses which can cause peripheral cracking.

Thermo-mechanical simulations of stress by Finite Element methods have been used to optimise design. Extrusion trials verify that these results can be employed to enable more complex shapes to be extruded.

INTRODUCTION

A material possessing exceptional wear resistance and low affinity for aluminium would be the ideal choice for aluminium extrusion dies Such materials are generally ceramic in nature, are difficult to machine and have low toughness. Nevertheless, engineering ceramics such as zirconia, silicon nitride and sialon have been used for many years for extrusion dies. Their application has been limited to products of circular section because of machinability and brittleness problems.

The present project, partly funded by the European Union, has the objective of extending the benefits of ceramic application to dies of more complex shape. Ten companies have cooperated in this programme including two aluminium extruders.

In recent years, ceramic manufacturers have endeavored to produce electro-machinable ceramics (partly under this project) by introducing very fine electrical y conducting phases into the structure of the material. Some success has been achieved and there are now a number of materials which can be electro-machined as easily as steel with excellent surface finish,

The main problem remains that of preventing cracking in ceramic dies particularly at points of stress concentration such as the corners of apertures. Although ceramics are comparatively weak in tension they have exceptional strength when stressed in compression. Advantage can be taken of this property by pre-compressing the ceramic inserts in a steel housing so that even under working conditions the stress remains compressive or is only slightly tensile.

CERAMIC MATERIALS FOR DIES

Ceramic Properties

Engineering ceramics such as zirconia, silicon nitride, sialon and alumina have been tested as tooling in the extrusion industry for over twenty years, In some applications such as circular sections and tube, ceramics have been adopted by some companies, however for other types of section, failures occur, often due to cracking at corners.

Table 1 Ceramic Properties

Property	Unit	ZrO_2 (Mg stabilized)	Si_3N_4 (electrically insulating)	Si_3N_4 (electrically conducting)	WC-9%Co	AISI H13 hot-work steel
Density	K m^{-3}	5730	3200	3950	13500	7800
Elastic Modulus	GPa	205	315	290	600	190
Poisson ratio		.31	.27	.23	.25	.29
Coefficient of Expansion	K^{-1} x 10^{-}b	10	3.3	6	5	12
Thermal Conductivity	W m^{-1} K^{-1}	2	19	33	50	25
Bend Strength	MPa	700	800	800	2700	1400*
Compressive Strength	MPa	2000	6000	2000	4000	1400

* Tensile yield strength

Available ceramic materials have a range of properties as illustrated in Table 1 and materials with quite different physical properties can be used successfully as dies. For example zirconia, a good thermal insulator, has a coefficient of expansion similar to steel. In contrast, silicon nitride has a similar conductivity to steel but has a low expansion coefficient, Despite these dissimilarities both materials are used for extrusion dies. The coefficient of thermal expansion in relation to steel is important for shrink-fitting, since ceramics generally expand less than steel as the die temperature is raised. The decrease in the insert/housing interference reduces the beneficial external pressure on the insert. From this point of view, zirconia has an advantage over silicon nitride as its expansion coefficient is better matched to steel.

For applications where transient thermal stresses are large such as in the extrusion of heavy metals the thermal shock resistance of silicon nitride is an advantage,

Electro - Discharge Machinability

Electrically conducting versions of silicon nitride and zirconia have been under development as part of this programme. However because of fabrication problems, the zirconia material is not currently being tested, though trials of its electro-machinability were promising.

The EDM performance of the silicon nitride material has been tested extensively on a Charmille Roboform 200 machine. Cutting rates were similar to those for steel. For finishing cuts, good surface quality was achieved with roughness values as low as 1.1 μm Ra at coverage rates between 85 and 280 $mrn^2 min^{-1}$.

STRESS IN EXTRUSION DIES

Previous Work

Gulati et al '[17]2) have investigated stress in zirconia dies housed in steel using Finite Element (FE) modelling. Shrink fitting pressure, extrusion pressure, thermal stress and transformation volume change were considered and it was found that some features of failures could be predicted. Lange '[3] investigated stress distribution in zirconia dies used for backward extrusion of cans and found a high axial stress in the bore of the ceramic at the end of the billet due to a step change in pressure at this position. Neitzer'[4] studied multi-component dies by Finite Element (FE), investigating levels of interference between insert and housing as high as 40 $^0/_{00}$ which caused partial yielding of the housing. Optimum designs were determined, however thermal stress was not considered, In the foregoing papers, no mention is made of the use of a yield criterion appropriate for a ceramic material.

Mechanical Stress

Under working conditions, the main component of stress in a die is a tensile circumferential (hoop) stress, caused by expansion of the die aperture under the action of the extrusion pressure acting on the bearing surface. At the corner of an aperture, this stress is amplified considerably. The die bearing is also subject to a shearing stress due to extrusion pressure on the front of the die and friction at the bearing surface. This component increases where a 'tongue' is present in the profile.

A compressive hoop stress is set up when a ceramic insert is shrunk into a steel housing and this counteracts the tensile hoop stress due to working pressure. Hence by suitable choice of the amount of interference between insert and housing, the tensile stress due to working pressure can be compensated.

Thermal Stress

The die bearing surface is normally hotter than the body of the die due to the heat generated in the extruding metal. This causes thermal stress, which is compressive at the surface and tensile in the interior of the material. The magnitude of this stress depends principally on the temperature gradient and is inversely proportional to the thermal conductivity of the ceramic. For aluminium extrusion, the tooling is maintained at a temperature relatively close to that of the aluminium, hence the temperature gradient is generally not as large as in the extrusion of heavy metals. When sudden changes in temperature occur, thermal shock resistance becomes important and this property is better for silicon nitride than for zirconia. However this parameter is not as important for aluminium as it is for heavy metal extrusion where temperature transients are more severe.

