

An introduction to Moiré method

Citation for published version (APA):

Wang, S. L. (1992). *An introduction to Moiré method*. (TH Eindhoven. Afd. Werktuigbouwkunde, Vakgroep Produktietechnologie : WPB; Vol. WPA1278). Technische Universiteit Eindhoven.

Document status and date:

Published: 01/01/1992

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

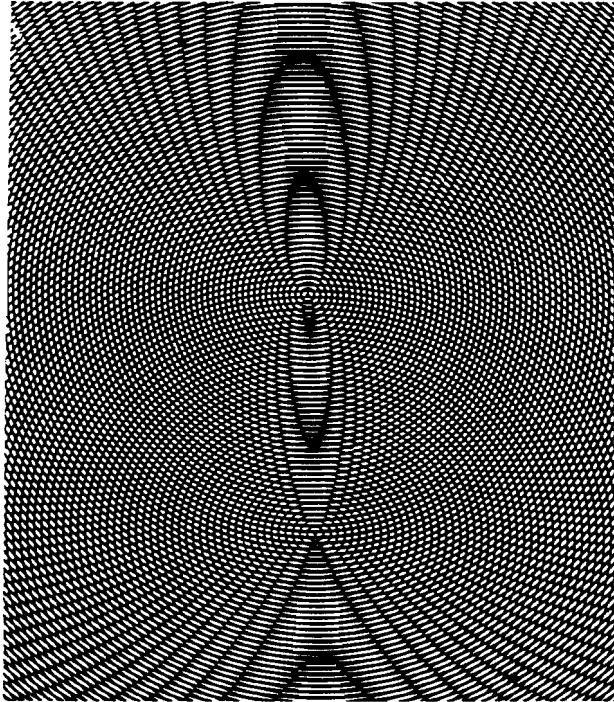
AN INTRODUCTION TO MOIRÉ METHOD

Wang Shunlong

Mar. 1992

WPA 1278

The Bride. Moiré associated with two elliptical gratings displaced along their minor axis.



CONTENTS

I.	SUMMARY	(1)
II.	THE PRINCIPLE OF IN-PLANE MOIRÉ METHOD	(3)
III.	AN INTRODUCTION TO OUT-OF PLANE MOIRÉ METHOD	(9)
IV.	THE MEASUREMENT OF PLASTIC DEFOR- MATION BY MOIRÉ METHOD	(12)
V.	CONCLUSION	(21)
VI.	REFERENCE	(22)

I. SUMMARY

Moiré method is a rather new experimental strain/stress analysis technique. The word "Moiré" comes from the phenomenon of a silk fabric which, when folded, exhibits patterns of light and dark bands, or fringes, produced by the superposition of two sets of gratings.

The geometrical interpretation of moiré fringe have been originated in Dutch in 1945 by D. Tollenaar. In 1954, M. Duntu introduced the interpretation of moiré fringes in terms of the components of the displacements. He put forward that a moiré fringe is the loci of points with the same displacement component normal to the direction of specimen gratings, this is the basis of the strain analysis by moiré fringes.

Based on the formation feature, moiré fringes are classified into two kinds: the first is "in-plane fringe", which is formed by two sets of gratings within one plane; the second is "out-of-plane fringe", which is formed by interference of one set of gratings and its shadow on an object. The physical interpretation of out-of-plane fringes is the contour line (loci of points at the same height). The in-plane moiré fringes are widely used in the measurement and analysis of elastic, plastic deformation; the out-of-plane fringes have been begun to be used in metrology, medical instruments and automation of industrial production.

With the rapid development of computer technology in the automatic processing of moiré data, moiré technique has been widely used to solve engineering problems, especially in metal forming processes. Moiré technique has the following characteristics compared with other experimental methods: it has very distinctive information, it is convenient to get the whole displacement field and the local strain/stress concentration, it

can be used not only to model material but also to prototype material, it has very wide ranges of measurement(such as, at room temperature and high temperature; elastic and plastic deformation until fracture; static,dynamic and creep loading). The moiré fringe analysis has been widely used in mechanical engineering, metallurgy, metal forming processes, shipbuilding, aviation and aerospace for the investigation of new equipment and new processes.

Moiré technique has been developed rapidly in theory, techniques(especially the invention of high temperature gratings, the use of "automatic processing system of moiré data", the equipment for out-of-plane moiré fringe) and applications in the recent years. The invention of high temperature moiré gratings has given us a powerful tool to investigate deeply into the metal forming processes, the material behaviour under high temperature, especially in the investigation of the forming process of new material(such as composite material, superconductor material) and material with low formability. The use of "automatic processing system of moiré data" has greatly accelerated the processing speed and accuracy of the moiré fringes. The out-of-plane moiré technique has been begun to be used in the CAD/CAM system.

II. THE PRINCIPLE OF IN-PLANE MOIRÉ METHOD

The in-plane moiré fringes are formed by the interference of two sets of gratings contacted directly. The gratings used in moiré method are specially made and regularly arranged, in high density and in dark and light bands. We call the distance between two lines of gratings one "pitch", signed as "p". The gratings are usually straight lines parallel to each other and with the same pitch(Fig 1.). Sometimes they are circles or radial lines(Fig 2.). Sometimes we use the crossing gratings or dots(Fig 3.), which are usually made of two systems of gratings perpendicular to each other. For the experiments under room temperature we usually print the gratings on stripping film before they are applied to the surface of the specimen. We can make gratings by etching, electroplating, etc for high temperature experiment.

Two sets of gratings are necessary to produce the moiré effect, the one which is deformed with the specimen is called specimen grating, the other is called the master grating(or the standard grating).

