IMPROVING SURFACE FINISH AND INTEGRITY IN CLOSED DIES USING ULTRASONICALLY AGITATED ABRASIVE MIXTURES

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Contract No. BREU-0432

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1 Summary

The main technical objective of the project was to improve the quality and reliability of surfaces of dies and moulds which are used in the forming and shaping of materials such as powder metals, casting or forged metals, plastics and glass.

In the manufacture of these dies and moulds a variety of machining techniques may be employed to produce the often complex shapes required. With few exceptions, the surfaces produced by these techniques demand additional treatment to bring them to the specified surface finish and integrity. The most common solution involves hand held tools, although there have been indications more recently of attempts to automate the treatment using robots or a modified form of copy milling. Current techniques remain slow and are very often of sub-standard quality.

It was anticipated that the use of the project technology in the form of an automated finishing process may reduce die and mould polishing time by 30 to 70%. Since typical finishing costs for complex dies and moulds represent 10 to 30% of total manufacturing costs this may represent cost reductions of 3 to 20°/0.

The initial project concept was the development of a polishing process based on the ultrasonic vibration of a polishing compound consisting oft mixture of a soft flexible polymer and abrasive particles. The intended performance for the process when developed was to polish surfaces with rugosities 1 µm Ra to 4µm Ra to achieve target finishes of 0.1 µm Ra to 0.4 µm Ra. In addition, where surfaces had been generated by thermal machining techniques (e.g. electric discharge machining) it was intended that stock removal would be of the same order of magnitude as the depth of recast layer resulting from the zonal heating and subsequent retooling of the work piece surface. The achievement of this objective would ensure the removal of micro-cracks and return the surface to the original material integrity.

The project was structured on a task by task basis. Tasks 1 and 2 involved the investigation of the energy transfer and heat generation aspects of the process' in order that the process may be well characterised and optimised. Task 3 was focused specifically on the development of the polishing process by the testing of experimental machines. These three tasks were closely integrated and the information generated was used to" specify and design a prototype polishing machine. This prototype machine was designed and manufactured within Task 4. Following manufacture of the prototype machine the process was evaluated within Task 5 of the project against the original performance criteria . .

All tasks were completed as specified within the workprogramme in a timely manner. Minor workprogramme amendments were implemented where appropriate. The project was concluded with the demonstration of a prototype polishing machine capable of achieving the original project objectives. Partner I is actively co-ordinating the further evaluation, development and marketing 'of this process within a series of post project activities.'

2. Objectives of the project

In the manufacture of dies and moulds a variety of machining techniques may be employed to produce the often complex shapes required. With few exceptions, the surfaces produced by these techniques demand additional treatment to bring them to the specified surface finish and integrity.

The main technical objective of the project was to develop an automated process to improve the quality and reliability y of surfaces which are used in the forming and shaping of materials such as powder metals, casting or forged metals, plastics and glass. It was intended that this would involve polishing surfaces with rugosities 1 µm Ra to 4µm Ra to achieve target finishes of 0.1 µm Ra to 0.4 µm Ra. Where surfaces have been generated by thermal machining techniques (e.g. electric discharge machining) it was intended that stock removal would be oft he same order of magnitude as the depth of recast layer resulting from the zonal heating and subsequent retooling of the work piece surface. The achievement of this objective would ensure the removal of micro-cracks and return the surface to the original material integrity.

It was anticipated that the use of the project technology in the form of an automated finishing process may reduce die and mould polishing time by 30 to 70%. Since typical finishing costs for complex. dies and moulds represent 10 to 30% of total manufacturing costs this may represent cost reductions of 3 to 20%.

As a result of the grinding action of the process and the improvement in surface integrity the effective life of the die cavities maybe increased. This would,& a very direct cost saving to the component manufacturer.

3. The structure of the workprogramme

The project workprogramme was split into six main task headings. In the early part of the project tasks 1,2 and 3 were structured to investigate the transducer design, heat generation and the polishing process respectively.

Following these initial investigations it was intended that all the data generated in tasks 1, 2 and 3 would be brought together to be used to design a prototype machine that would polish on an industrial scale a wide “variety of closed cavities in components made from a variety of materials. Attention would be given to the polishing of complex shapes in aluminium and a variety of steels. The criteria of interest would be specific levels of improvement in the degree of roughness at all points on the surface of the die and a limitation on the temperature rise at any point within the polymer.

Selected industrial dies in aluminium and steel would be tested on the prototype machine constructed within Task 4. It was intended that the changes in Ra, as a result of polishing, the variation in this parameter around the polished surface, the extent of micro-cracking, and the nature of the residual stress at the surface of the die cavities would be compared with that achieved by hand polishing operations. These comparisons would be used in the evaluation of the prototype machine. Any improvements necessary to the prototype design would be completed.

3. Technical review of the work completed

Task 1- Method of high frequency energisation of the media

The primary objective of this task was to develop a model of the pressure and energy distribution in the polishing compound in order to be able to optimise the acoustic system to give the best polishing performance. In order to develop such a model it was necessary to identify the energy transfer mechanisms within the total ultrasonic system (Figure 1). The complete ultrasonic system consists of an ultrasonic generator and transducer which transmits vibration through a mechanical booster and sonotrode into the abrasive polishing compound. The first transfer of energy in the system occurs in the ultrasonic generator, the transducer, the booster and the sonotrode, when the electrical energy input is converted to mechanical energy. This transfer results in the generation of heat and sound with a corresponding efficiency reduction. The efficiency of the transfer was quantified by measuring the electrical input to the ultrasonic generator and the vibration amplitude at the tip of the sonotrode.

Energy transfer also occurs across the interface between the end of the sonotrode and the abrasive polishing media. It order to determine the interface impedance losses, it was first necessary to determine the acoustic impedance of the materials involved. The acoustic impedance of a material is the product of its density and the velocity of ultrasonic compression waves within it. The velocity of ultrasonic compression waves within a wide range of abrasive polishing media was measured. The viscosity, abrasive size and abrasive concentration were the three variables investigated. The velocity of the acoustic compression waves was measured at a source to detector spacing of 25, 50 and 75mm. From the velocity of acoustic compression wave measurements, and the calculated densities, the impedances of the abrasive mixtures were calculated.

Having determined the acoustic impedance of the various media mixes, it was possible to combine them with those of steel and aluminium and hence calculate a transmission coefficient for the different interfaces.

The energy distribution within the abrasive polishing media was investigated. Initial attenuation measurements within the abrasive polishing media were completed using 1 MHz broad band piezoelectric transducers. It was found that within this range the attenuation of the acoustic energy gradually increased with frequency.

Having established these general trends across a broad frequency range it was concluded that increased transfer efficiency could be achieved by operating at lower frequencies. Further attenuation measurements were therefore completed using lower frequency 150kHz transducers. The attenuation data was used to develop mathematical models to predict the pressure and energy distributions within the ultrasonically agitated abrasive mixtures.

The variation in attenuation with distance from the transducer for medium viscosity polishing media can be seen in Figure 2. It was found that the attenuation increased with increasing distance from the transducer. This data further reinforces the proposal that lower frequency ultrasonic systems will give the optimum energy transfer.

In order to develop an empirically based predictive model of the pressure distribution within the polishing media, a large number of pressure measurements was taken within the media at a range of axial and radial distances from the sonotrode working end.

The variation in dynamic pressure with distance from the working end of the sonotrode for a variety of generator power settings can be seen in Figure 3. An exponential reduction in dynamic pressure with distance from the sonotrode can be seen for all power levels investigated. Mathematical analysis of these results gave a predictive model of the form

$$p = 0.1 \times P \times e^{(-0.064 \times X^{1.476})} \qquad \text{equation 1}$$

where p is the dynamic pressure in the media (MPa), P is the ultrasonic generator power setting ('??), and X is the axial distance (mm) from the working end of the sonotrode. The predictive nature of this “model is represented graphically in Figure 4.

Having established this predictive model for the variation in dynamic pressure with axial distance from the sonotrode working end a similar investigation was completed to determine the variation in dynamic pressure with radial distance from the sonotrode working end. It was found from these results” that the dynamic pressure decreased with radial offset until a minimum value was obtained. The decrease in dynamic pressure with radial offset was found to be closely related to the diameter of the sonotrode. Mathematical relationships were derived to express these results, and these results were tied to modify equation 1 (given above) to give a complete representation of the dynamic pressure distribution within the polishing media. The equation derived was as shown below:

$$p = 0.1 \times P \times \frac{R-r}{R} \times e^{(-0.064 \times X^{1.476})} \qquad \text{equation 2}$$

where r is the radial offset from the centreline of the sonotrode (mm) and R is a radial offset at which the dynamic pressure becomes constant (mm) (for a 10mm diameter sonotrode R= 10mm).

