Invited Paper

Moire based Optical Surface Profiler for the Minting Industry

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ABSTRACT

An Optical Surface Profiler (OSP130) has been developed for the metrology of master tooling used in the coin stamping process. The OSP130 measures, in a non-contacting manner, the surface relief of tools ranging in diameter from 10 mm to 300 mm. Rapid measurements are performed simultaneously on a large grid of equispaced points across the surface of the tool. From the relief data, many parameters such as the location of high and low features, volume of impression, background curvatures and various diameters can be quickly evaluated.

The technique used is phase-shifting moire profilometry. A white light projector illuminates a periodic transmission grating which is then imaged onto the object surface. The light pattern on the object is viewed by a high resolution TV camera connected to a computer. The grating is shifted under computer control to a number of positions and corresponding intensity images of the deformed pattern on the object surface are stored in the computer. From the intensity images a phase map, representing the deformation of the periodic grating by the surface relief, is evaluated and compared with an undeformed pattern. This results in an accurate contour map of the surface relief with an uncertainty less than 1% of the relief excursion on the object. Details of the instrument and its use at the Royal Australian Mint are presented.

1. INTRODUCTION

The Optical Surface Profiler (OSP130) is an instrument developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) in collaboration with the Royal Australian Mint (RAM), specifically for the assessment of master tooling used in the coin stamping process.

The major reason for developing this instrument was to overcome the many limitations imposed by traditional assessment techniques and by so doing to offer a comprehensive metrology instrument for quality and process control in the fabrication of master tooling.

The OSP130 is an optically based instrument which measures the surface relief in a non-contacting manner. Rapid measurements are performed simultaneously on a large grid of equispaced points (typically 520 x 520) across the surface of the tool. From the relief data many parameters such as the volume of impression, the location of high and low points, background curvatures and various diameters can be quickly evaluated. All the master tools, irrespective of their material or size in the range of 10 mm to 300 mm diameter, can be assessed and characterised with the OSP130. The relief measurement uncertainty at any point on the surface is typically less than 1% of the peak to valley relief excursion of the tool or object being measured.

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2. BACKGROUND

In the coin production process a significant part of the cost is associated with the design and fabrication of master tooling. In a typical tooling chain (figure 1), a plaster model of the coin surface is made from which an incuse (ie. negative) silicone rubber mould is cast. The rubber model is then slumped over a hemisphere to superimpose a background curvature on the relief design. This is necessary to ensure efficient metal flow during the final stamping of coins in a blank. An epoxy mould is then produced from the curved silicone model. The epoxy is a positive relief which has the background curvature as part of the relief. The epoxy model is then used in a three dimensional pantograph engraving machine which cuts a reduced size replica into soft tool steel. This results in a 'reduction punch' which is then hardened and used to press an incuse replica in a soft metal. This is the 'master die'. From this die a number of 'working hobs' are made and from each of these a much larger number of 'working dies' are made. The working dies are then used in pairs (one die for each side of a coin) in a press to stamp out the coins from the blanks.