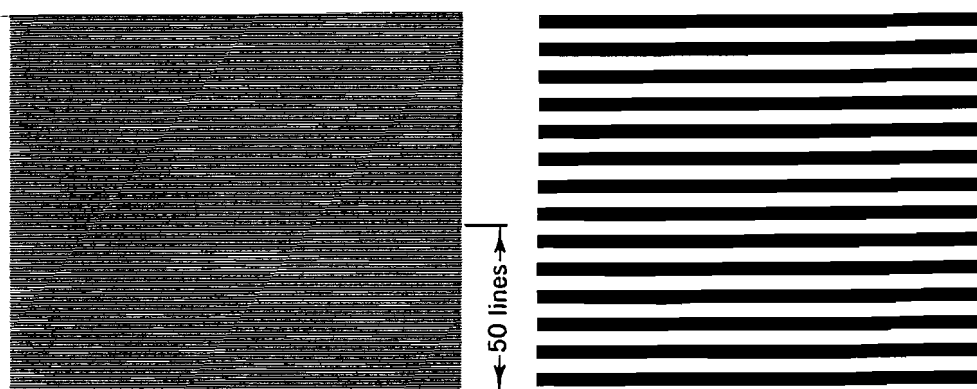


Fig 1. Typical gratings of straight parallel lines

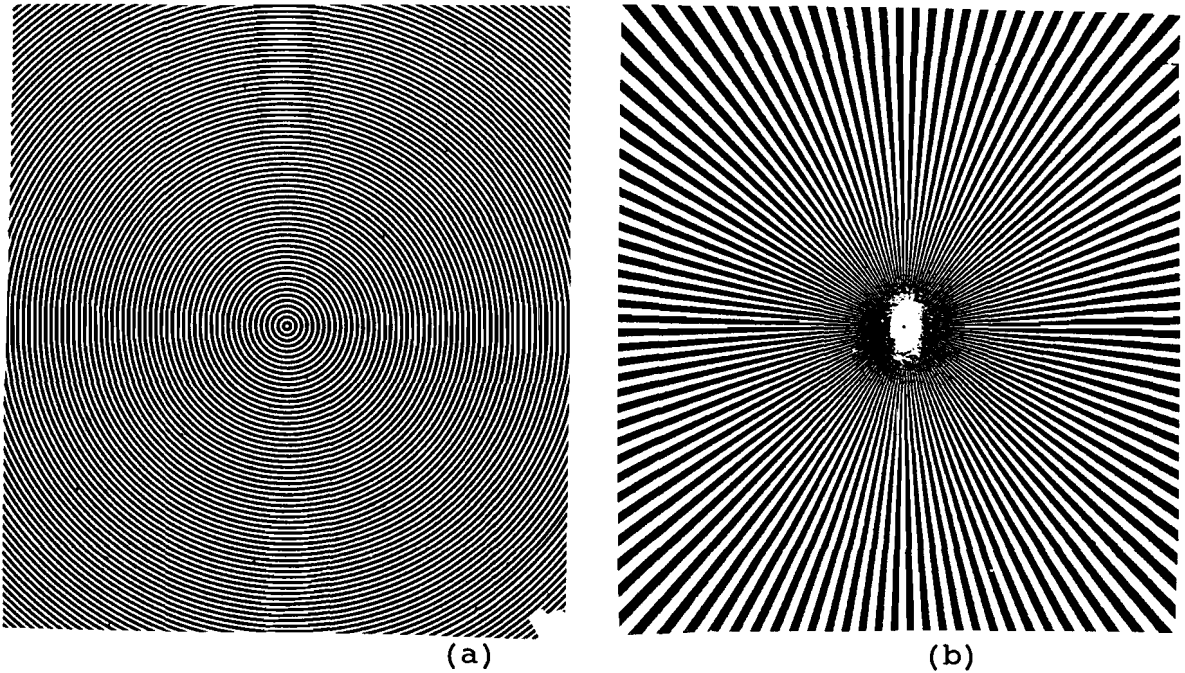


Fig 2. (a). Gratings of concentric circles with constant pitch and line width equal to interline width
(b). Gratings of radial lines with variable pitch and line width equal to interline width

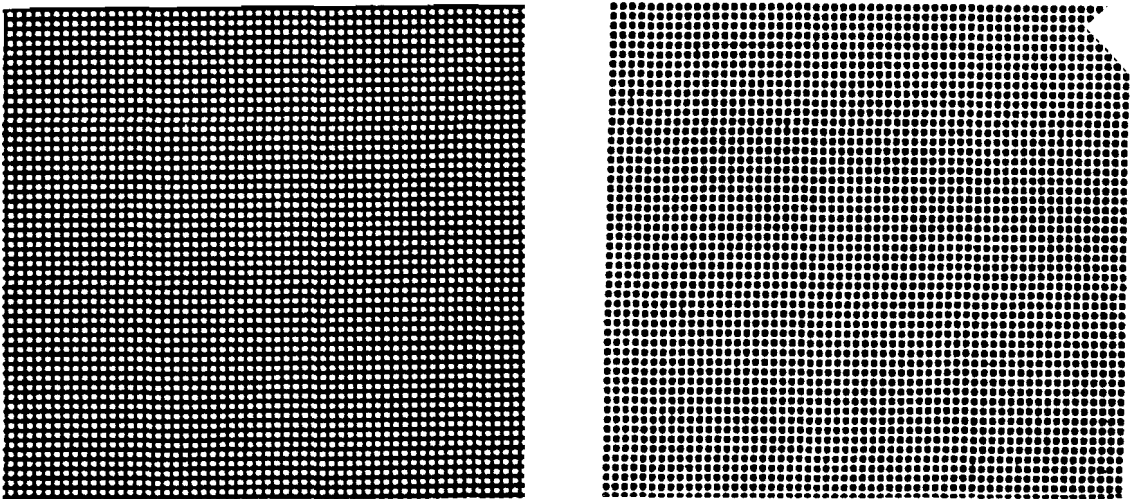


Fig 3. Gratings of crossed lines(left) and gratings of dots in a square array(right)