Thus a predictive model had been derived to predict the dynamic pressure distribution within the polishing compound which could be used to optimise the polishing process. A three dimensional graphical representation of the predicted dynamic pressure distribution for a 10mm sonotrode energised at 40% of full power can be seen in Figure 5.

Task 2- Measurement and modelling of process heat generation

The objective of this task was to determine the effect of heat generation in the die cavity on temperature distribution within the polyborosiloxane energised with high frequency acoustic waves. It was intended that the data obtained would be used to produce a mathematical model to predict the temperature distribution in a variety of closed cavities in industrial dies subject to polishing with the abrasive polishing media. This information would be used, if necessary, to control the temperature distribution within the polishing system by either controlling the heat generation of the process or by introducing suitable cooling systems.

In order to develop a thermal model of the polishing process it was necessary to , determine a number of fundamental thermal properties. The thermal conductivity was determined for low, medium and high viscosity polymer mixed in concentrations from O to 75% by mass with silicon carbide abrasive. These experiments were repeated for two abrasive particle sizes; 14 µm and 142µm. In all cases the thermal conductivity of the polishing compound was found to increase with increasing abrasive content. The specific heat capacity of a range of polishing compounds was also determined experimentally. The specific heat capacity was found to be reasonably constant for abrasive concentrations between O and 50°/0 by mass. The specific heat capacity was found to decrease when the abrasive concentration was increased from 50 to 75% by mass. The surface heat transfer coefficient between steel and polishing media mixed 1:1,2:1, and 3:1 by mass with abrasive was determined experimentally for low, medium and high viscosity polymer across the interface temperature range of 30°C to 60^{O}C. The surface heat transfer coefficients for polymers without abrasive were also determined. In general it was found that the surface heat transfer coefficient of the polishing compound decreased with both increasing interface temperature and increasing abrasive content .-

As part of the ultrasonic process the ultrasonic wave will attenuate as it passes through the polishing compound (see Task 1). A proportion of this attenuation will be converted to heat within the polymer. It was necessary to quantify this heat generation for a range of experimental conditions@ order to incorporate this heat generation into any thermal models of the polishing process' to be developed. It was assumed that all the energy attenuated by the sound wave was converted to heat. The heat generation within the polymer could therefore be calculated by subtracting the energy used for the polishing process at the die surface from the mechanical energy generated at the sonotrode tip. In order to calculate the mechanical energy at the end of the sonotrode an experimental programme was completed to determine both the amplitude and the force at the end of the sonotrode as described below.

The displacement at the free end of the sonotrode was measured by means of a capacitive transducer. '1 'his device measured changes in capacitance between two parallel faces. The change in capacitance was related to the change in distance which occurred between the vibrating surface of the sonotrode and the stationary transducer. The equipment used is shown in Figure 6. The capacitive transducer employed was calibrated with a known displacement of low frequency. The measured amplitude of a variety of sonotrode sizes (diameters) for a range of ultrasonic generator power (between 100 and 700 W) can be seen in Figure 7. 'l-he measured amplitude generally increased with increasing generator power and decreasing sonotrode diameter.

The force was measured at the free end of the sonotrode using a load cell. Thus the energy generated at the tip of the sonotrode could be calculated for a range of operating conditions. The heat generation within the polishing media was calculated by combining the calculated energy input at the tip of the sonotrode with the attenuation of the ultrasonic wave within the polishing media (Task 1).

It became apparent, through experimentation on the test equipment at Partner 2, that, when the sonotrode was vibrated freely in air, heat was generated within the sonotrode itself This was an additional term to consider within the modelling of the heat generation and transfer of the polishing process. Consequently it was necessary to quantify the heat generation within the sonotrode for a range of operating conditions. This was completed by measuring the temperature of the sonotrode during excitation for a range of operating conditions.

A two dimensional finite difference thermal model of the polishing process was developed A series of heat transfer equations was derived to describe the heat transfer between control volumes whilst maintaining an energy balance. It was assumed that heat transfer was by conduction in the polishing compound, in the work piece, and within the sonotrode. Heat transfer by convection was assumed at the interface between the polishing media and the sonotrode, work piece and containment device. Natural convection was assumed at the" system boundaries, Heat generation terms were included in the polishing compound and in the sonotrode.

The thermal model was modified as the polishing process was developed (Task 3). The first of these modifications was the incorporation of the effects of pressurizing the polishing compound, and the flow of the polishing compound in the polishing chamber. The model was used at this stage of its development to model the heat generation and transfer within hemispherical die cavities. Work was simultaneously completed to optimise the polishing process for these die cavities (Task 3). A five section nodal mesh was created for this investigation as can be seen in Figure 8. The model was used to predict temperature distributions within the system for a range of processing conditions. A typical output of the thermal model can be seen in Figures 9 to 12. These results show the temperature at four time intervals during the polishing process. It was noted that maximum temperatures were generated in the region directly below the sonotrode. However, the flow of the polishing compound up the sonotrode resulted in heat transfer from the 'region under the sonotrode to the centre of the sonotrode.

In order to validate the thermal model a large number of temperature measurements was completed during operation of the polishing process. Subsequently, the heat transfer model was' modified to take into account the reversal of the flow direction of the polishing media flow from up the sonotrode to down the sonotrode.

It was evident from these experiments that both the ultrasonics and the flow of media contributed heat to the system. It was proposed that flow of media contributed heat to the system through shear heating. In all cases the temperatures generated were well below that considered acceptable for a polishing operation.

Task 3- The development and assessment of the polishing process

The main objective of this task was to be the development of a practical polishing process by the development of the initial concept of ultrasonically agitating an abrasive mixture in a die cavity. The polishing process developed was to be evaluated for the effectiveness of its polishing on the surface of die cavities. It was intended that the polishing parameters to be investigated would be frequency and amplitude of vibration, power, static force and time. The material properties to be (considered would include change in surface roughness, uniformity of polish, and surface integrity.
During the first six months of the project an experimental polishing machine was designed and constructed at Partner 4 as shown in Figure 13. The test piece to be polished was clamped into position opposite the acoustic system as shown. The system was filled with a mixture of soft polymer, flowable at room temperature and a silicon carbide abrasive.' The machine was fitted with a pressure and displacement transducer-Commissioning trials on the machine included the measurement of the pressure on the surface of test samples during the operation of the acoustic system. It was found that the application of a static pressure greatly increased the effective transmission of the ultrasonic dynamic pressure to the work piece surface. The pressurisation of the system was achieved by the use of a hydraulically driven piston as shown in Figure 13.

During the second six months of the project, experiments were completed to investigate the effectiveness of the experimental polishing machine described above. Initial trials involved investigating the effects of media viscosity, abrasive particle size and sonotrode design on the polishing action produced. In addition the repeatability of the polishing action produced was also investigated.

Surface roughness improvements achieved in these early trials were at best around 19% (Ra before 3.1 µm to Ra after of 2.5 µm). However, considerable damage occurred to the work piece surface in some cases (deep cavities).

Despite these limitations the results of these first tests were very encouraging as they demonstrated that the ultrasonic vibrations could be transmitted from the acoustic system through the abrasive medium to the work piece surface, and effect a surface roughness improvement by agitation of the abrasive particles.

In order to improve the polishing process the sonotrode was drilled axially down its centre to obtain a circulation of the abrasive mixture and to allow the transverse motion of the abrasive particles relative to the work piece surface. The configuration of this experimental set-up can be seen in Figure 14. A series of experiments was completed in order to investigate the effect of sonotrode to work piece spacing. processing time, polymer viscosity, abrasive size and concentration, and ultrasonic amplitude. Results of these experiments were very much improved on the previous non- flow trials described above. Surface damage was minimal and Ra improvements of up to 76% were achieved (0.5 pm to 0.12 µm).

Despite the promising Ra improvement, some erosion oft he *work* piece surface at the centre and periphery of the polishing zone occurred and a central non-polished zone was evident.

In order to reduce this effect an eccentric work piece, holder was used to rotate a flat disk sample relative to the sonotrode. This experiment produced an excellent surface finish result (Ra before 4.3 µm, Ra after 1.5 pm) and the central dead zone was virtually eliminated.

Polishing of both steel hemisphere and aluminium slot samples was completed on the modified polishing machine. The most promising result for hemispheres was 45°/0 Ra improvement (4. 12 µm before, 2.26 µm after) and for slofs was 70°/0 (1.34 µm before, 0.39 µm tier). In addition, no damage of the die surface was evident (due to sonotrode to die contact or other mechanisms). However, many of the trials did not produce such large surface roughness improvements and the polishing produced was not homogeneous over the entire work piece surface.