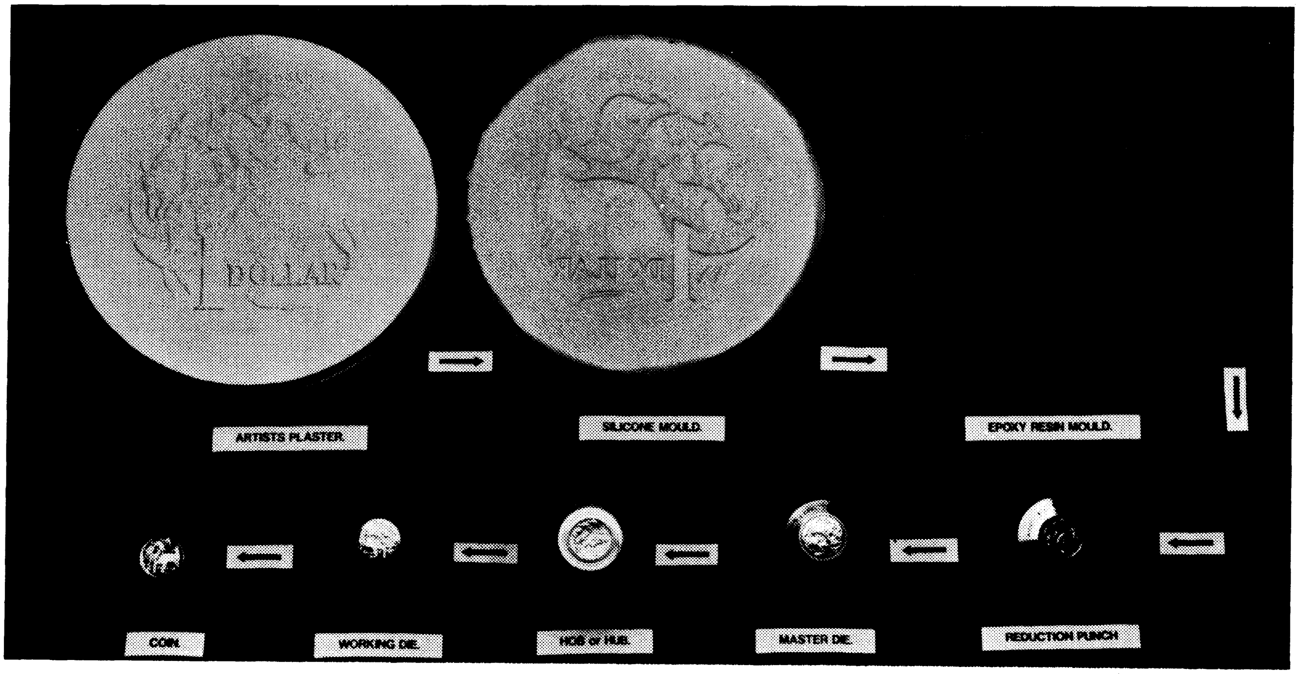

Figure 1. Range of tools used in the coin minting process.

The longevity of the dies, the press pressure required to properly coin a blank and the quality of coins produced, are all intimately related to the relief design. How this design affects each of these practical characteristics is not well understood and has been somewhat a subjective issue amongst the minting community. However the RAM through their many years of experience have identified a number of design parameters which directly influence the practical characteristics. Parameters such as the relief statistics of specific profile sections, high and low features on the coin, various diameters, the volume of material displaced on coining and the background curvature, all play a vital role (see section 10 for further discussion). The problem so far has been to measure these parameters accurately and efficiently during all stages of master tooling fabrication.

In the past these parameters were measured by a combination of slow and labour intensive techniques such as point contact measurements for selected profiles, weighing an amount of oil which fills the die cavity for volume calculations and the use of various gauges and hand tools for dimensional measurements. Furthermore most of the measurements were done on the metal tooling since it was very difficult if not impossible to perform measurements on the rather fragile models and moulds. Hence the development of the OSP130.

3. FUNCTIONAL OVERVIEW

A functional schematic of the OSP130 is shown in figure 2. It consists of a projection assembly, an object or sample platform, an observation assembly and a computer for processing and control. The object is positioned on a platform having three axes (X,Y,Z) of translation adjustments and a rotational (θ) adjustment. A white light projector illuminates a quasi-sinusoidal transmission grating which is then imaged by a lens on to the object surface. The projected light pattern on the object surface is imaged at normal incidence by a lens onto the CCD array of a TV camera connected to a digitising card inside a computer. The intensity image seen by the camera is thus converted into an array of numbers representing the light distribution over the object surface.