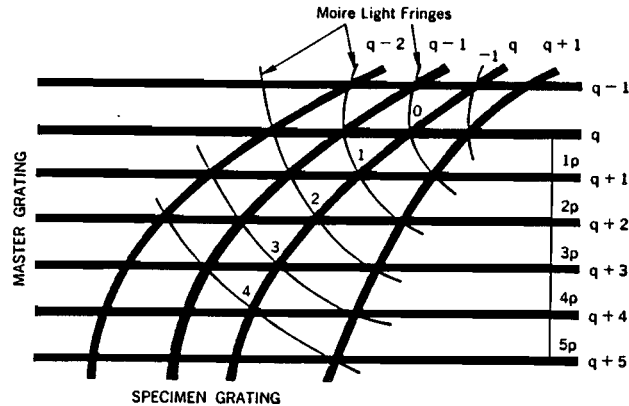


Fig 4. The sketch map of moiré fringe formation

Fig 4. is the sketch map of the moiré fringe formation. Moiré fringes are the loci of the points having the same value of component of displacement in the direction normal to the master grating (general case including relative rotation of gratings). For the purpose of the illustration, the lines have been made thinner than the interlines and the deformation is very large. The curved thin lines are deformed specimen gratings, the parallel regular thin lines are master gratings. The specimen gratings are not only elongated/compressed, but also rotated relatively to the master gratings. Assumed that the corresponding lines of the two sets of gratings are at the same place before the specimen is deformed, the numbers of them are as follows: $(q-1)$, q , $(q+1)$, $(q+2)$, When the specimen is deformed, the intersection point of the two corresponding gratings are not moved in the direction perpendicular to the master gratings, so we regard them as the point on the "0" grade moiré fringe. We can see all points on the first grade ($n=1$) moiré fringe have moved for one pitch ($1p$) in the direction perpendicular to the master gratings, the same, all points on the second grade ($n=2$) moved for $2p$, the m grade ($n=m$), moved for $m \cdot p$. We conclude that the moiré fringe is the loci of the points whose relative displacement in the direction perpendicular to the master

gratings are equal, their displacement are integer pitches of the gratings. So the moiré fringe is equal-displacement fringe.

Fig 5. is an example of a bending antilever beam. We stick specimen gratings on the side face before the beam is deformed. The gratings are parallel to the x axis with the same pitch p. When the beam is bended, the specimen gratings will be curved. We put the master gratings on the bending beam, we obtain the moiré fringes in Fig 5.

The number of moiré fringe "n" can be derived from the numbers of the two intersected gratings:

$$n = l - k \quad (2.1)$$

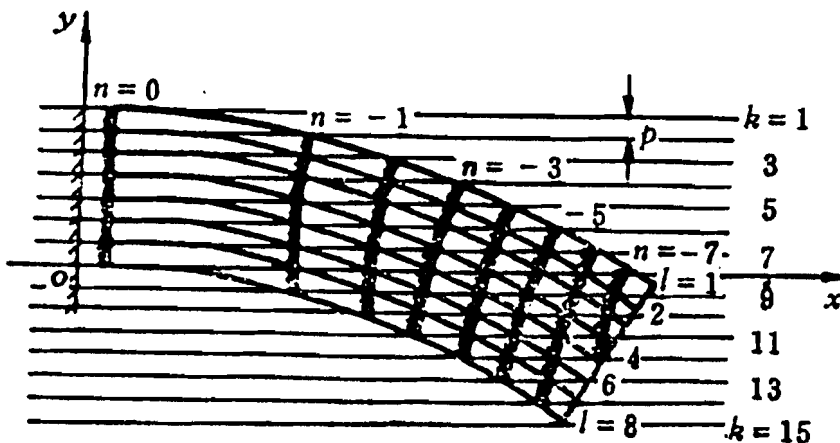


Fig 5. The bending antilever beam

k -- the number of the master gratings

l -- the number of the deformed specimen gratings

n -- the number of moiré fringe

We define u, v representing the displacement components in the direction of the x axis and y axis respectively. Fig 6. is the u displacement field (assume the x axis is perpendicular to the master gratings). δ_{xx}, δ_{xy} are the spaces between two moiré fringes in the direction of x axis and y axis respectively. The difference of the u component of displacement between the two fringes at any point is constant p. Assume $\Delta x = \delta_{xx}, \Delta y = \delta_{xy}$,

then $\Delta u / \Delta x = p / \delta_{xx}$, $\Delta u / \Delta y = p / \delta_{xy}$

In case of small deformation, the limitations are

$\partial u / \partial x \approx p / \delta_{xx}$

$\partial u / \partial y \approx p / \delta_{xy}$

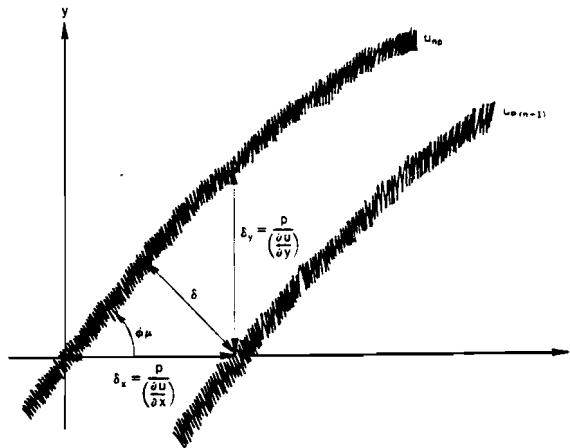


Fig 6. The u family of moiré fringes

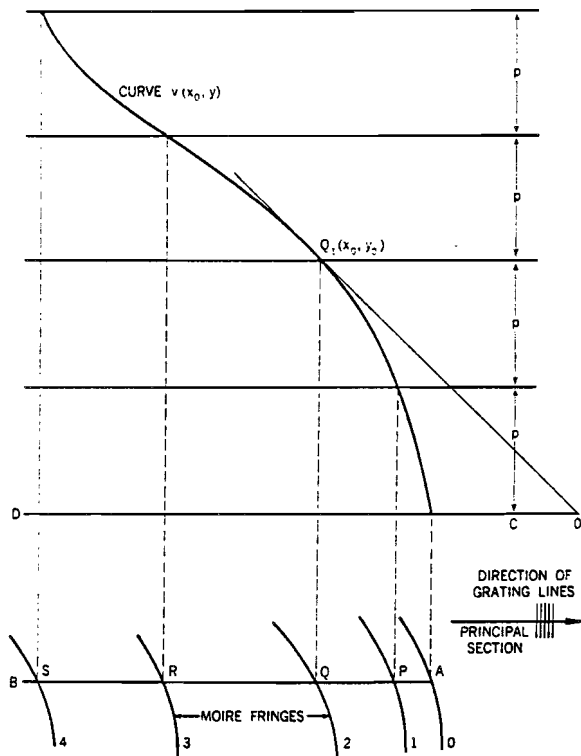


Fig 7. Construction of the intersection curve of surface $v(x, y)$ with the plane $x=x_0$