Following discussions it was decided to modify the experimental polishing machine such that the flow of abrasive media was down the sonotrode and exhausting to atmosphere between-the die and the sonotrode tip as opposed to the previous arrangement whereby the die was in a pressurised container and abrasive media was forced between the die and the sonotrode, up the sonotrode and out to atmosphere: It was thought that this method would still produce a polishing effect as polishing medium-would still be directed under pressure between the sonotrode and the die. This modification eliminated the need for a pressurised container which offered considerable advantages if future process development required relative sonotrode to die cavity movement. Relative movement between the sonotrode and the die cavity has subsequently been shown to be advantageous to achieving a homogeneous polishing effect.

Initially ten hemisphere samples were processed. Good polishing results were achieved although longer processing times than had been previously used were found to be necessary. Despite the extended processing times (up to 60 minutes), Ra improvements of up to 5o^{0}A were achieved.

As detailed above, a number of developments to the polishing process was identified including;

- The reversal of the flow direction of the abrasive media
- Movement of the sonotrode relative to the die improves the polishing effect and enables larger areas to be polished
- Multi-axis movement of the sonotrode relative to the work piece to enable the polishing of side walls as well as the base of the die cavities
- Control of the axes movement to achieve an effective polishing action and to eliminate any surface damage of the die.

To satisfy these requirements new test equipment was designed and built and mounted on a numerically controlled 3-axis table which was formerly part of a milling machine. An overall view of this test set-up is shown in Figure 15. The transducer, booster and sonotrode assembly were mounted on the decommissioned vertical spindle assembly of the machine. The table could be numerically controlled in three axes and the machine head could be manually rotated about a horizontal axis.

Figure 16 shows, in detail, the transducer, booster and sonotrode along with the new media pressurisation/feed arrangement. The media was contained within an easily refilled reservoir (shown on the left) which was pressurised by means of a 150mm stroke hydraulic pump. The reservoir fed the sonotrode through nylon hoses and a manifold (hidden behind the transducer). The manifold had four delivery ports but only two were used since it was necessary to strike a compromise between media delivery and sonotrode cross-section in the region of the feed ports.

Task 4- Specification and design of prototype equipment

The objective of this task was to specify and design a prototype polishing machine based on the results and conclusions of tasks 1, 2 and 3. Based on these designs a prototype machine was to be constructed to allow the evaluation of the process on industrial dies (Task 5).

The polishing action is achieved by pumping a viscous abrasive polymer mixture axially down the centre of a metal tool whilst subjecting the tool to an ultrasonic vibration. The main components of the polishing tool are shown in Figure 17. The tool is traversed over the die surface to achieve a uniform polish.

It was intended that the prototype polishing machine would be capable of polishing a minimum die size of 150 x 300 x 450 mm by pumping a viscous abrasive polymer mixture axially down the centre of a metal tool whilst subjecting the tool to ultrasonic vibration. T'he prototype was to be capable of traversing the tool over the die surface to achieve a uniform polish. A typical cavity shape to be polished would be a bottle cavity.

In order to design the machine frame and base it was necessary to specify the axis movements required. After considering various concepts it was decided to use a linear x, y table combined with a linear (z) and two rotary (a and c) axes on the ultrasonic head.

For the prototype polishing machine it was necessary to motorise and control the x, y and z axes. AC brushless motors/encoders were selected to the following specification.

Constant stall torque	1.6Nm
Peak torque	6.0Nm

It was intended that these motors would be used in combination with digital amplifiers to give closed loop velocity and torque control on the x, y and z axes via rotary encoders on the motor shafts. The digital amplifiers would be supplied by a 2.5 KVA transformer. The transformer has sufficient capacity to power two additional amplifiers for the a and c axes at a future date. The z-axis would also be fitted with a brake to ensure that the ultrasonic head maintains position when the power is disconnected..

A CNC controller would be required to control the axis movement in order to polish complex die cavities automatically. A Heidenhain TNC 415 CNC controller was selected on the basis of technical features, technical support, compatibility with motor amplifiers, motors and encoders, price and delivery. Important features of this unit to the prototype design were 5 axes of control, excellent graphics, a tilt the working plane feature (essential for the tilting ultrasonic head), ISO software compatibility and a digitizing capability for co-ordinate measuring. The unit is also capable of controlling other machine functions as well as axis movement including the media flow and the ultrasonics.

Whilst the electric motors are fitted with integral encoders: or closed loop torque and velocity control with the drive amplifiers, it was intended that positional location signals would be generated by glass scale linear encoders. These encoders would be connected directly to the CNC unit.' Linear encoders offer the advantage that they offer accurate positional control, as they are not sensitive to lead screw pitch errors, backlash, torsional wind-up, thermal expansion or end float errors.

The ultrasonic system was designed to incorporate a sonotrode, booster, transducer, amplitude measurement device, ultrasonic generator, variac (power control) and a computer. A media feed system was required to pump abrasive media to the ultrasonic sonotrode. The media feed reservoir consisted of a piston and cylinder complete with abrasive resistant piston seals. The media piston was driver. pneumatically. Two solenoid pneumatic valves control the media feed system (one to advance the feed cylinder, one to retract it). These control valves are controlled automatically through the CNC unit.

Task 5 - Evaluation of the prototype equipment

The primary objective of this task was to complete a full evaluation of the prototype machine constructed within Task 4. The performance of the prototype was to be compared with the initial project objectives and with the requirements of the project partners. It was intended that any modifications necessary:0 enhance the performance of the prototype would be implemented within this task..

Within Task 5 the prototype machine software was completed. This included setting up the machine parameters in' the CNC unit (to define such parameters as number of axis movements, traverse lengths etc.) and writing the PLC program which interprets the CNC program commands and coverts them into appropriate output signals (move x axis etc.).

Figure 18 shows the finished prototype ultrasonic flow polishing machine installed at Partner 1's development facility.

During commissioning trials the prototype was found to exceed all the design specifications of Task 4. The axis traverse lengths and weight bearing capabilities of the machine were more than adequate for evaluating the complex die cavities designed within Task 3. The traverse speed and control was tested, the media feed system functioned well and the ultrasonic system functioned as specified.

In order to assess the performance of the prototype machine a number of CNC software programs was formulated. These programs defined the traverse pattern of the sonotrode, the traverse speed of the sonotrode and turned the abrasive media flow on and off. The programs were written in both 1S0 language and in Heidenhain conversational language. As well as writing programs directly for the prototype, Partners 5 and 6 processed a number of CNC milling programs into polishing programs for the prototype machine. This was achieved by putting a tool offset into the milling program. These programs were written in 1S0 CNC language and were loaded directly into the prototype controller via floppy disk. This method of programming will be very important for the future development of the process.

In the evaluation of the polishing performance of the prototype machine a CNC program using an x axis linear traverse with a y axis increment after each x axis traverse was used. Initially the y axis increment was fixed at 0.1 mm, the traverse speed at 180 mm/min and the ultrasonic power at 300/0." These parameters were selected from the optimum parameters determined within Task 3.

For the final project meeting a milled aluminium sample measuring 40mm x 40mm was polished from an initial roughness of 2 µm Ra to a final roughness of 0.2 µm Ra.

This demonstration showed the prototype to be capable of achieving the original project objectives of polishing to achieve a 10 to 1 improvement in surface roughness.

Post project evaluations completed during the production of this report indicate that modifications to the process parameters may significantly increase the polishing speed of the prototype machine.

4. Comparison of the work planned with that accomplished

Throughout the project the workprogramme was co-ordinated centrally by Partner 1 to ensure effective communication and maximum productivity. Regular review and planning meetings were organised to ensure good project progress with respect to the workprogramme.

The work completed has followed very closely that which was originally outlined in the workprogramme. "Tasks 1 and 2 were completed in order to quantify the acoustic and thermal properties of the system. Additional work to that planned within these tasks included the determination of the heat capacity of the polishing media and the modification of the predictive mathematical models to take into account modifications to the polishing process implemented within Task 3. ,

A prototype polishing machine was designed and constructed within the project. This design and construction was delayed by 3 months because the process was not fully developed at the time when the prototype design was scheduled to commence. However, additional resources were applied to the construction of the prototype *to* ensure that it was completed and demonstrated at the *final* project meeting.

5. Conclusions

The main project objective was achieved by the development of an ultrasonic flow polishing process for polishing blind cavities. The thermal and acoustic properties of the system have been quantified. A prototype polishing machine has been designed, constructed and demonstrated.

The process is capable of polishing to the quality specified in the project objectives (typically 10:1 improvement in Ra).