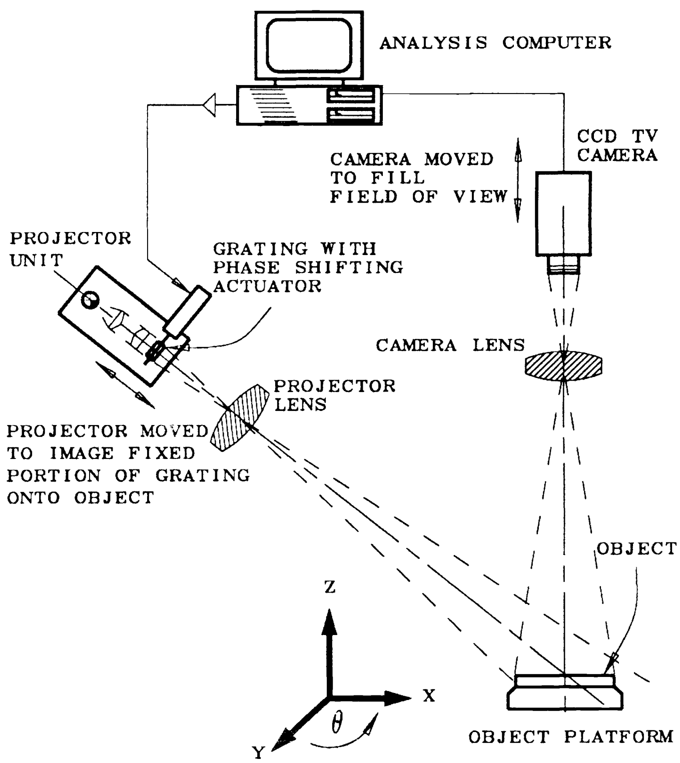

Figure 2. Functional schematic of the OSP130 instrument.

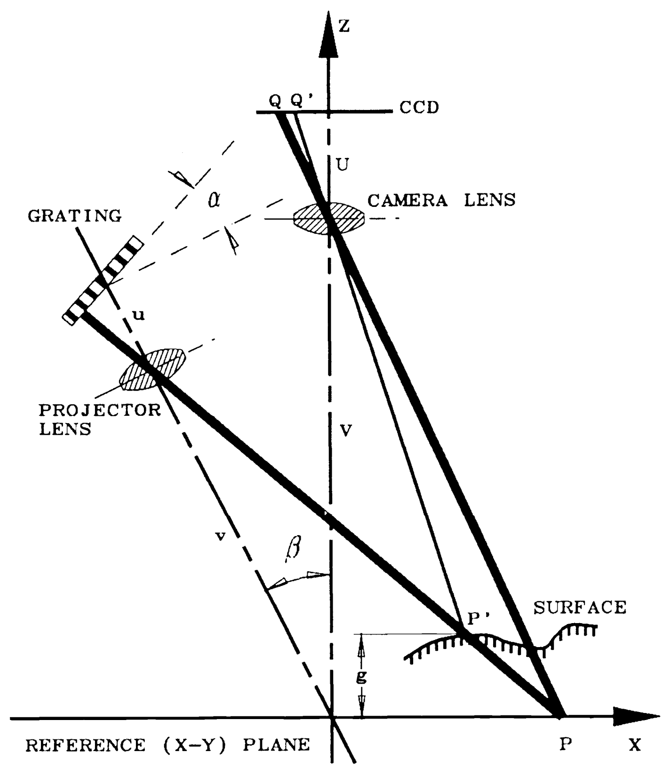

Figure 3. Schematic of the OSP130 projection and observation geometry.

Since the diameters of the objects to be measured vary from 10 mm to 300 mm the magnification of the optical system must adjusted over a 30:1 range. This is achieved by moving both the camera and projector assemblies correspondingly along their optical axes and refocussing the two lenses. The TV camera uses a 55 mm fixed focal length lens for object sizes up to 150 mm diameter and a 28 mm focal length lens for larger objects. The projector uses a single 85 mm fixed focal length lens for all object sizes.

Since the axis of the projector is not normal to the object surface, to ensure a good focus of the grating over the entire object surface, a tilt mechanism is used in the grating sub-assembly to achieve the Scheimpflug[1] condition.

4. MEASUREMENT TECHNIQUE

The shape measurement technique implemented is *phase-shifting moire profilometry*[2,3]. When a spatially periodic light pattern is projected onto an irregular surface such as that of a die, it deforms with the surface shape. If this deformed pattern is compared (eg by subtraction in a computer) to an undeformed pattern produced by a flat surface, the result is a coarse pattern which is a relief contour map of the irregular surface.