Effective Stress

At any point in the die, the complex stress due to all of the above effects can be represented by a matrix characterizing uniaxial and shear components of stress. These components can be combined to form a single effective stress and this can be compared to a characteristic failure stress for the material.

The way in which the stress components are combined depends upon the failure criterion employed. Conventionally, for metallic materials the Von Mises failure criterion is used. This assumes equality of compressive and tensile yield strength and independence from the effect of hydrostatic pressure. Such a criterion is not appropriate for a ceramic whose compressive strength is much larger than its tensile strength and whose strength improves with increasing hydrostatic pressure, A failure criterion appropriate for such materials, called the Mohr-Coulomb criterion has been used in this work. This is used elsewhere for modelling work in areas such as civil engineering and rock mechanics. Data is available for silicon nitride and alumina stressed in a biaxial mode in compression and/or tension(7). It was found that the two-dimensional yield locus determined from the Mohr-Coulomb criterion agrees well with experimentally determined boundaries for these two materials.

RESULTS OF STRESS CALCULATION

Thermo-mechanical stress calculations were performed using FE programmed developed at the University of Swansea[5,6] An appropriate mesh was first of all generated allowing the temperature distribution to be calculated, which is then input to the stress programme using appropriate boundary pressures and constraints. The output is in the form of stress and strain components and effective stress at each nodal point of the mesh. The illustrations in this paper are of effective (Mohr Coloumb) stress.

Stress Concentration at Corners

One of the primary aims has been to investigate, the stress concentration at the corners of an aperture.

The dies considered were pre-compressed into steel housings using various degrees of interference and the effect of this pre-compression in alleviating tensile stress concentrations was investigated. For example in Figure 1, it is seen that increasing the interference from O to $4\ ^0/_{00}$ (parts per thousand) decreased the effective stress at a 2 mm corner from 1380 MPa (tensile) to 120 MPa (compressive). The effect of curvature is quite marked, for example by decreasing the radius from 3 mm to 0.5 mm at the same interference level, the stress is increased from 180 MPa to 660 MPa, Figure 2.

Stress in more complex sections follows a similar trend. For example in a channel section, Figure 3, stress concentrations occur at external corners though at internal corners there is no stress.

Generalization of Stress Concentration

A generalized formula for the maximum effective stress has been derived from these studies of simple sections. It is found that the stress concentration at a corner (tensile due to working pressures p_0 and the compressive due to shrink-fitting pressure p_E), can be combined in the following form:

$$\sigma_\theta = \alpha p_0 - \beta p_E \qquad \textbf{(1.)}$$

Where α and β are coefficients appropriate for internal and external pressure respectively and are given by the empirical relationships derived from the FE results:

$$\alpha = 1.44\left[\frac{r_0}{r}\right]^{0.47}\alpha_0 \qquad \textbf{(2.)}$$

$$\beta = 1.01\left[\frac{r_0}{r}\right]^{0.39}\beta_0 \qquad (3.)$$

The values of α_0 and β_0 are simple functions of external and internal die dimensions. The length **r. is** the distance of the corner from the geometric centre of the die and **r** is the radius of curvature of the corner itself Relationships (2.) and (3.) are found to hold for a range of shapes including square, rectangular and channel section apertures.

Equation (1.) can be used to define boundaries between safe and fail conditions as illustrated in Figure 4, in a diagram of internal versus external pressure. The fail/safe boundaries shift with the degree of curvature at the comer, reflecting the increasing risk of failure with decreasing radius. In general, it is found that the required external pressure is less than the internal pressure needing compensation.

Effect of Temperature

The interference between insert and housing determines the external pressure on the insert. To achieve a pressure of 200 MPa approximately 2.8 $^0/_{00}$ interference is required. However at the operating temperature of the die the interference is reduced considerably due to differential thermal expansion. For example for a die operating at 400° C with a thermal expansion coefficient difference of 6 x 10^{-6} K^{-1}, the interference would be reduced by 2.3 $^0/_{00}$. Shrink-fitting involves placing the insert into a pre-heated steel housing and allowing the assembly to cool. However there is a limit on pre-heating temperature to which the hardened steel can be subjected due to the possibilities of softening and oxidation of its surface It is not feasible therefore to achieve a room temperature interference of much more than 4.0 $^0/_{00}$ by shrink-fitting, though higher values could possibly be obtained by press fitting. Hence at an operating temperature of 400° C, the maximum interference is restricted to about 1.7 $^{0}/_{00}$, equivalent to an external pressure of about 120 MPa.

Temperature gradients caused by heat input from the product and loss to the support tooling will cause additional stress which can be significant.

Two Stage Shrink-Fitting

Higher external pressures are needed to prevent cracking at sharp corners. This can be achieved by two stage shrink-fitting using an intermediate ring (shrink-ring). A promising development of this approach is to use a tungsten carbide shrink-ring. As can be seen from Table 1, Tungsten carbide has a similar thermal expansion coefficient to conducting silicon nitride and also has a very high elastic modulus. Because of these two factors, a modest degree of interference (-1.5 $^{0}/_{00}$) is sufficient to provide the required external pressure and more importantly, this is not diminished by differential thermal expansion at the working temperature of the die.

Stress Calculation in Multi-Component Dies

To help to arrive at an appropriate design, algorithms have been developed to calculate the stress distribution in two or three-piece dies, in which each part is made from a different material. The following components are calculated:

- Shrink-fit stress
- Stress due to extrusion pressure
- Stress concentration at corners
- Thermal stress due to temperature gradients in the die

As an example the stresses for a three-piece die subject to an extrusion pressure of 300 MPa shown in Figure 5 A & B. In A the temperature is isothermal across the die, however in B there is a radial temperature difference of 200° C and the stress distribution is modified due to thermal stress.