The same way, from the v displacement field, we can also obtain

$$\partial v / \partial y \approx p / \delta_{yy}$$

$$\partial v / \partial x \approx p / \delta_{yx}$$

In the circumstances of small strain, we can obtain the strain distribution:

$$\left. \begin{aligned} \epsilon_x &= \partial u / \partial x \\ \epsilon_y &= \partial v / \partial y \\ \gamma_{xy} &= \partial v / \partial x + \partial u / \partial y \end{aligned} \right\} \quad (2.2)$$

Another way to get strain field from moiré fringe can be derived, we call it derivative of displacement method. Fig 7. is the v family moiré fringes. Consider the AB section, we can easily get the $v = \varphi(y)$ curve by projecting points A, P, Q, R, S on the equal displacement lines. From the curve $v = \varphi(y)$, we can get the partial derivative $\partial v / \partial y$. The same way, we can get $\partial v / \partial x$, $\partial u / \partial x$, $\partial u / \partial y$. So we can calculate the strain distribution. In case of small deformation, the strain formula are:

$$\epsilon_x = \partial u / \partial x$$

$$\epsilon_y = \partial v / \partial y$$

$$\gamma_{xy} = \partial u / \partial y + \partial v / \partial x$$

In case of large deformation and large rotation, with the Lagrangian strain expression and Eulerian strain expression, we can obtain the ϵ_{ij}^L and ϵ_{ij}^E (see reference [1]).

III. AN INTRODUCTION TO OUT-OF PLANE MOIRÉ METHOD

The out-of plane moiré method uses one piece of master gratings, to project or reflect the master gratings on the surface of the workpiece, then the master gratings will interfere with its projection or reflection to form out-of plane moiré fringes. We also call it "shadow moiré method". Using this technique, we can measure the shape of a curved surface (height, slope, curvature, etc) and the non-plane displacement (deflection, change of thickness etc.).

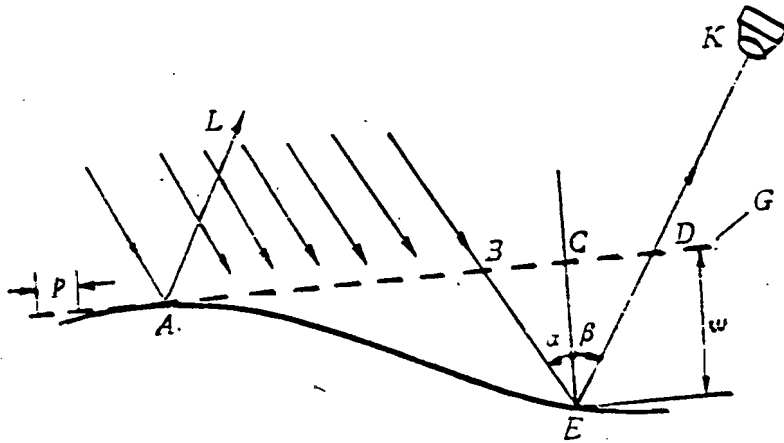


Fig 8. The principle of out-of plane moiré method

- L: parallel light beam
- K: camera
- G: master gratings

We will express the principle of out-of plane moiré method by an example: the master gratings shined by parallel beam light source.

First, put the master gratings on the surface of the workpiece to contact the highest point. Then project the master gratings to the workpiece surface by a parallel light beam at a

α angle with the normal of the master gratings. The camera separates from the master gratings faraway. Its axial is at a angle with the normal of the master gratings. Assume at point B the master grating projects to point E on the workpiece surface, when we observe at the camera, point E will be at the same place with point D on the master gratings, we can find a moiré fringe at point D.

Assume that AD contains m lines of gratings, AB contains n lines of gratings, then

$$AD=m*p$$

$$AB=n*p$$

$$BD=AD-AB=(m-n)*p=N*p \quad (3.1)$$

N represents the grade number of moiré fringe at point D, $N=m-n$. From Fig 8., we obtain:

$$BD=w*(\tan\alpha+\tan\beta) \quad (3.2)$$

where w is the distance between the master gratings and point E on the workpiece surface, that is CE.

From equation (3.1) and (3.2), we can derive:

$$w=N*p/(\tan\alpha+\tan\beta) \quad (3.3)$$

So, when the inclination α of light source, observe angle β and the pitch "p" of the master gratings are all fixed, we can define the height of the all curved surface from the moiré fringes. Obviously, the moiré fringes here represent the loci of the points on the workpiece surface which have the same distance from the master gratings. The height difference between two moiré fringes is $p/(\tan\alpha+\tan\beta)$. If the light axis of the camera coincides with the normal of the master gratings, that is $\alpha=0$. Then we can obtain:

$$w=N*p/\tan\beta \quad (3.4)$$

Practicaly, it is impossible to install the camera far away from the master gratings, but when the measuring size of the workpiece is far less than the distance between the camera and the master gratings, equation (3.3) and (3.4) are fairly good

approximation. Fig 9. is the contourline of an automobile engine connecting rod, every grade of fringes represents 1.2mm in height. Fig 10. is the contour of the vane of a steam turbine, every grade of the fringes represents 0.91mm in height.

Using this technique, we can measure the curved shape very simply and conveniently. It has been widely used in the medical science, art, light industry, public security. Now in Japan, they began to investigate to use this technique in the real-time inspection of the strip rolling.