To improve the accuracy of measurement a phase-shifting technique [4,5] is utilised in which a number of deformed grating intensity images are recorded for each object with the pattern shifted slightly between each recording. The pattern is shifted by a motorised actuator in the projector under computer control (figure 2). The acquisition of intensity data is completed in about two seconds. In a typical measurement cycle (see section 8) both the deformed pattern on the object and the undeformed pattern produced by a flat reference surface (see section 5.1) are recorded. From the deformed and the undeformed patterns, corresponding phase maps (see section 5.1) are calculated for the object and the reference surface respectively. The phase maps describe the deformation or the deviation from straightness of the intensity pattern. By subtracting the two phase maps the shape of the object surface is obtained.

Since the gratings used are not perfectly sinusoidal but instead have a considerable higher harmonic content a new seven-sample phase-shifting algorithm [6] has been developed to give good quality phase data from the intensity maps. This algorithm is quite insensitive to a number of harmonics present in the gratings used and also performs well in the presence of phase-shift errors.

5. PRACTICAL CONSIDERATIONS

The configuration described above poses a number of challenging problem which need to be solved in order to produce a reliable, accurate, flexible and cost effective instrument. Some of these problems will now be discussed.

5.1. Height sensitivity variation

Figure 3 is a schematic diagram of the projection and observation geometry employed in the OSP130. White light illuminates the transmission grating which is tilted at some angle α so as to satisfy the Scheimpflug[1] condition. The grating is then imaged by the projector lens onto the surface of the object whose relief is to be measured. If we assume that the grating lines are parallel to the y axis then since the light projected onto the object surface is not collimated, the spacing of the grating over the surface will vary in the x direction. This results in a varying height sensitivity s(x) along the x direction. If $\Phi(x,y)$ is the measured phase [6] of the deformed grating resulting from the variation of the object's relief, then the surface relief g(x,y) can be evaluated from the following expression

$$g(x,y) = s(x)\, \Phi(x, y). \tag{1}$$

It can be shown that for our configuration

$$s(x) \simeq \frac{(1+bx)^2\ \lambda g\ m \cos \alpha}{2\pi\cos\beta\ \{(\frac{1}{V} - \frac{1}{v\cos\beta})x - \tan\beta\}} \tag{2}$$

where: $$b = \frac{\sin(\alpha+\beta)}{V \cos\alpha}, \tag{3}$$

λg is the spatial wavelength of the grating, m is the projector magnification and other parameters are as shown in figure 3.

As can be seen from equation (2) the height sensitivity depends on many geometrical parameters. To evaluate the height accurately these parameters must be known to a high degree of precision for every magnification of the system i.e. for every object size. One way to achieve this is to design and build a tightly toleranced opto-mechanical system whose parameters are accurately known and do not vary substantially with usage. In practice, such systems are prohibitively expensive and difficult to maintain.

Our approach to this problem was to measure the grating phase distribution over a flat reference surface as well as the object surface whose relief is to be determined. From the reference phase map, most of the geometrical parameters of the opto-mechanical configuration can be obtained through least squares fitting of data to a theoretical expression of reference phase. Furthermore, the reference phase map is subtracted from the object phase map to obtain the object's relief. A single, flat reference surface was constructed, large enough to be used with any object diameter up to 300 mm. The sequence of measurements is discussed in section 8. With the use of a physical reference surface as discussed above it was possible to relax the opto-mechanical tolerances of the instrument by a considerable amount (e.g. a factor of 20 for some parameters).