The technology has been patented and is currently undergoing industrial evaluation with a number of interested parties.

From a technical viewpoint the project has been very successful with all partners performing well as a co-ordinated unit. In addition to the technical achievements a number of non-technical achievements were experienced during the project term:

- a considerable amount of 'networking' has occurred. Partners and individuals have made contacts with third parties leading to further exchanges of information, meetings, new project ideas, etc.
- cultural exchanges have been significant through the technical and steering committee meetings which have occurred at the various partners' organisations
- the academic/industrial interface has been beneficial to all partners. As each meeting was hosted the activities and capabilities of each institute or company were demonstrated to the other partners
- the development of personal skills and acceptance of personal challenges was noticeable, particularly with personnel being exposed to working and communicating on an international level for the first time.

6. Acknowledgements

The project partners gratefully acknowledge the financial contribution of the European Commission to this BRITE/EURAM project. Without this financial and organisational support this project would not have been completed.

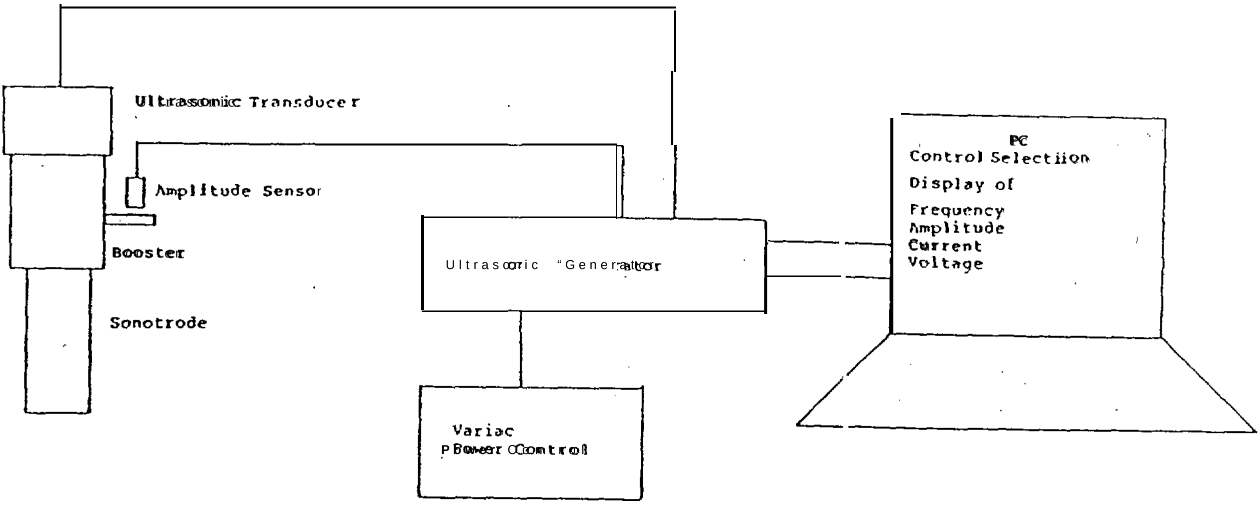

Figure 1: The ultrasonic components. of the prototype polishing machine.

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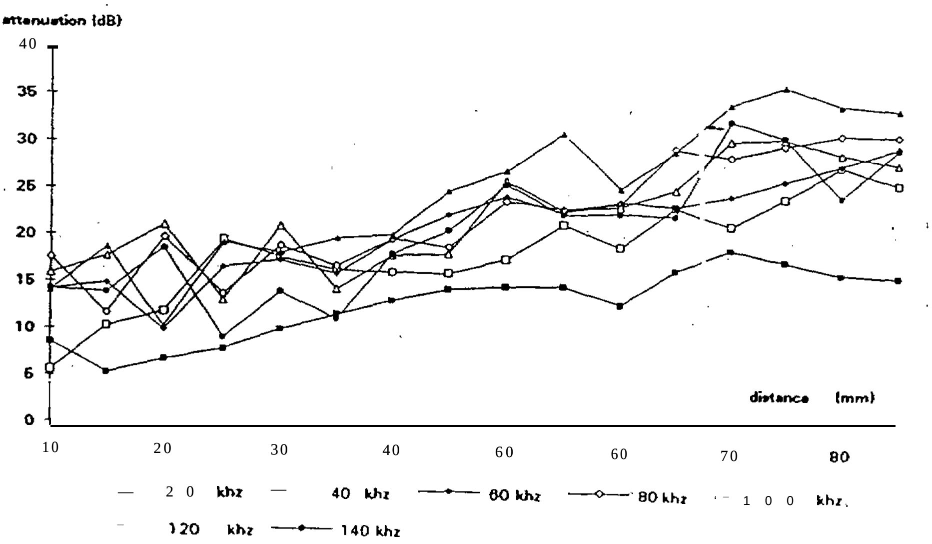

Figure 2: The acoustic attenuation with distance from the acoustic source for the frequency range 20 to 140 kHz.

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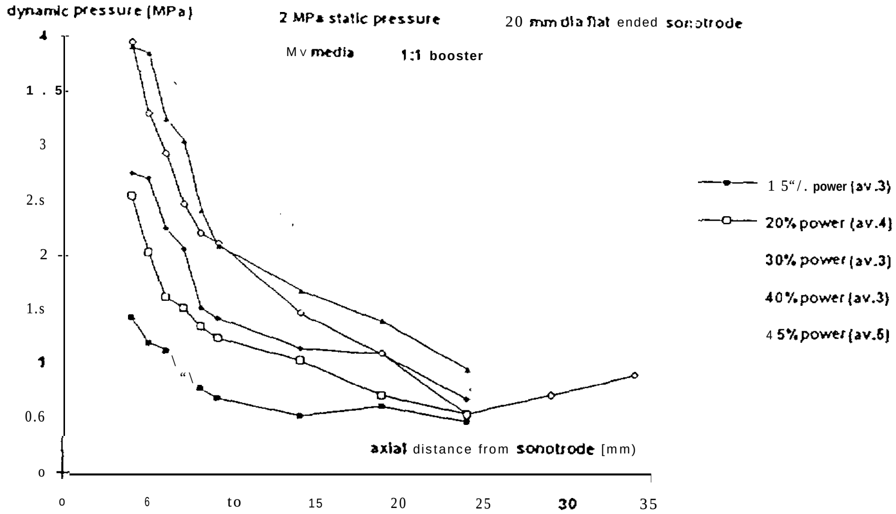

Figure 3: The measured experiment variation in dynamic pressure with axial distance from the working end of the sonotrode for a range of ultrasonic generator power settings (% of full power).

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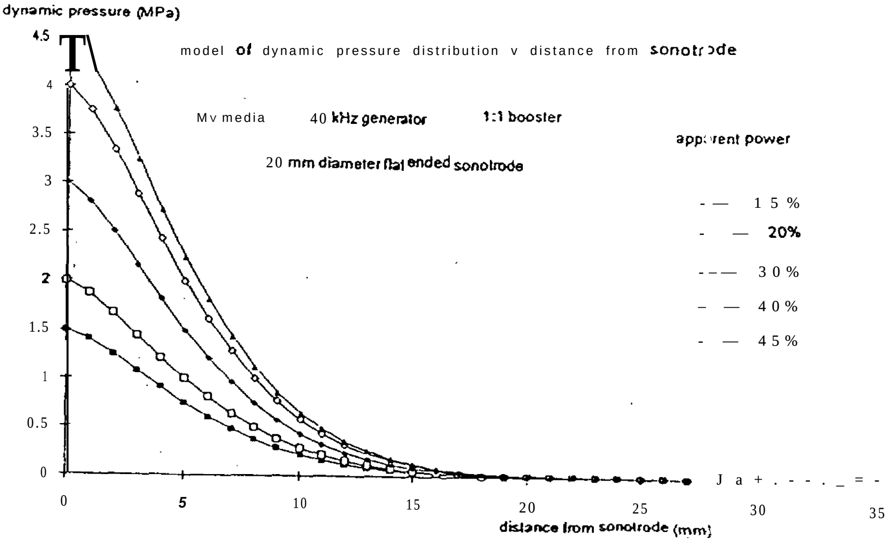

Figure 4: The calculated (from equation I) variation in dynamic pressure with axial distance from the working end of the sonotrode for a range of ultrasonic generator power settings (% of full power).