The elastic part of this model has been checked by measuring the strain distribution produced by two stage shrink-fitting of a silicon nitride insert into a tungsten-carbide shrink-ring and a steel housing, Figure 6. Strain was determined using a traveling microscope to measure distances between hardness indentations or component edges before and after assembly. The correlation with calculated strain values is seen to be within the accuracy of strain measurement.

Peripheral Cracking

Planar cracks have been observed frequently circumscribing the bearing surface of the die after shrink-fitting, Figure 7. These cracks initiate at the bearing surface and propagate perpendicular to that surface implying the existence of a tensile stress parallel to the die axis. They can be seen only after EDM and polishing of the die aperture, but their morphology suggests that they existed prior to these operations. FE modelling show that such a stress does indeed exists due to friction at the insert/ housing interface. As the housing cools after shrink-fitting, it contracts axially as well as radially and this displacement is transmitted by friction to the outside of the ceramic insert compressing it in the axial direction. Relaxation of this compressive constraint towards the interior of the insert results in tensile stress which reaches a maximum at the centre of the bearing surface, Figure 8

During extrusion an axial compressive stress is imposed and this offsets the shrunk-in stress, Hence these peripheral cracks are fairly stable during subsequent die use, but eventually small chips come away, as seen in Figure 9, rendering the surface appearance of the product unacceptable.

The incidence of peripheral cracking has been lessened by lubrication of the housing/insert interface before shrink-fitting. Also, the use of thinner inserts and a tungsten carbide shrink-rings help to reduce the problem. It is envisaged that a combination of these techniques can eliminate the cracking altogether.

EXPERIMENTAL EXTRUSION TRIALS

Experimental Details

Extrusion trials of conducting silicon nitride die material were carried out on a **5 MN (500** ton) vertical press at AEA Technology using an 80 mm (3,1 in) container and 6063 aluminium billets. The shape chosen was a 14 mm (O. 55 in) square with different radii at each corner. These radii were 3, 1.5, 1, and 0.75 mm. (O. 12, 0.06, 0.04 and 0.03 in). The bearing length was 17 mm (O. 67 in). Apertures were cut by wire EDM after shrink-fitting and the bearing surface was polished by the EXTRUDE HONE process.

The main results are summarized in Table 2. All four dies had peripheral cracks initially and these acted as sites for chipping during subsequent extrusions, Figure 9. In die 3, the carbide shrink-ring cracked during extrusion of the first billet at a calculated tensile hoop-stress of 700 MPa. This lowered considerably the pressure on the insert as seen in column 4 of Table 2. Radial cracking at corners was only observed in the later part of trials and was delayed for longer in dies 1 & 4 having higher external pressure. This suggests that a low cycle fatigue mechanism may be involved and the incidence of cracking is more when exposure to tensile stress during extrusion, is greater. Flaking from the plane parts of the bearing surface was a more serious problem occurring early in the trials of dies 2 & 3. However as flaking was less prevalent in dies 1 & 4 than 2&3, this suggests that external pressure on the insert is beneficial in suppressing this mode of failure.

Table 2 Extrusion Trials of Conducting Silicon Nitride with Square Apertures.

Die No	Shrink-ring Material	Shrink-fit (‰)	External Pressure on Insert* (MPa)	Billets Extruded	Comments
1	steel	3.4 + 3.0	254	15	Comer cracking after 10 extrusions at radii 0,75 & 1 mm. Chipping from peripheral cracks.
2	steel	2.3 + 2.0	146	3	Flaking from faces of aperture after first extrusion.
3	WC-9%C	2.3 + 4.3	167**	5	Tungsten-carbide shrink-ring failed due to excessive tensile hoop stress causing comer cracking in the ceramic.
4	WC-9%C	1.1 +4.9	286	10	Comer cracking after 10 extrusions.

* Calculated for 500° C product temperature and 300° C external housing temperature.

** Shrink-ring failed, hence the pressure calculation assumes that its hoop stress was zero.

Investigation of Elastic Strain Relaxation in the Housing

The shrink-ring and housing materials are subject to conditions which could lead to creep whilst in the pre-heating oven and under operating conditions leading to relaxation of the elastic stress which maintains pressure on the ceramic insert.

The strain distribution before the extrusion trials was measured as described above. After the trials, the faces of the die components were again marked with hardness indentations and their separation measured accurately with a traveling microscope. The housing and shrink-ring were then cut to release the internal components. After removal, the indentation separations were re-measured and the strain distribution calculated again.

Figure 10 shows strains measured before and after extrusion for die 1. Before the trial there is fair agreement between measurement and calculation strain. However, measurements made after the trials show that the strain in the steel shrink-ring had changed from tensile to slightly compressive, though the tensile strain in the housing remained the same as before.

In this case, it is believed that damage to the ceramic insert was responsible for the strain relaxation in the shrink-ring and it was concluded that there was no appreciable creep of the shrink-ring or housing (made from QRO90 steel) during the trials. Hardness measurements confirmed that no softening of these components had occurred

SUMMARY

Experimental trials have shown that electro-machinable ceramic dies with non-circular apertures can be used for aluminium extrusion. Although the dies tested in trials reported here had limited life, more recent trials ondies having much shorter bearing lengths have been more promising and these have been used to extrude 20 billets without sign of deterioration so far. Methods of housing inserts to minimize their exposure to tensile stress have been developed and these findings could have wider application with benefit to other insert materials such as cemented carbides metal-matrix composites and other materials with limited toughness. More detailed results are summarized below:

- Silicon nitride and zirconia base ceramics having electro-discharge machining properties similar to those of steel have been prepared.
- Finite element simulations show that stress concentration at corners of apertures can be compensated by applying pressure to the outside of the insert.
- Such external pressure can be applied by shrink fitting. and can be increased by the use of a three component assembly including a shrink-ring.
- The loss of external pressure at the operating temperature of the die due to differential expansion can be overcome by the use of tungsten carbide as a shrink-ring material.