5.2 Steep surface gradients

A special characteristic of coins and the master tooling used to produce them is the very steep surface features such as the rims and lettering. In some cases these gradients approach 83° from horizontal, i.e. almost vertical. This can pose severe difficulties in choosing a suitable measurement configuration and in the interpretation and analysis of phase data. Another compounding problem is the large variation of the aspect ratio, defined as the ratio of the coin diameter to the maximum relief excursion. This ratio can vary from about 20:1 to 300:1 for different coins. A good compromise was achieved between height measurement accuracy, spatial resolution, complexity of fringe interpretation and practicality of configuration by selecting the optimal grating frequency (from a limited number of gratings) for each object to be measured. In the simplest selection scheme a grating frequency is chosen so that the maximum relief of the coin produces less than one fringe deformation. This avoids phase discontinuity removal problems and allows very steep gradients to be simply measured. However, measurements with two separate gratings having different frequencies have also been used to improve the range and accuracy of relief measurements.

5.3 Shadowing

The configuration depicted in figures 2 and 3 leads to illumination shadowing over the areas of the coin which have surface slopes greater than or equal to the angle between the camera and projector axes (i.e. β in figure 3). To overcome this problem, two measurements are performed on each object with the object rotated by 180° between the two measurements. The two sets of measurements are then combined, with the aid of specifically developed software, to give a shadow-free relief map.

5.4 Surface reflectivity

Some of the coining tools have a white diffuse surface finish e.g. the plaster and silicone models. These can be measured on the OSP130 without any surface treatment. Metal tools have either a specular shiny or dull surface finish. Such surfaces are coated with a thin diffuse white coating prior to measurement. The coating, which is applied by spraying, is quick and easy to apply and remove and does not change the surface detail by more than a few micrometres. This is well within the total measurement uncertainty for most coining tools.

6. OPTO-MECHANICAL HARDWARE

Figure 4 is a photograph of the OSP130 instrument. The vertical column supports the television camera viewing assembly while the tilted column carries the projector assembly. Both the camera and projector can be moved along their respective columns either manually as shown in this picture or under motor control. The positions of the camera and the projector are determined by the object's diameter. The object platform is located between the two columns. The instrument has been designed to allow easy access to all the necessary adjustments and a single operator can operate the entire instrument and monitor the state of the instrument from the computer console.

7. SOFTWARE

The operation of the OSP130 is controlled through menu-driven software. Figure 5 shows an example of one of the menus. The software guides the operator through the initialisation and calibration of the instrument. It then controls the acquisition and processing of the data, displays the requested results and finally generates the measurement report. The software can be operated in either the developmental or batch modes. The developmental mode is used to execute the programme in any sequence that the operator chooses at the console. The batch mode is used to execute a predefined sequence of procedures usually implemented in a typical measurement and analysis cycle. This mode requires little user interaction or knowledge about the intricacies of the software. A more experienced user of the instrument can easily create new batch files. For further discussion of software capabilities see section 10.

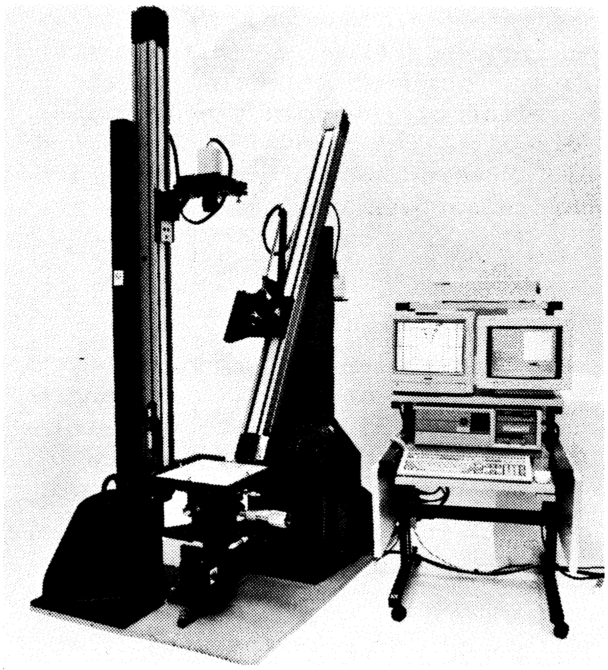

Figure 4. OSP130 instrument.