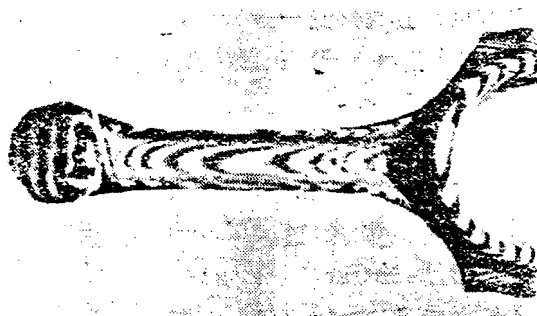


Fig 9. Moiré fringes of an automobile engine connecting rod



Fig 10. Moiré fringes of the vane of a steam turbine

IV. THE MEASUREMENT OF PLASTIC DEFORMATION BY MOIRÉ METHOD

Since the end of 1960's, the moiré method has been widely used in the measurement of plastic deformation. The moiré method has several advantages in measuring the plastic deformation: high accuracy and sensitivity than grid method; the deformation information can be easily processed; can be used to the prototype material; very large scope of deformation: unsteady processes, static loading, dynamic loading, creep loading, even to the fracture; can give the whole field deformation information; can distinguish the elastic zone and plastic zone very easily by comparing the loading and unloading moiré fringes; can obtain the incremental strain field very easily, this makes it very convenient to use the plastic flow theory. The development of high temperature moiré method is of very high importance to the investigation of hot metal forming processes. The moiré method has been widely used in such plastic forming processes: sheet metal forming processes, like deep drawing, bending, sheet metal properties and forming limit drawing investigation etc.; bulk forming processes, like forging, rolling, upsetting, extrusion etc; the elastic/plastic fracture problems.

It is very difficult to obtain theoretical solutions of the plastic deformation problems. Until now, we can just obtain several solutions of some tailored processes by a lot of assumptions. The plastic F.E.M has been widely developed and used, but the accuracy of both the theoretical solution and F.E.M solution depend on the correctness of boundary condition to a very large extent. The boundary condition, such as friction and temperature, is very complex. It can only be determined exactly by experiment. The moiré technique combined with plasticity theory has been used to analyse the internal strain/stress

distribution of the specimen. Fig. 11 shows the procedures to solve plastic deformation problems by moiré method.

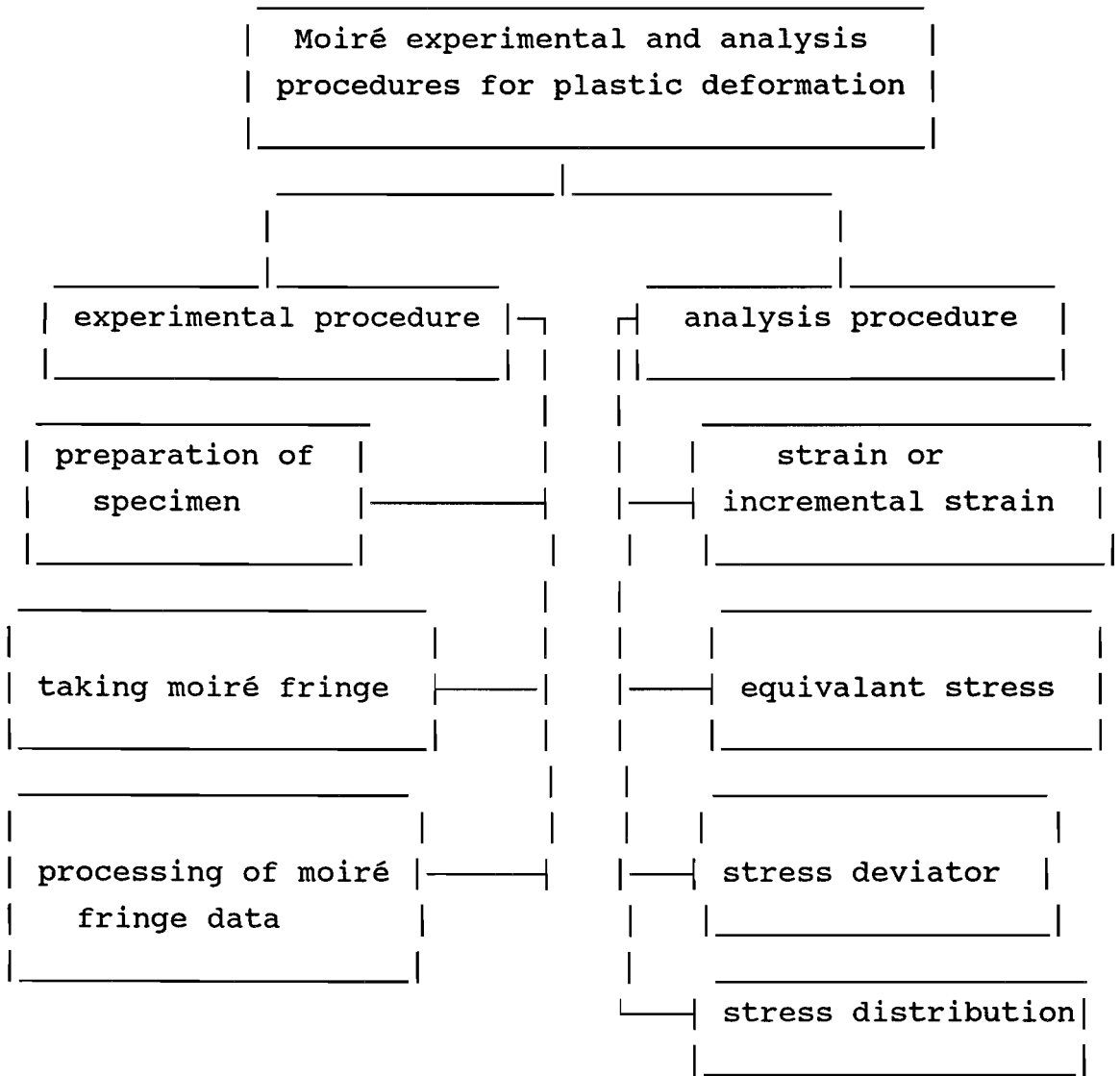


Fig 11. The procedures for plastic deformation problems by moiré method

Most of the metal forming processes are large plastic deformation process, so we can neglect the influence of elastic deformation to use the Lévy-Mises incremental plasticity theory.

$$d\epsilon_{ij} = 3 \cdot d\epsilon_i \cdot s_{ij} / (2 \cdot \sigma_s) \quad (4.1)$$

here $d\epsilon_{ij}$: the components of incremental strain
 $d\epsilon_i$: the effective incremental strain
 σ_s : the yield stress
 s_{ij} : the components of stress deviator

The essential presupposition to use incremental plasticity theory is to obtain the incremental strain. Using moiré method we can obtain incremental strain field very easily. For steady state processes, we can stick specimen grating on the workpiece, then loading to cause an incremental strain field. For unsteady state processes, we first load to the N step without gratings, then we stick specimen gratings to load to N+1 step. With this moiré fringe, we get the incremental velocity field, then we can calculate the incremental strain field.