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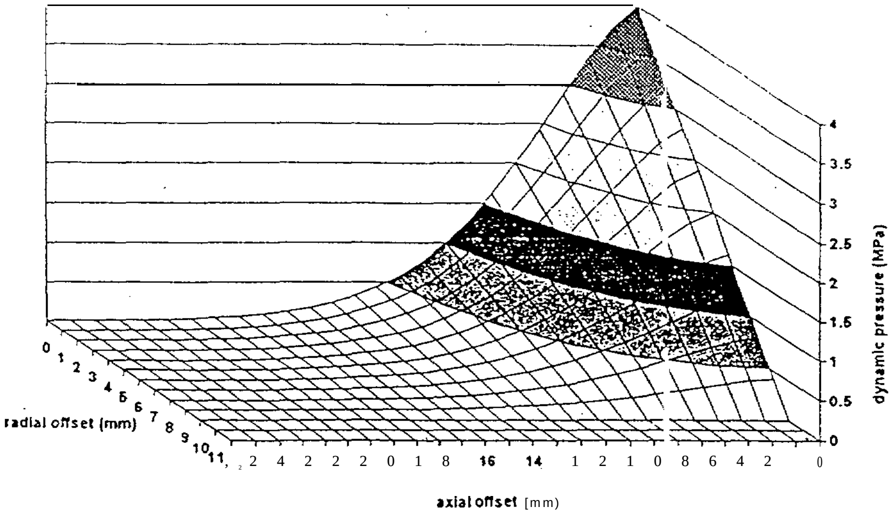

Figure 5: A three dimensional graphical representation of the dynamic pressure distribution within the polishing 'media under a 10mm diameter sonotrode energised at 40% of full power as calculated by the predictive model described within Task 1.

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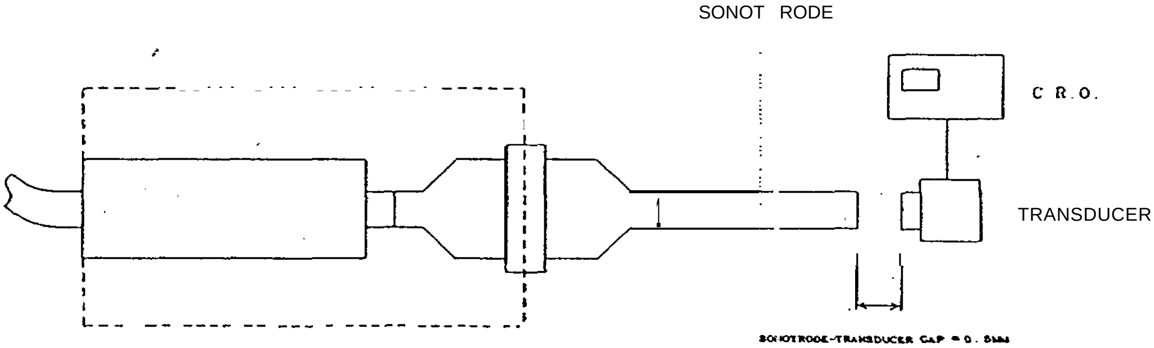

Figure 6: The equipment used to measure the amplitude of ultrasonic vibration at the tip of the sonotrode.

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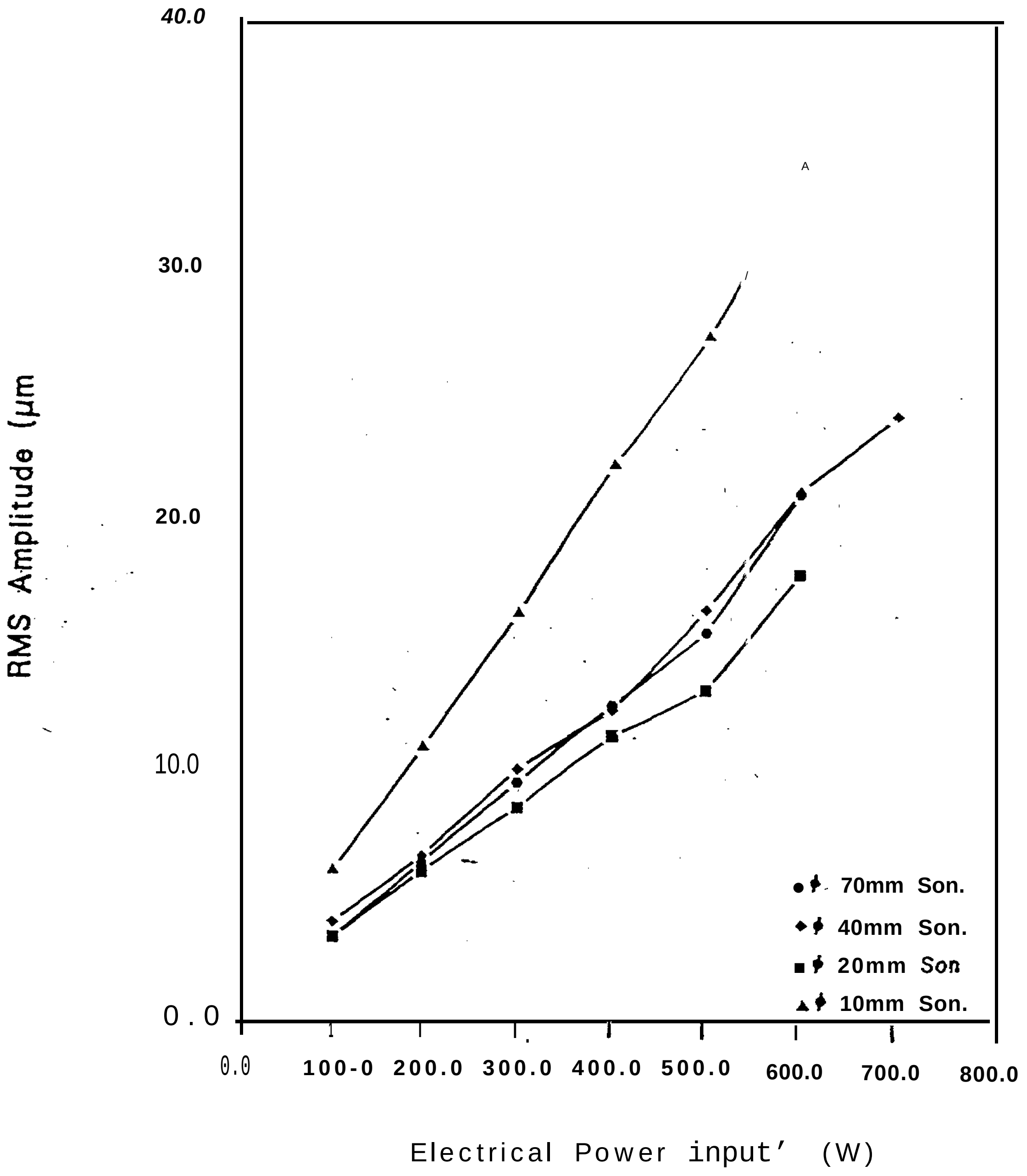
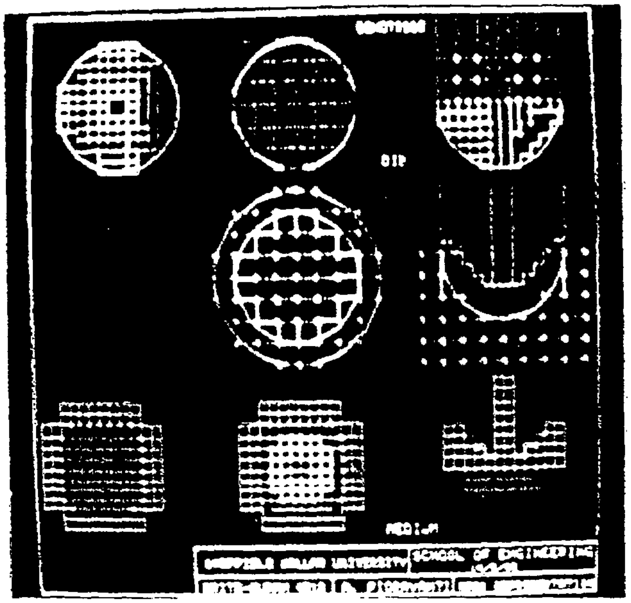
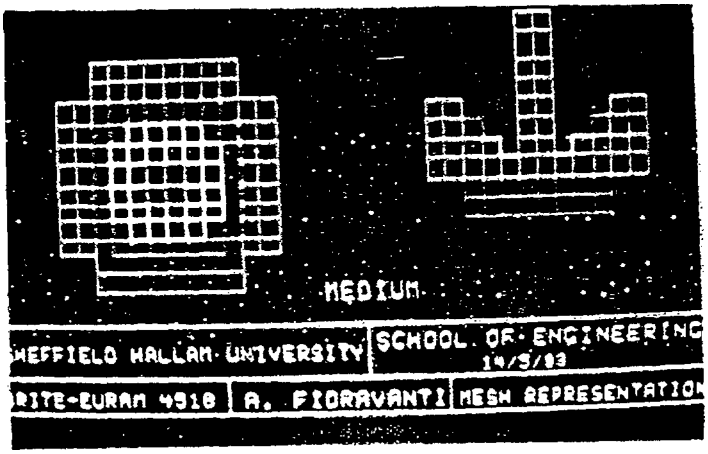


Figure 7: The variation in sonotrode amplitude with ultrasonic generator power for a range of sonotrode sizes.