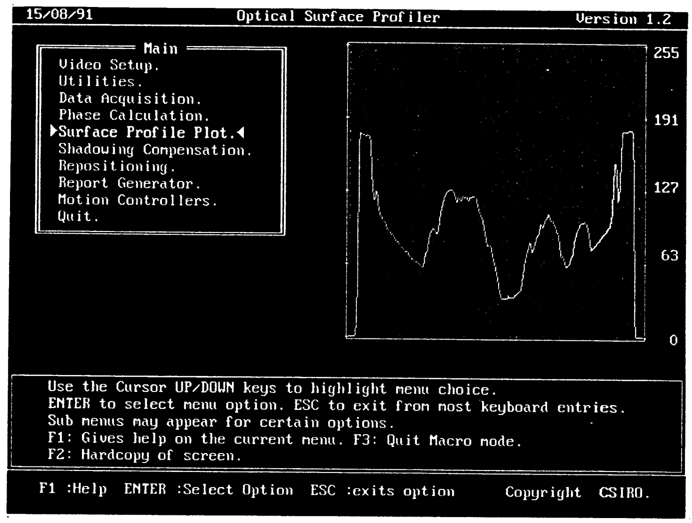

Figure 5. Main menu of the OSP130 software.

8. TYPICAL MEASUREMENT CYCLE

To indicate how all the above factors are brought together we outline a typical measurement procedure. First the operator enters into the computer the nominal dimensions of the object to be measured (eg. diameter and height). The instrument then automatically moves the camera and projector to their correct positions. With software assistance the operator then adjusts the camera and projector lenses. The instrument is then calibrated by measuring a flat reference surface. The reference surface is then replaced with the object (tool) to be measured with the assistance of a positioning target displayed on the computer monitor. Data is then acquired for the object in two positions 180° apart and automatically processed in the computer to give the surface relief map. Finally, the operator interactively generates and prints out the measurement report.

9. MEASUREMENT OF HALF DOLLAR USA COIN

Figures 6 to 10 show the relief measurement results on a half dollar USA coin. Figure 6 shows a phase map derived with a seven-sample phase-shifting algorithm. The phase at every pixel is stored and processed in the computer as a one byte number and is displayed in the figure as 16 equispaced grey levels with black being the lowest value of phase and white the highest. The periodic wrap around in the phase is evident due to the periodicity of the arctangent function used in the evaluation of the phase. Once the phase map produced by a flat reference surface is subtracted from the above object phase map a relief map of the coin is obtained. This is shown as a 16 level grey scale contour plot in figure 7 where dark shades represent low relief and bright shades, high relief. The background convexity or curvature in the coin relief is evident from the circular nature of the relief contours. Also shown in the figure with two small squares are the locations of the highest and lowest features inside the rim area. Figure 8 shows the relief details of a sectional profile AB identified in figure 7. Figure 9 shows a perspective three-dimensional relief plot of the coin derived from the above measurement. From the relief data a number of other parameters useful to the minting industry are calculated. Some of these are summarised in figure 10.

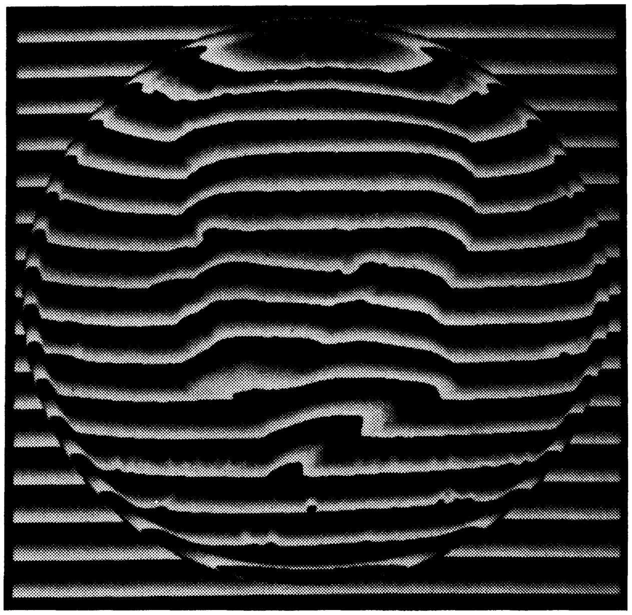

Figure 6. Grating phase map for a half dollar USA Coin (JFK side).