Peripheral cracking of inserts is found to be due to an axial tensile stress generated in the process of shrink-fitting. This problem can be ameliorated by lubrication of the insert/housing interface prior to shrink-fitting, the use of thinner inserts and tungsten carbide shrink-rings. The problem has not occurred in recent trials where these measures have been adopted.

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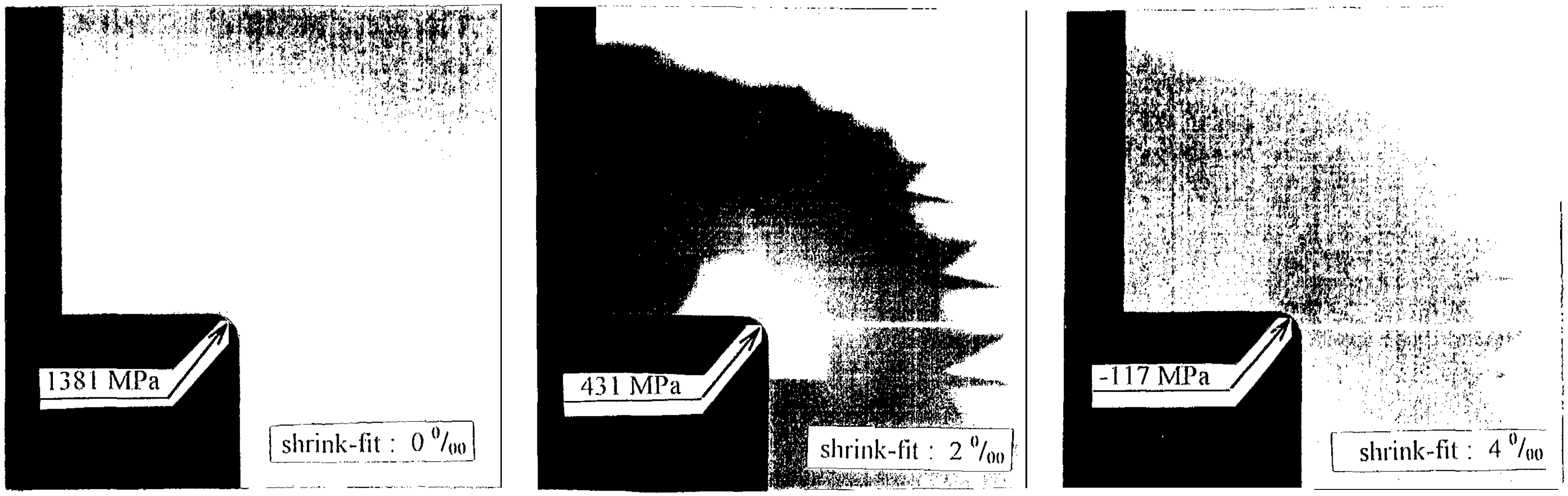


Figure 1 Effect of 'shrink-fitting' on the stress concentration at the corner of an aperture, (radius; mm). Increasing the degree of interference between insert and housing reduces the stress from tensile to compressive.