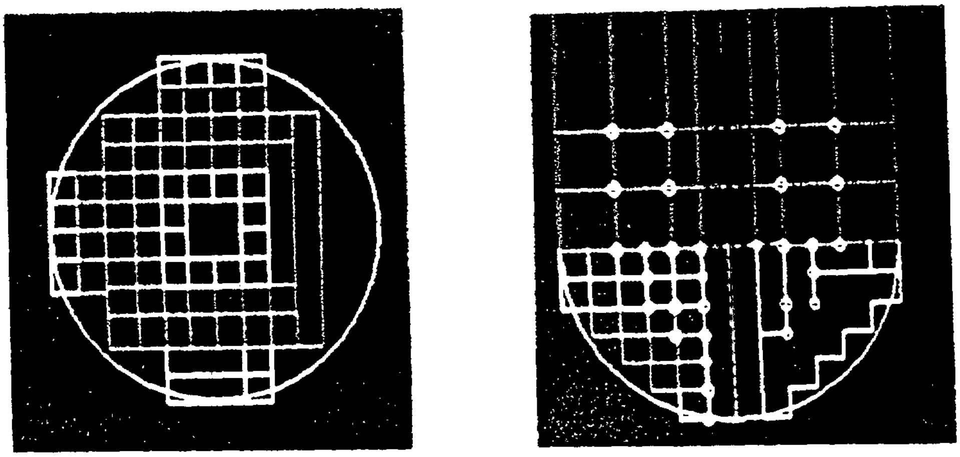
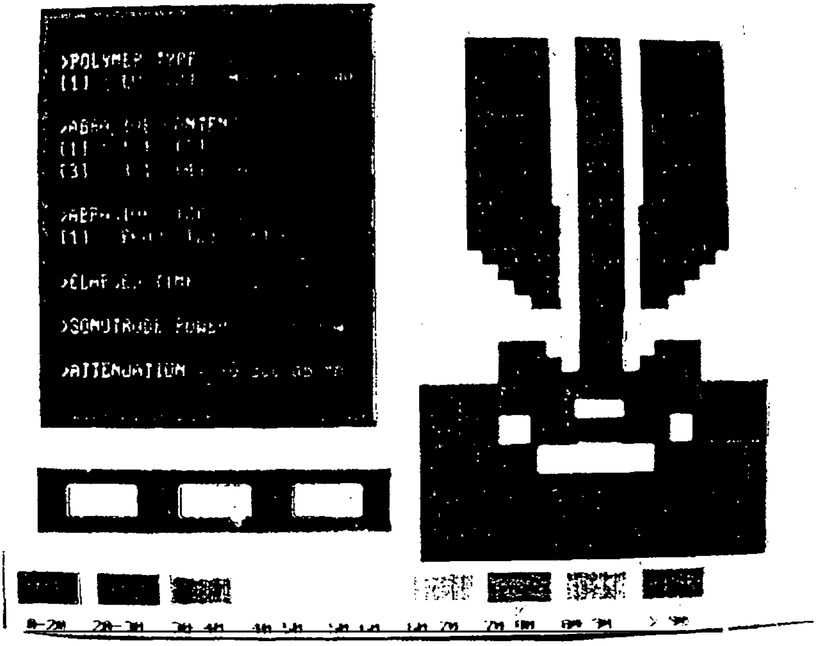


Figure S: The three dimensional nodal mesh used to model the heat generation during the ultrasonic polishing ofa hemispherical steel die sample



```
>POLYMER TYPE
>ATTENUATION
```

Figure 9: The predicted temperature distribution within the ultrasonic polishing system calculated from the finite element thermal model. The simulation is for 14µm silicon carbide abrasive mixed with medium viscosity polymer and shows the temperature distribution in the die, the polishing media and the sonotrode after 120 seconds of polishing.

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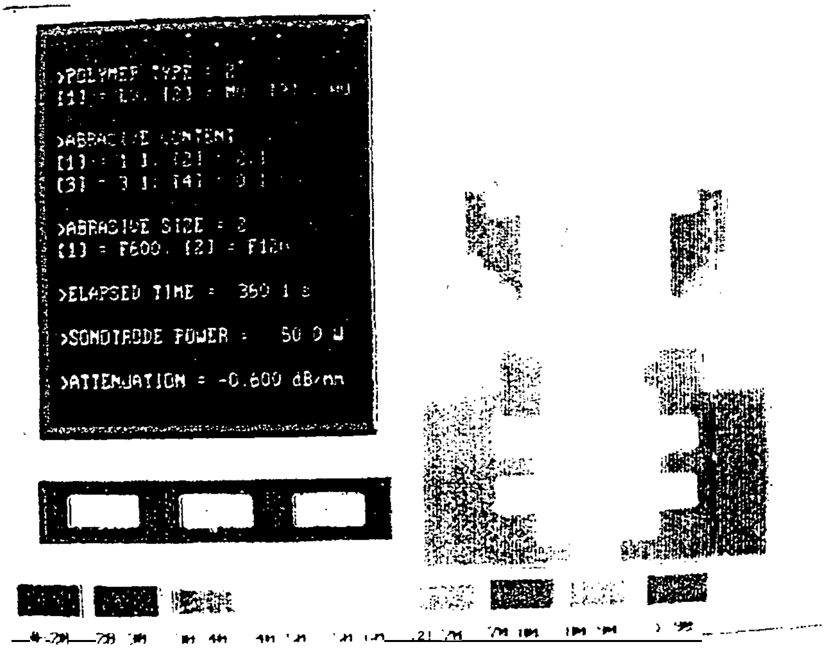

```
>POLYMER TYPE = 2
>ABRASIVE CONTENT
>ABRASIVE SIZE = 2
[1] = F600. [2] = F1
>ELAPSED TIME =  360 1 s
>SONOTRODE POWER =   50 0 W
>ATTENUATION = -0.600 dB/mm
```

Figure 10: The predicted temperature distribution within the ultrasonic polishing system calculated from the finite element thermal model. The simulation is for 14µm silicon carbide abrasive mixed with medium viscosity polymer and shows the temperature distribution in the die, the polishing media and the sonotrode after 360 seconds of polishing.

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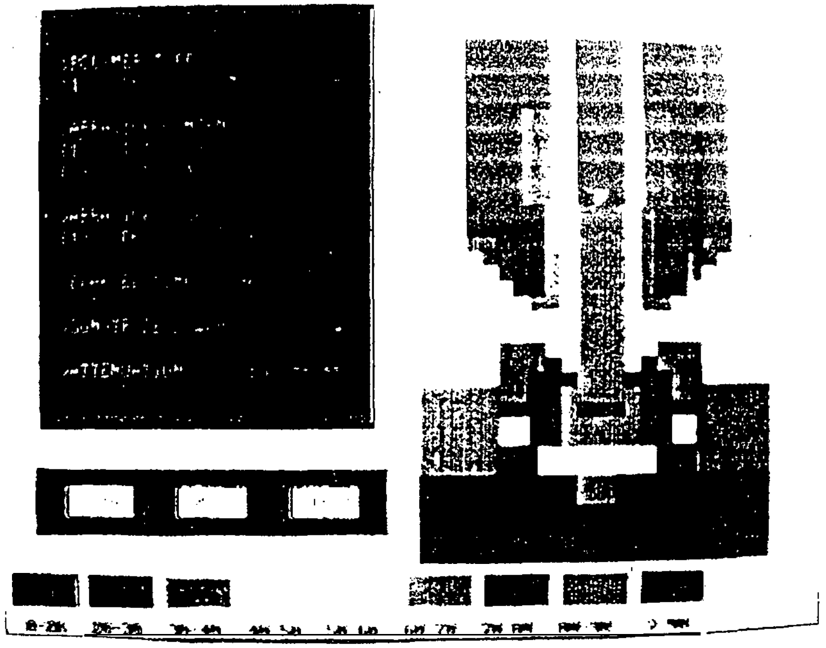

Figure 11: The predicted temperature distribution within the ultrasonic polishing system calculated, from the finite element thermal model. The simulation is for 14pm silicon carbide abrasive mixed with medium viscosity polymer and shows the temperature distribution in the die, the polishing media and the sonotrode after 960 seconds of polishing.