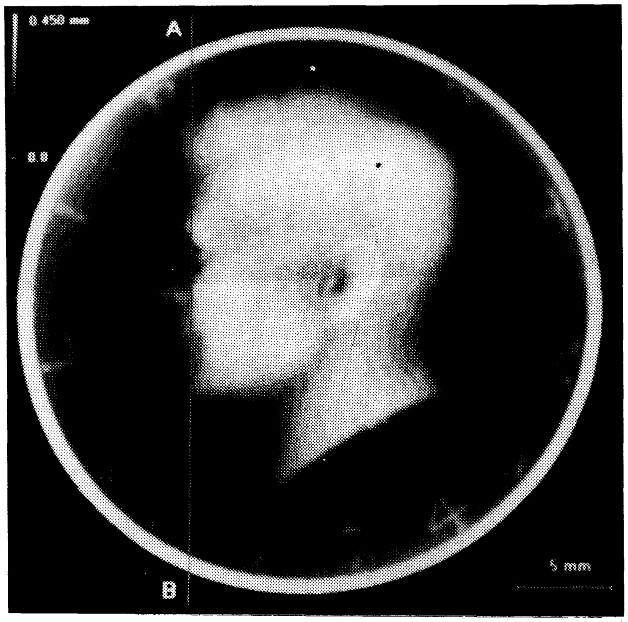

Figure 7. Relief contour plot for a half dollar USA coin.

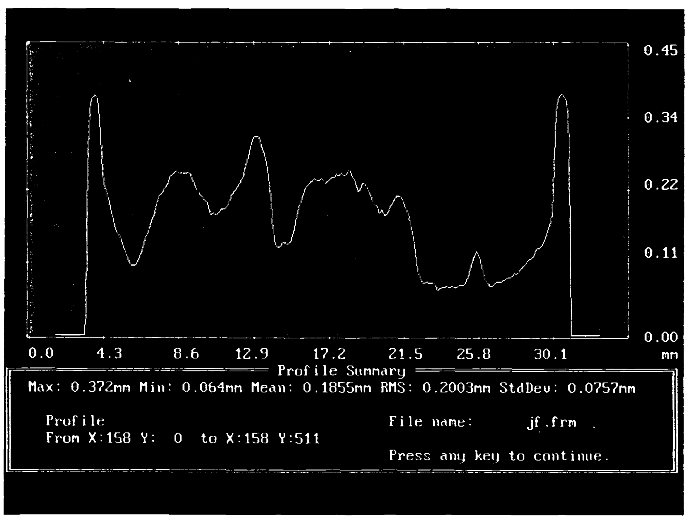

Figure 8. Relief profile AB shown in figure 7.

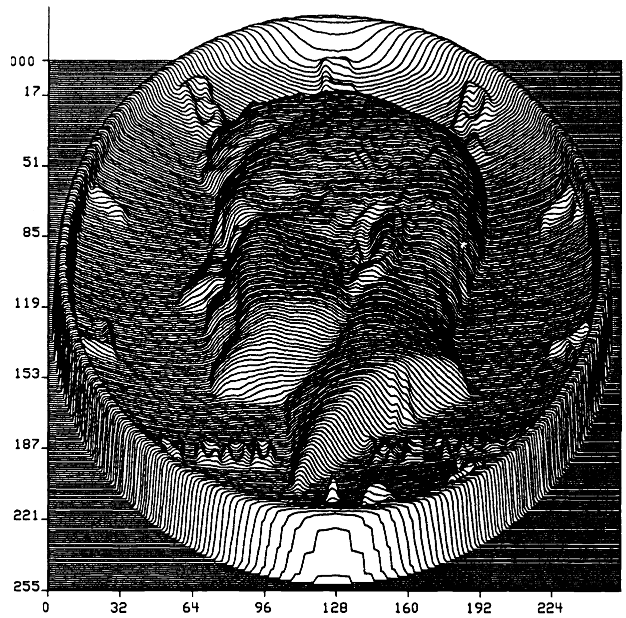

Figure 9. Three-dimensional relief plot of the half dollar USA coin.