Using the Lévy-Mises plasticity theory, we can only get the stress deviator. The hydrostatic stress has not been determined. We can use the equilibrium equation and the boundary conditions to get the stress field by the differential method of shear stress. For two dimensional problem, we first use equation (4.2) and the known stress σ_x at the boundary to obtain the σ_x distribution.

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \quad (4.2)$$

We can change equation (4.2) into differential equation (4.3):

$$\frac{\Delta \sigma_x}{\Delta x} + \frac{\Delta \tau_{xy}}{\Delta y} = 0 \quad (4.3)$$

After the σ_x is determined, we can obtain σ_y by equation

$$\sigma_x - \sigma_y = s_x - s_y \quad (4.4)$$

Now we have obtained the whole stress field.

When the elastic deformation is of the same order to the plastic deformation, we must first record the loading moiré fringes (total deformation, including elastic and plastic deformation), then record the unloading moiré fringes (the plastic deformation). We can use the Prandtl-Reuss plasticity theory to solve this kind of problem.

Here we have some examples of the use of moiré method to the plastic deformation.

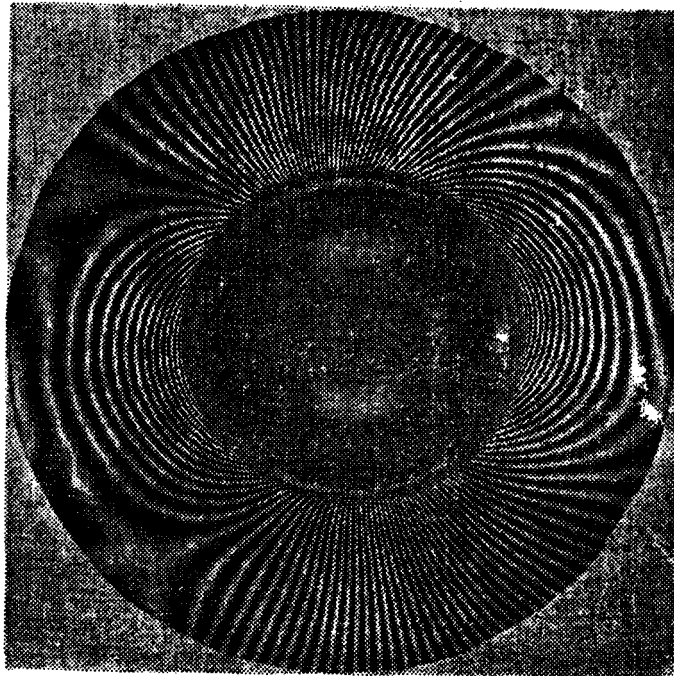


Fig 12. Moiré fringes at the flank region
in the deep drawing process

Fig.12 is the moiré fringes at the flank region in the deep drawing process. The deformation of deep drawing is mainly occurred in the flank region, the waste product rate has a strong relation with the material flow in the flank region. Fig 13,14 give the difference of the strain and stress distribution between the experiment and theory for deep drawing process. We can see the strain ϵ_θ (the circumference strain) coincides very well, the

ϵ_r (the radial strain) has a slight difference which is equivalent in dimension to the ϵ_t (the thickness strain) neglected by the theoretical solution. The stress distribution coincides in tendency, but there are some difference in numerical value, the reason is the theoretical solution is obtained by using a lot of simplifications (neglect the thickness change, simplify the yield criterion as $\sigma_1 - \sigma_3 \approx 1.1\sigma_1$, using the ϵ_θ as ϵ_i to take account on the strain hardening effect, etc.).

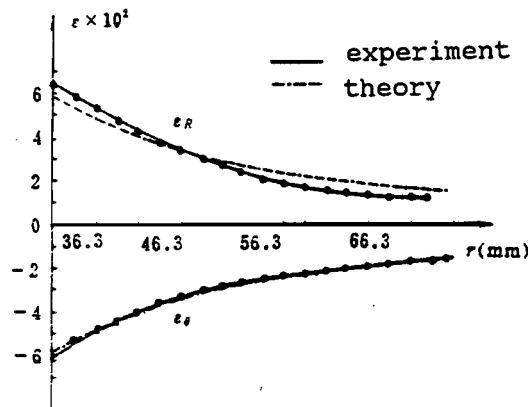


Fig 13. The comparison of strain

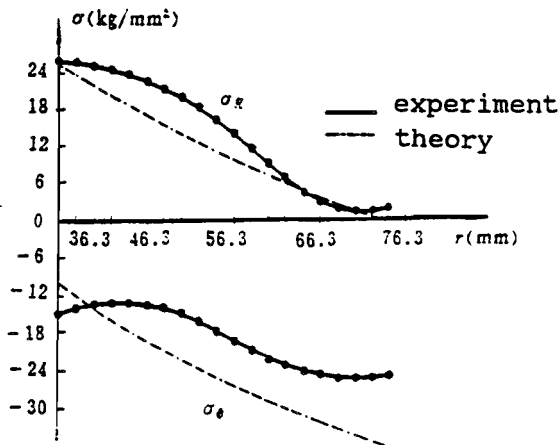
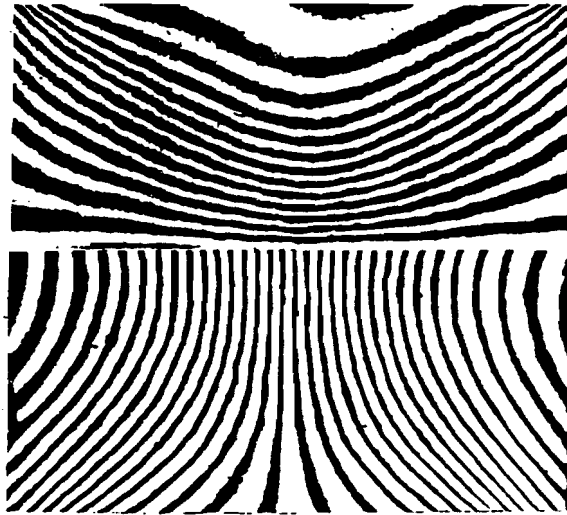