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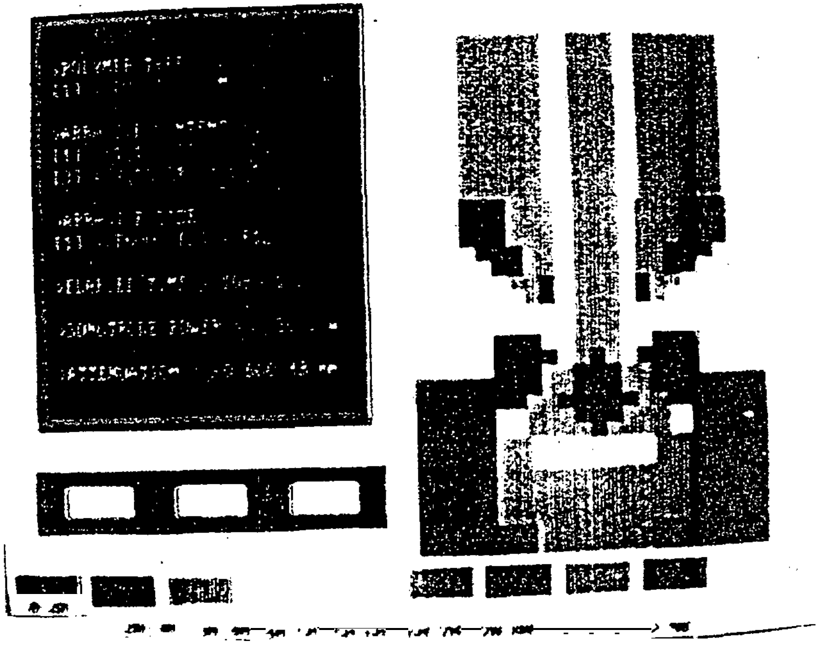

Figure 12: The predicted temperature distribution within the ultrasonic polishing system calculated from the finite element thermal model. The simulation is for 14pm silicon carbide abrasive mixed with medium viscosity polymer and shows the temperature distribution in the die, the polishing media and the sonotrode after 1080 seconds of polishing.

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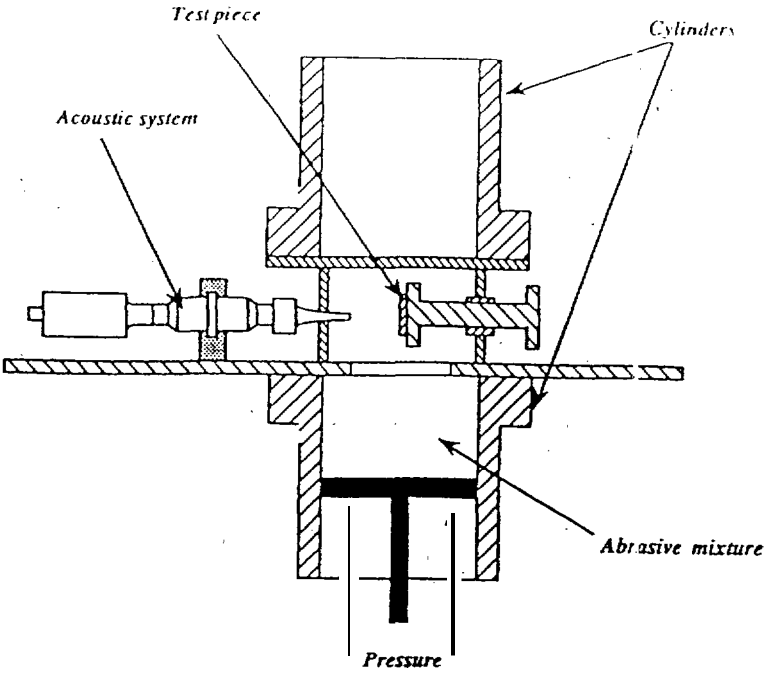

Figure 13: The initial experimental ultrasonic polishing machine developed at Partner 4.

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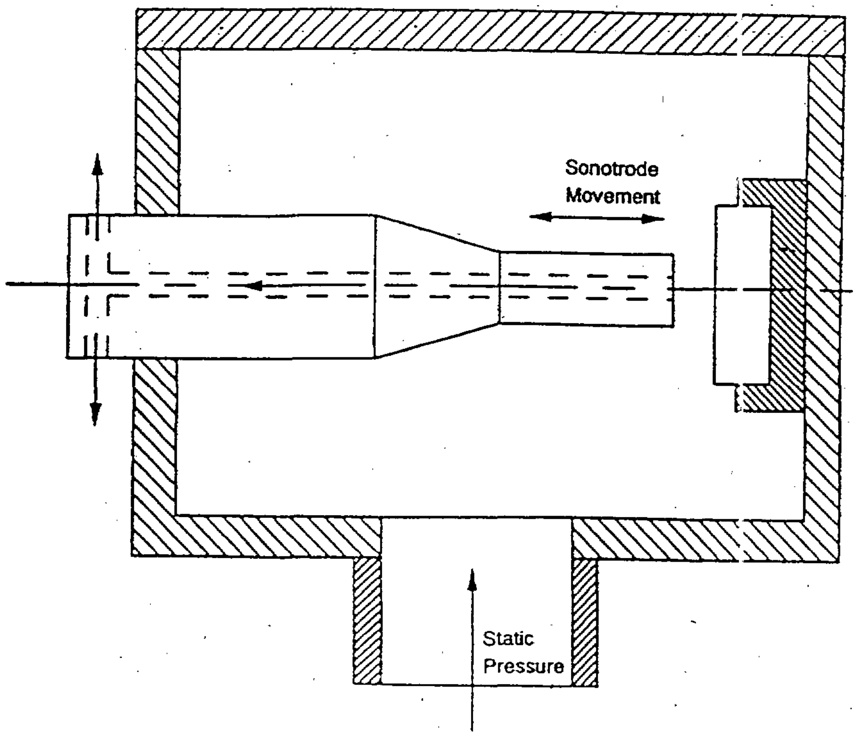

Figure 14: The modification to the experimental polishing machine to introduce the flow of polishing media up a flow channel in the sonotrode.

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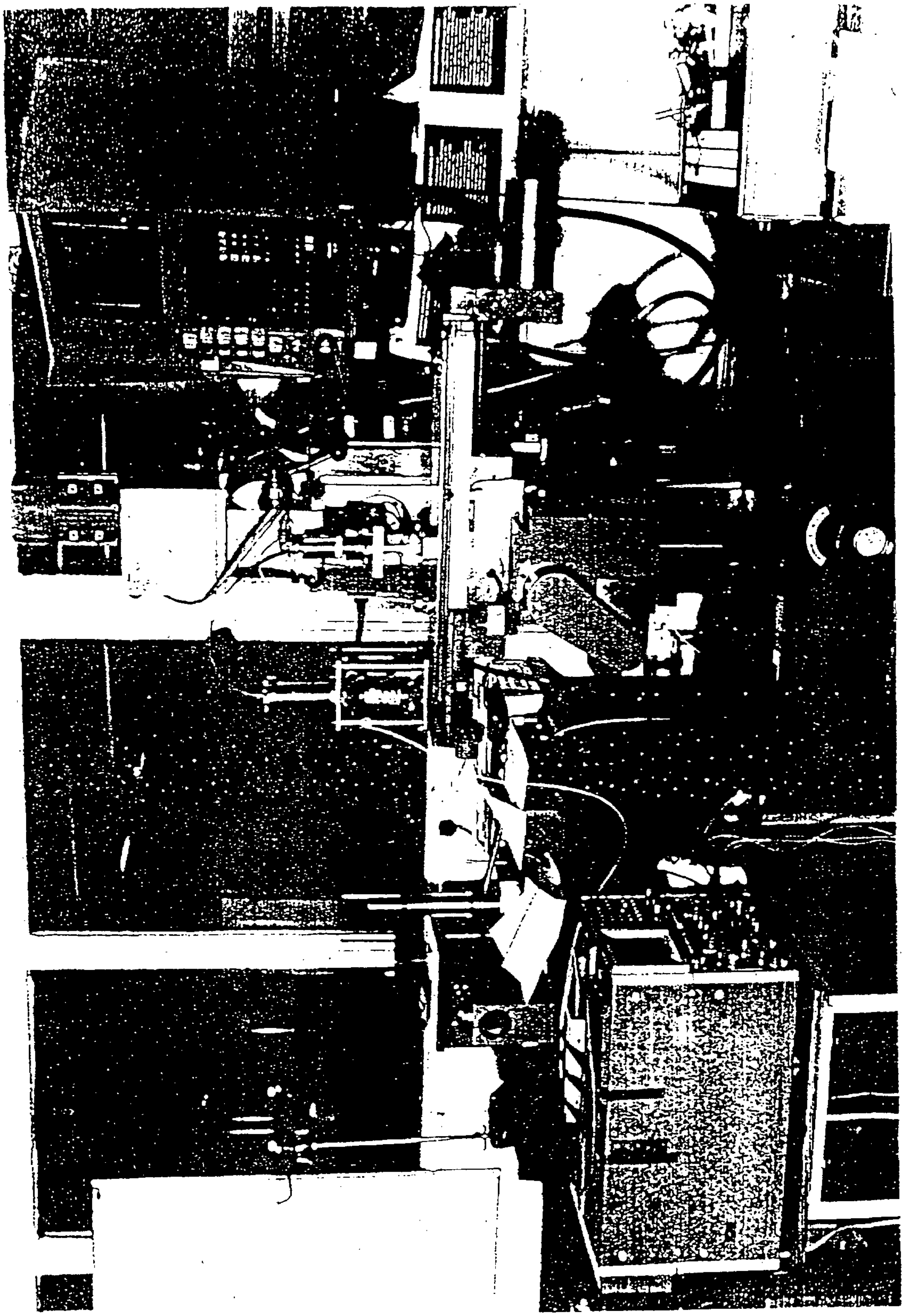