10. PRODUCTION CONTROL AT THE ROYAL AUSTRALIAN MINT THROUGH OSP130

Research at the Royal Australian Mint has shown that the height difference between the lowest and highest points in the coin relief, the background convexity and volume below rim, have a major effect on the press load required, and in turn, the die life. In extreme cases the full design cannot be struck at any load. Established metrology methods can only measure all these parameters at the metal tooling stages such as the working hob and this procedure can take many hours to complete. Changes are easily made at the plaster stage whereas only minor changes can be made to metal tooling.

```
=Report on measurements from the Optical Surface Profiler=

    Report File: jf.frm   Date: 28/08/91   Time: 13:30:47
    Object's Center:
    Outer rim  X: 254 Y: 257           Inner rim  X: 254 Y: 257
    Object's diameters:
    Outer rim vertical   : 30.32 mm    Inner rim vertical   : 29.08 mm
    Outer rim horizontal : 30.36 mm    Inner rim horizontal : 29.01 mm

    Highest point at X: 311 Y: 133 is  0.409 mm
    Lowest point at X: 261 Y:  50 is  0.007 mm
    Mean Rim height is  0.353 mm
    Distance between  rim and highest point is -0.056 mm
    Distance between rim and lowest point is  0.346 mm
    Empty volume below rim is  84.654 cubic mm
    Empty volume below highest point is 122.528 cubic mm
    Volume of material is 121.938 cubic mm
    Mean spherical radius is 285.259 mm
    Effective surface convexity is  0.370 mm

                             Press any key to continue. F2 Hard Copy
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Figure 10. Relief related parameters for the half dollar USA coin.

Since the instrument can be used to measure the early stages of tooling such as the artist's plaster model, it is possible to assess and characterise the tool design at this stage. Artificial rims and background curvatures can be added in software thus enabling a full characterisation of the tool, without the need to obtain a suitable metal tool.

The relief plots shown as either a two-dimensional colour contour plct or as a three-dimensional perspective plot offer a tremendous amount of useful, accurate and objective data which can be easily interpreted by the operator. Many faults in the tool being measured or characteristics of its design can be readily identified eg. 'squirt' along the rims, tilt over the tool, location and extent of high and low areas. Tools may be accurately repositioned on the instrument, with respect to a previous measurement. This allows direct comparison of relief and other features on any tool during various stages of fabrication to identify the quality of replication from one stage to the next and the effect of certain metallurgical procedures such as heat treatment. Die wear can also be assessed objectively.

A simple yet powerful software feature which aids in the comparison between different stages is the positive to negative relief conversion algorithm. This allows the relief map of a negative tool to be converted into a positive relief and then directly compared with any positive relief tool of the same impression.

The software allows the superimposition of the two sides of a coin and a slice or section through this composite image gives important information about coin thickness variation over the surface. The software also allows for rotation of images and it is therefore possible to change the relative angular orientation of the two sides of the coin and then study the thickness variation.

11. CONCLUSION

The OSP130 is an optically based precision instrument, custom designed to improve metrology and quality control capabilities of the Royal Australian Mint. The instrument can assist in quality and process control by providing measurements and data leading to answers for many important issues such as: differences between dies, optimal impression designs for the press force available, effects of heat treatment and hardening, and optimum profile parameters for different materials.

A major feature of the OSP130 is that one operator can carry out the entire measurement and data analysis procedure and produce the test report in as little as 15 minutes while a similar report derived from traditional measurement techniques would take a number of hours. The OSP130 reduces the time a tool spends in the metrology laboratory and provides information on 270,000 points to enhance the production of a high quality tool.

12. ACKNOWLEDGEMENTS

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13. REFERENCES

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