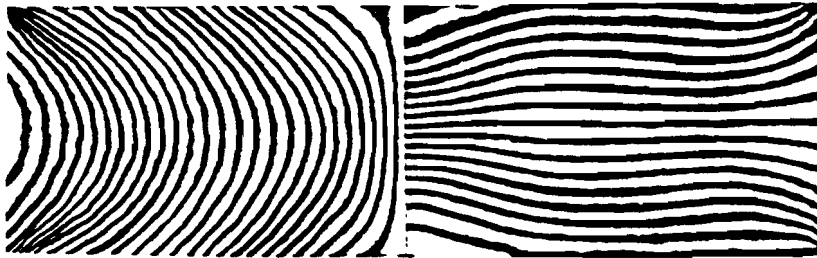
Fig 14. The comparison of stress

Fig 15. are the velocity fields for plane strain compression. To process these moiré information, we can get the whole field of strain rate and stress distribution. We can obtain

the normal stress and shear stress very near the border, so moiré method is an effective technique for plastic contact problems.



(a). v (upper) and u (lower) field ($B/H=1$)



(b). u (left) and v (right) field ($B/H=3$)

Fig 15. The velocity field for compression



Fig. 16 The constitutive reduction process

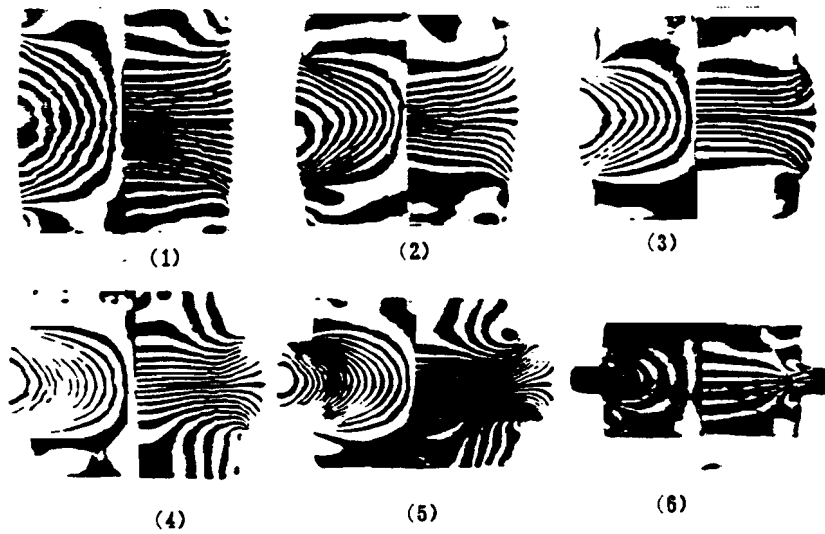


Fig 17. The 6 steps moiré fringes of die forging process

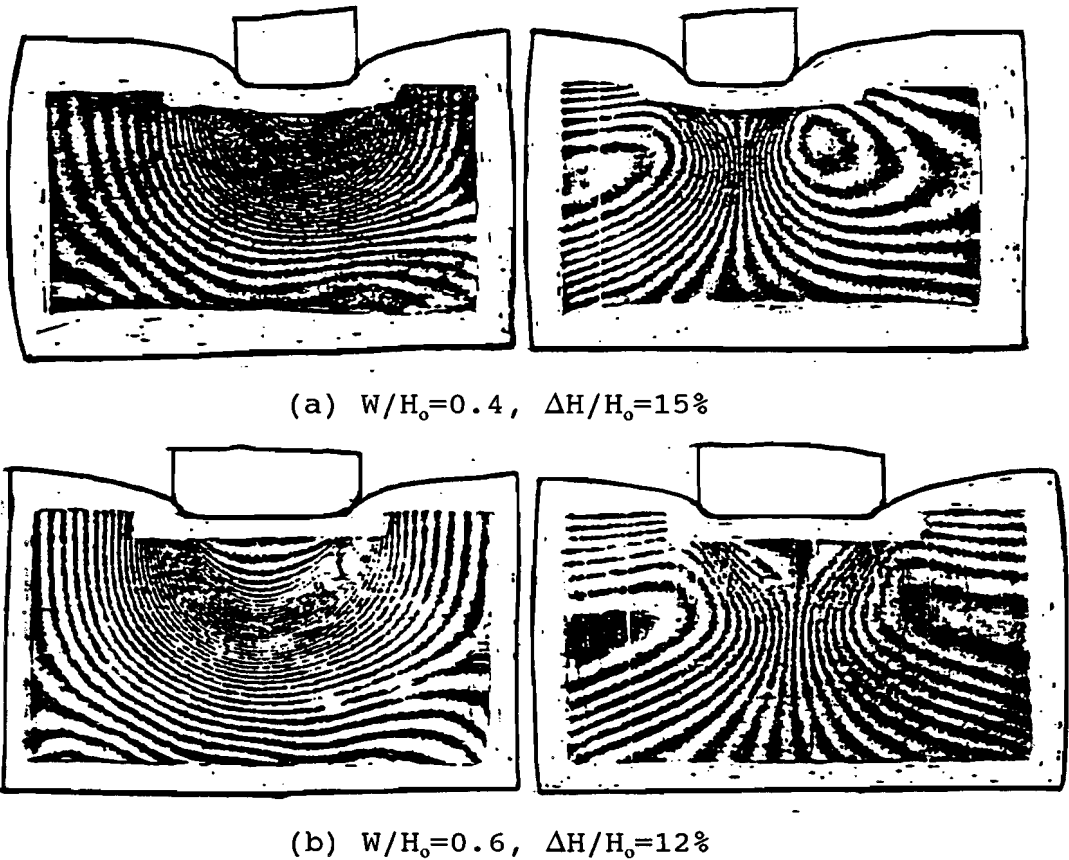


Fig 18. Heavy forging process(FM), steel specimen after deformed at 1200°C , $\dot{\epsilon}=3.5 \cdot 10^{-2}\%$