Extrusion pressure	300 MPa.
Corner radius	2 mm

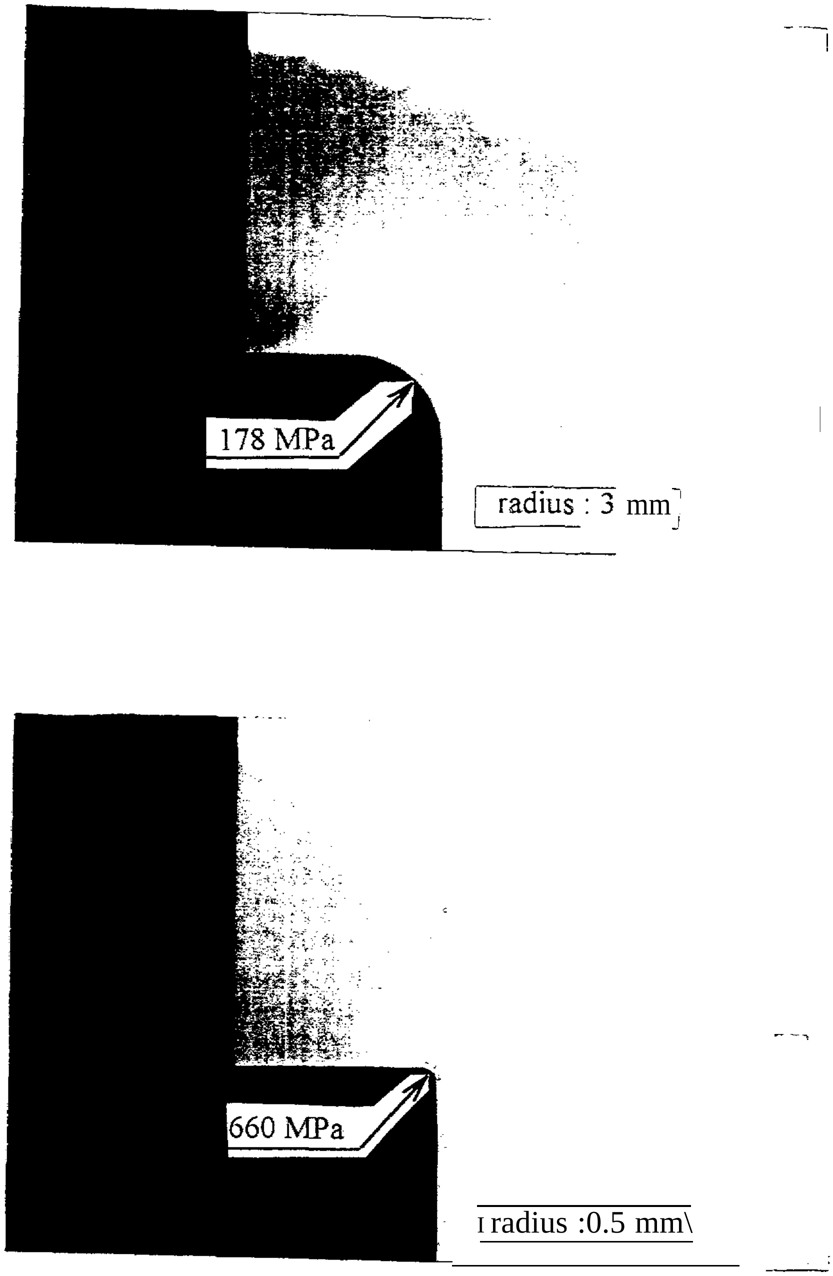


Figure 2 Effect of corner radius on stress concentration in a die aperture.

Extrusion pressure 300 MPa

Shrink-fit : 2 ‰

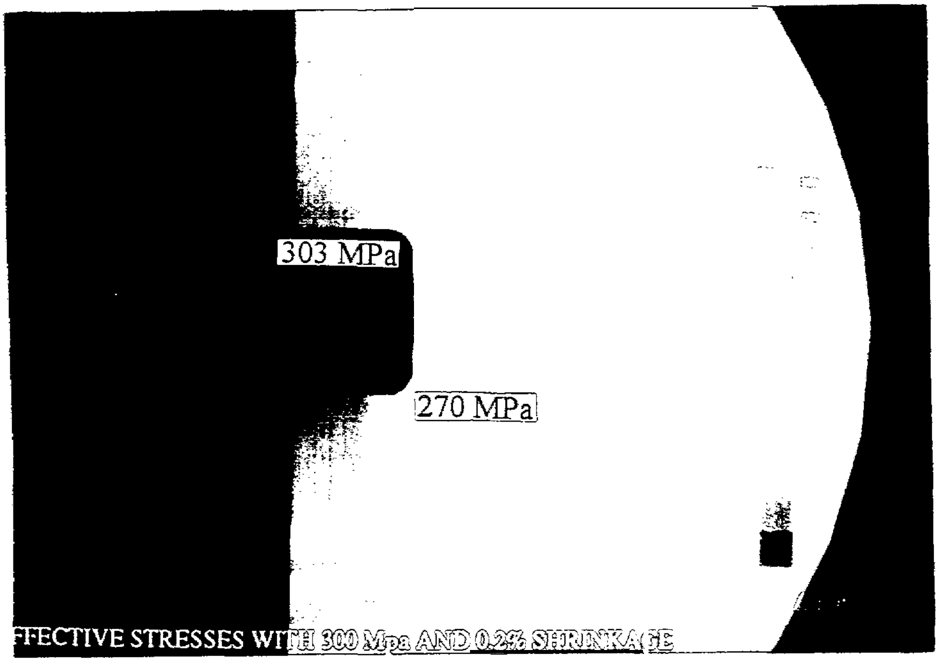


Figure 3 Stress concentrations at the corners of a channel section.
Extrusion pressure 300 MPa