Figure 15: The numerically controlled experimental ultrasonic flow polishing machine developed at Partner 3.

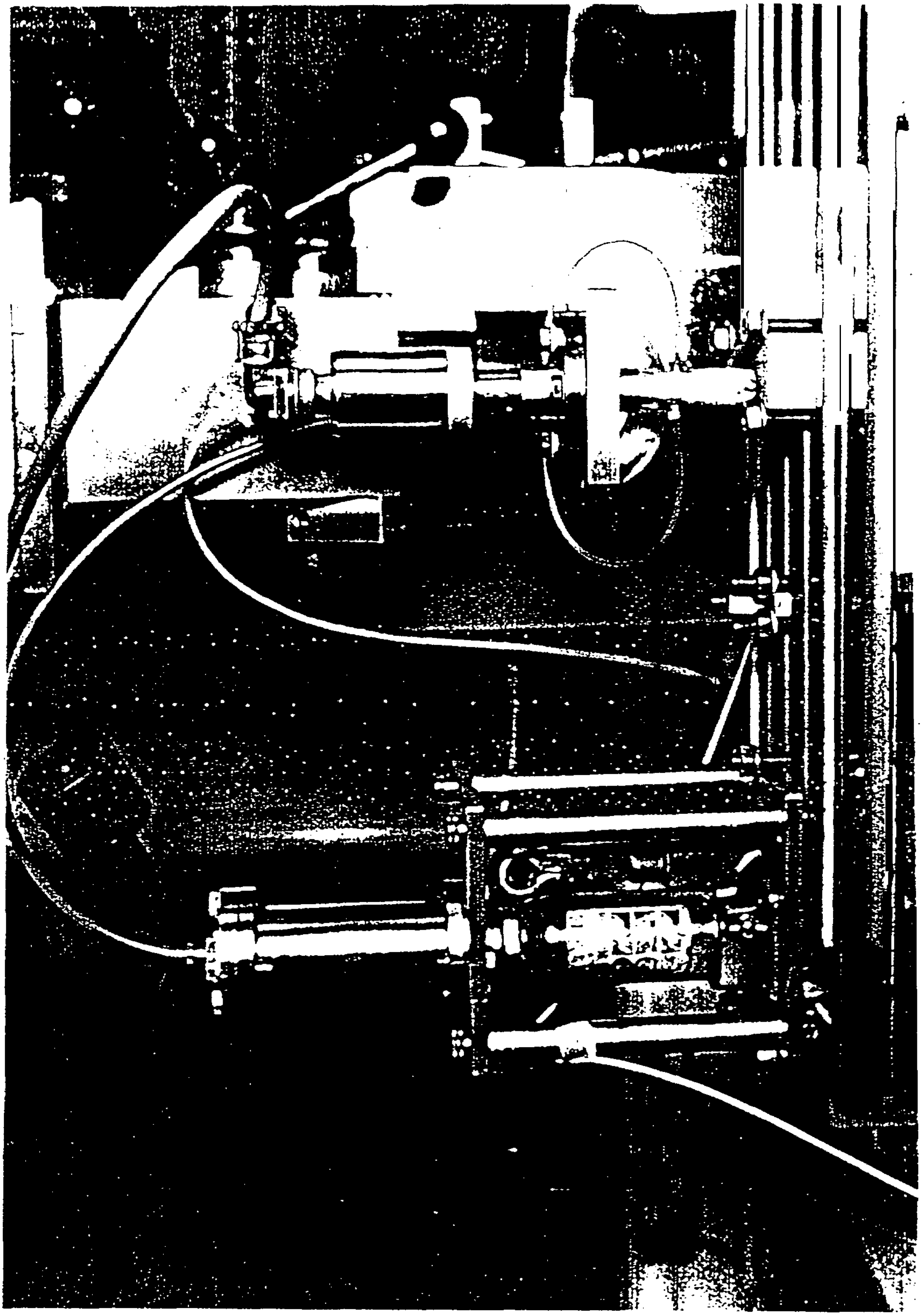

Figure 16: The acoustic system and abrasive media feed system used on the numerically controlled ultrasonic polishing machine at Partner 3.

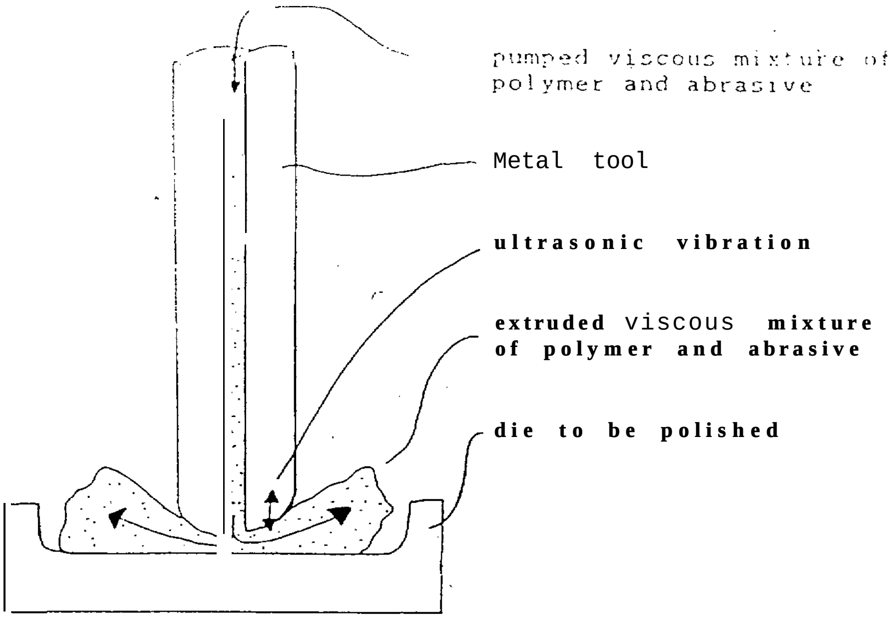

Figure 17: The ultrasonic flow polishing action showing the flow of viscous abrasive mixture and the ultrasonic vibration.

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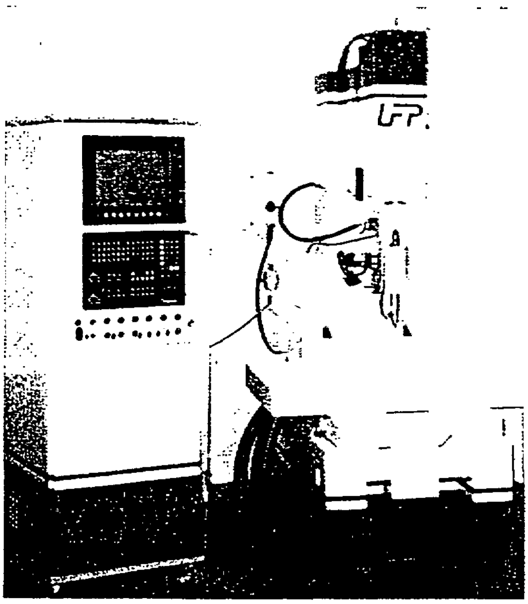

Figure 18: The completed prototype ultrasonic flow polishing machine **currently** installed at Partner 1's development facility.

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