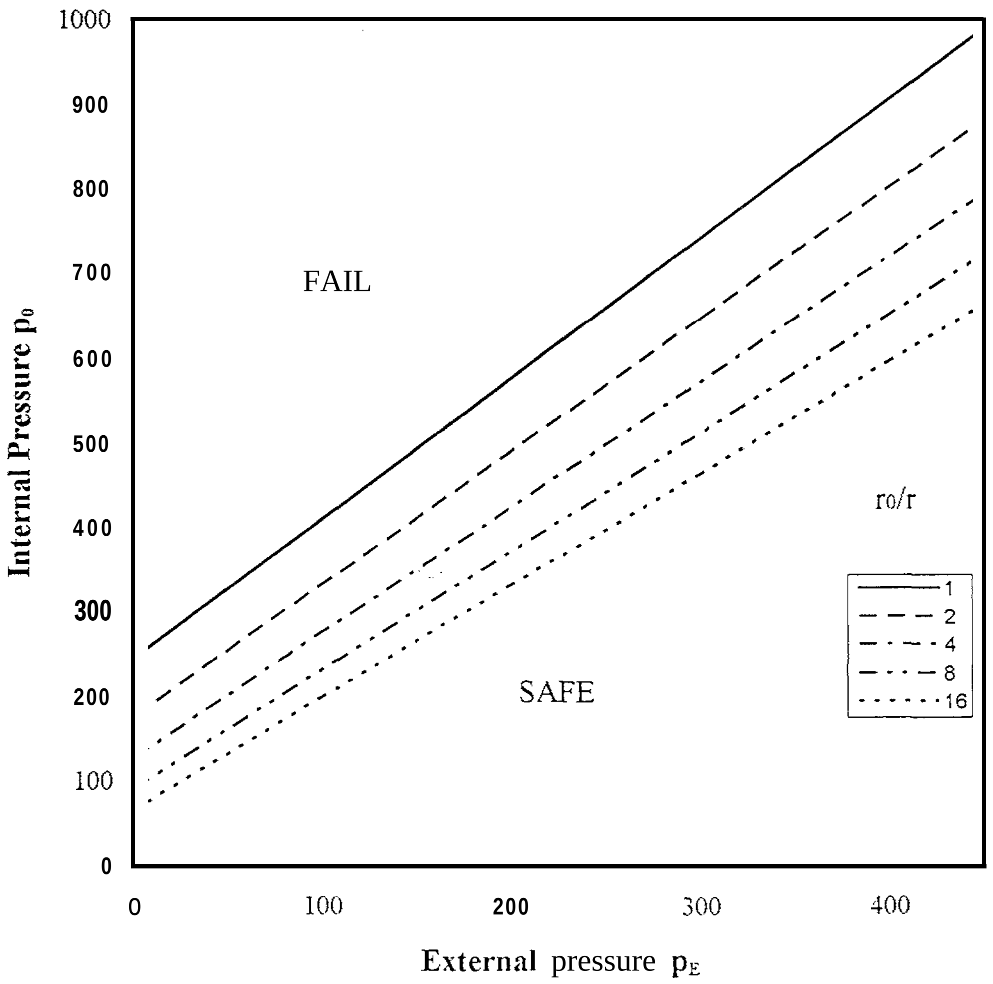
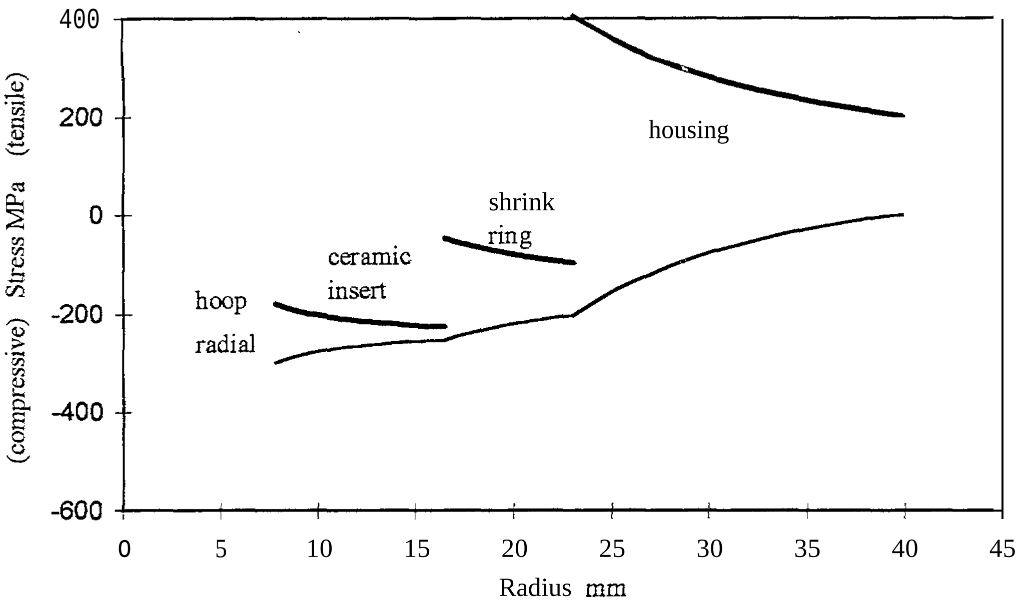
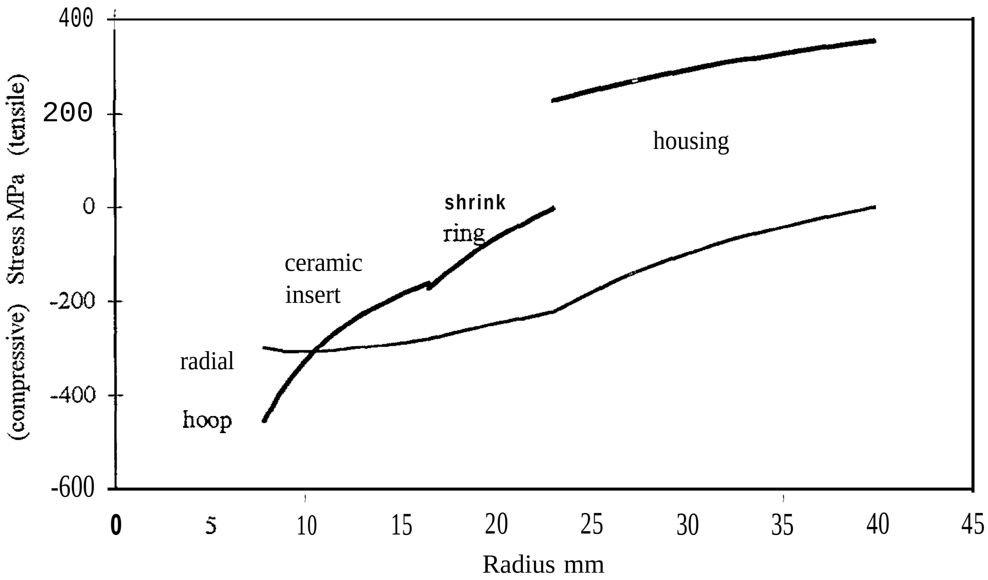


Figure 4 Showing fail/ safe boundaries in a diagram of internal (extrusion) pressure versus' external (shrink-fit) pressure for a die aperture with rounded corners. The fail / safe boundary location depends upon the ratio r_0/r where r_0 is the position radius and r is the corner radius. Susceptibility to corner cracking increases with this ratio.



A. Internal temperature 400° c
External temperature 400° c



B. Internal temperature 500° c
External temperature 300° C

Figure 5 Variation of stress in a radial direction in an axi-symmetric die having a silicon nitride insert contained in a steel shrink-ring and steel housing. In A the temperature is isothermal whereas in B there is a radial temperature difference of 200° c

Shrink-ring interference	3 $^0/_{00}$
Housing interference	3 ‘/**
Extrusion pressure	300 MPa

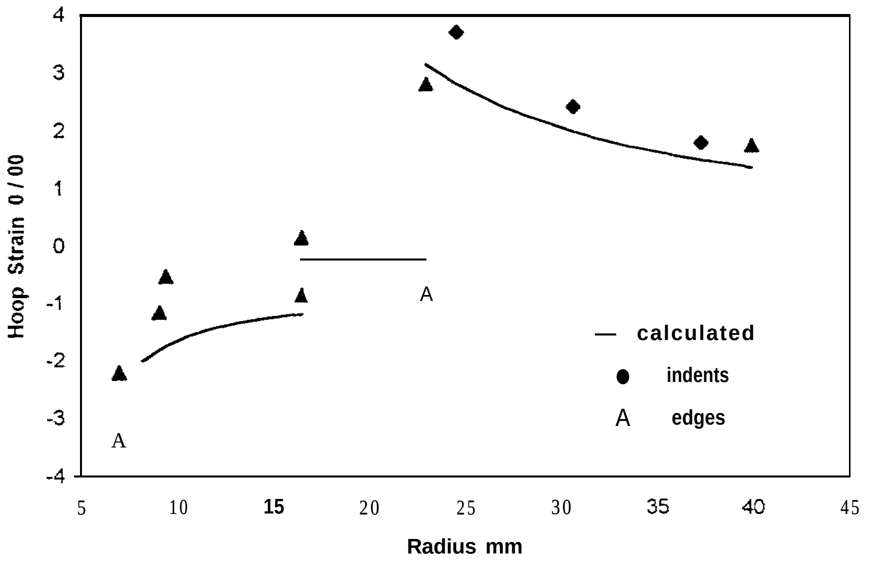
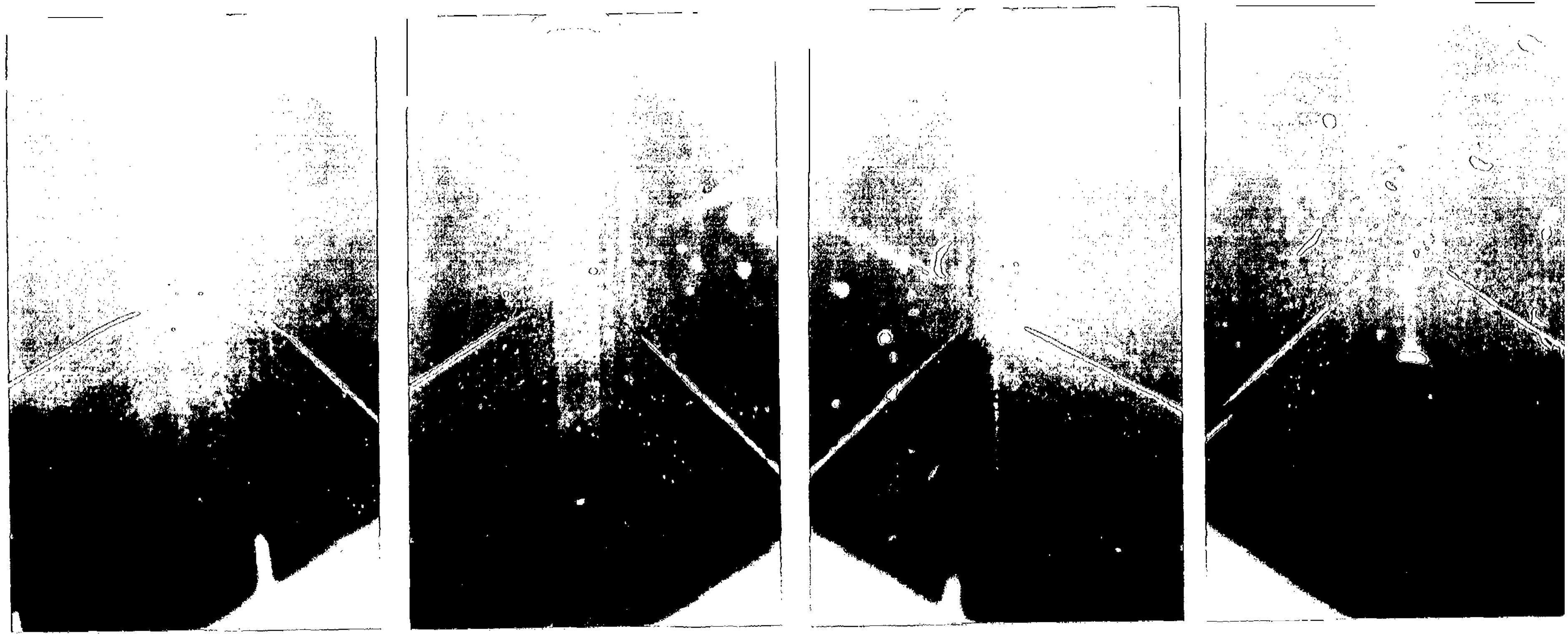


Figure 6 Measured shrunk-in strain distribution for a die consisting of silicon nitride insert (left), WC-9%Co shrink-ring (centre) and steel housing (right).

Shrink-ring interference 1. I ‰

Housing interference 4.9 ‰

Top of die



1 2 3 4

1- corner radius 3.0 mm. 2 2- corner radius 1.5 mm. 3 - corner radius 0.75 mm. 4 - corner radius 1.0 mm. (x6 magnification).

Figure 7. Circumferential crack around the bearing surface of a silicon nitride die after shrink-fitting.

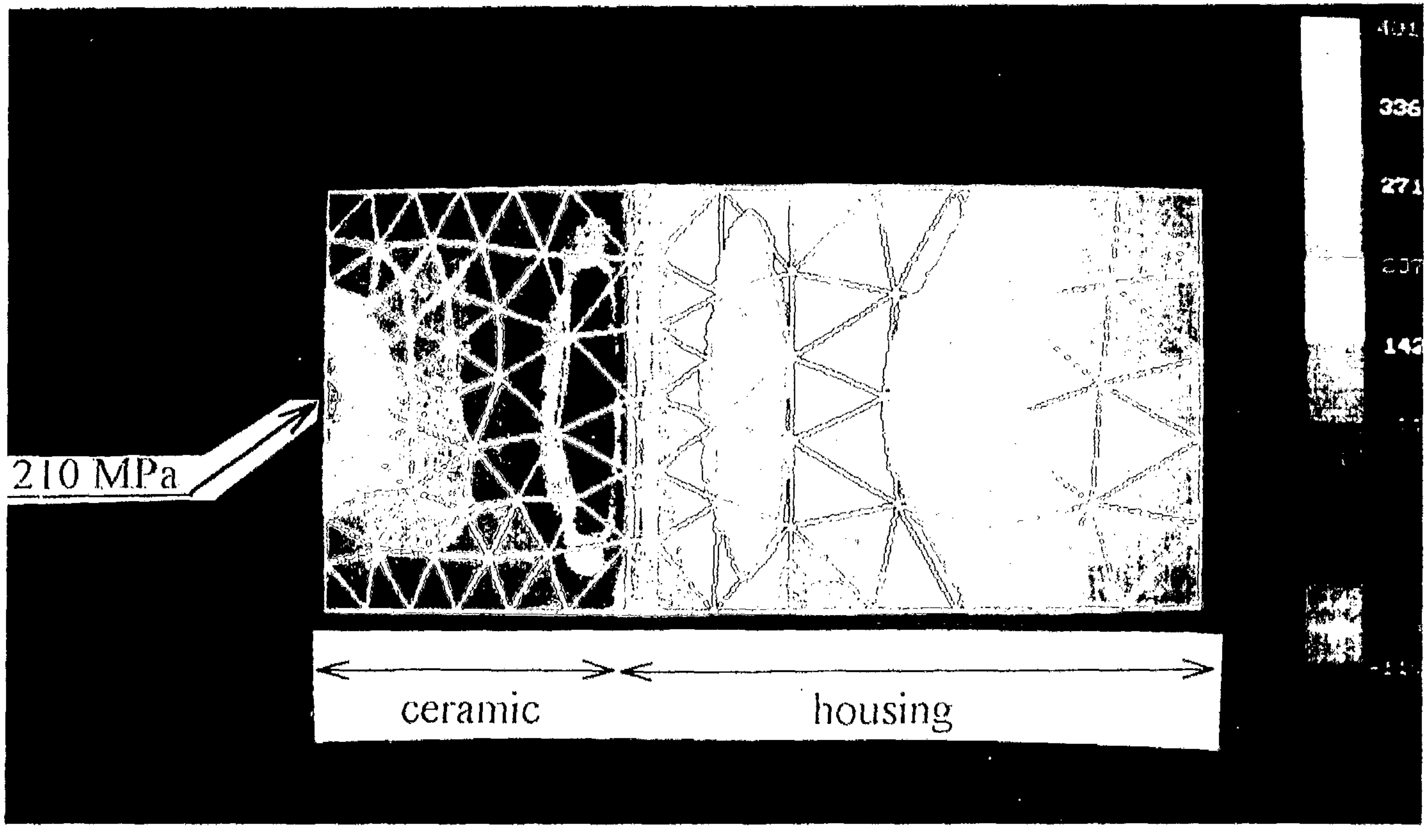


Figure 8 Tensile stress generated at the centre of a die bearing caused by shrink-fitting.

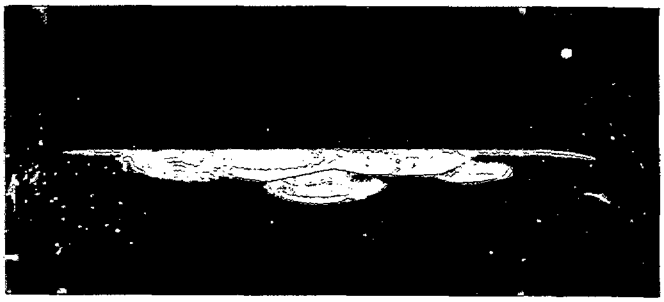


Figure 9. Chipping from peripheral crack around the bearing surface of a silicon nitride die .

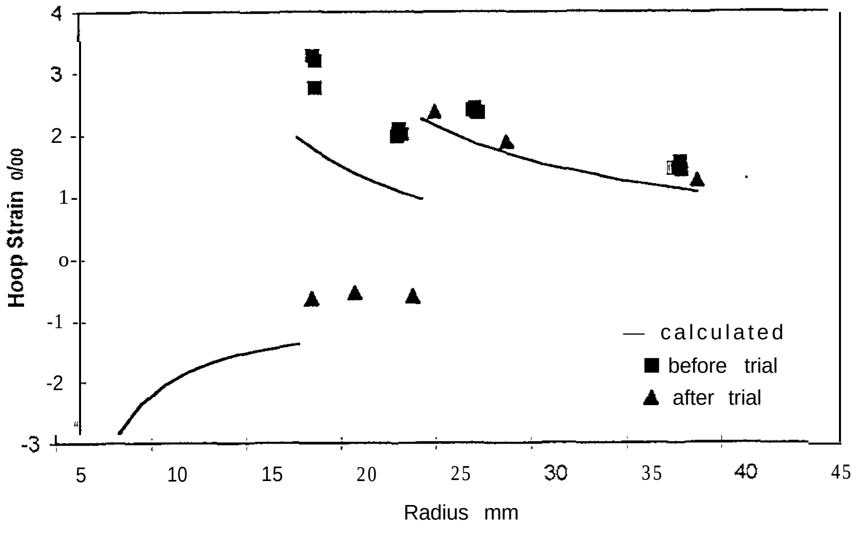


Figure 10. Die 1 (3.4 $^0/_{00}$ + 3.0$^0/_{00}$ shrink-fit) showing the strain distribution before and after the extrusion trials. The silicon nitride insert is on the left, the steel shrink-ring in the centre and steel housing on the right.