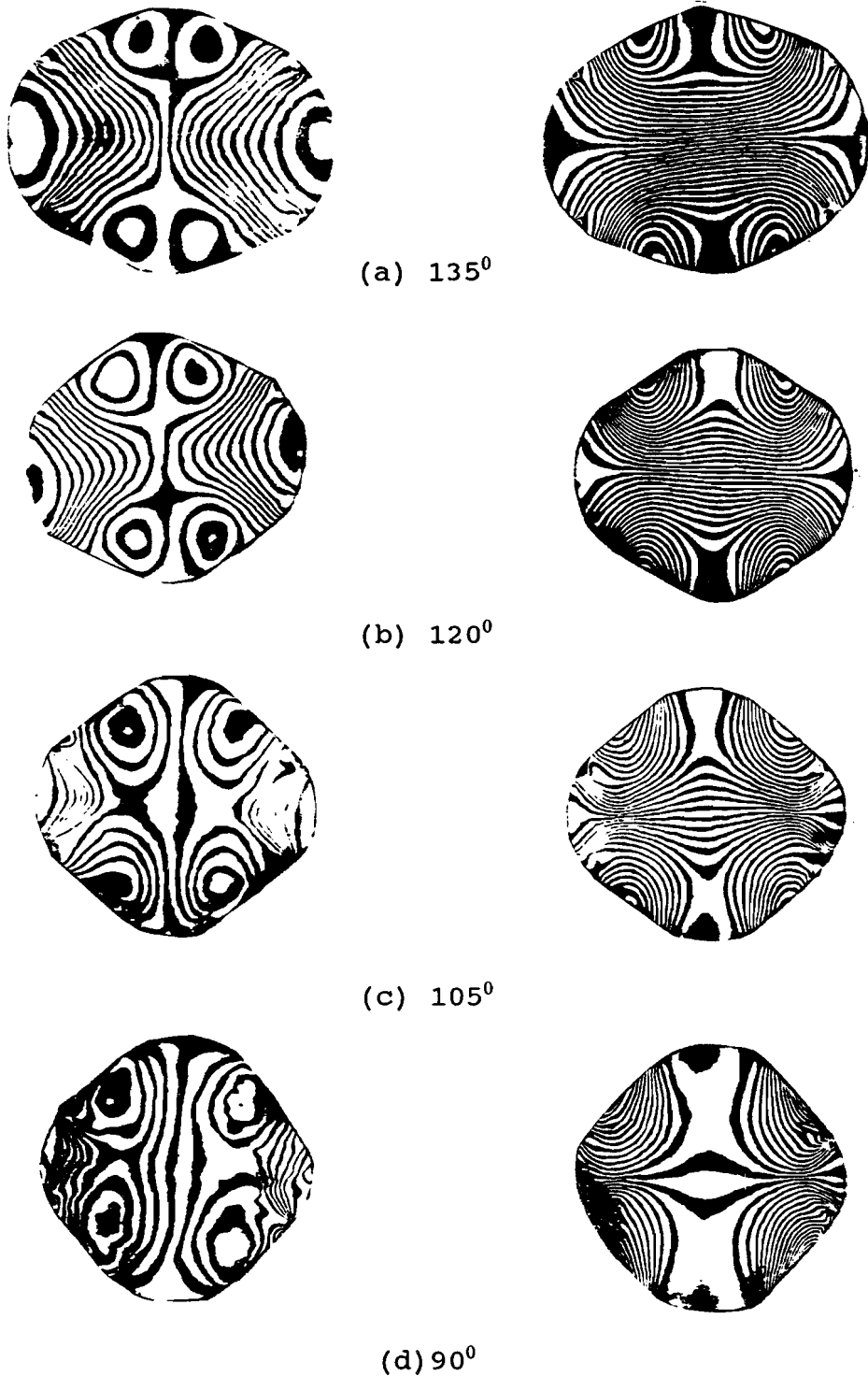


Fig 19. The moiré fringes for V shaped anvil with different angles ($W/D_0=0.6, \Delta H/D_0=14.64\%$)

The metal forming processes are very complex thermal/mechanical processes, the internal strain/stress, temperature distribution of the specimen are not uniform. A lot of assumptions must be made to modelling these processes by Finite Element Method. It is fairly difficult to simulate the hot forging processes with constitutive reduction by F.E.M. With the high temperature moiré method, we can use the real working material to get the high temperature strain distribution. In order to establish the quality control system of forgings, it is necessary to find out the critical closing/welding criterion of internal holes(or cracks),to find out the relation between the steel grain size and the local strain/stress, temperature distribution. These two very important problems can only be solved by real working material experiments. The F.E.M results also need the correct boundary conditions by experiments or verified by experiments.

From the above examples, we can see many metal forming problems can be solved with moiré method very easily and effectively. So we can expect that moiré technique can play a fairly important role in the research of metal forming problems.

V. CONCLUSION

The moiré method is a new type of whole field experimental analysis method, it bases on the interference of two sets of gratings to form various moiré fringes to obtain the displacement component field, then to calculate the strain/stress distribution. The slight changes in the grating pitch and direction can cause a fairly large changes in the position and inclined angle of the moiré fringes, so it is a high sensitive technique for measuring some mechanical quantities such as the relative movement, rotation, deformation etc.

We can determine the strain distribution directly from the simple geometric relations of the gratings, without the transform from other intermediate quantities (such as the photo-elastic method from optical value to mechanical value, the resistance strainometer from electric value to mechanical value). The in-plane moiré method can be used to various investigations, such as elastic, plastic, creep, static loading, dynamic loading, vibration, explosion, high temperature processes etc. The out-of plane moiré method can be used to measure the shape of a curved surface (height, slope, curvature etc) and the non-plane displacement (deflection, change of thickness etc).

For the investigation of high temperature forming processes, such as the material property, strain/stress field, the forming limit, the analysis of forming defects, the relation between the process parameters and the internal structure/property of products, the moiré modelling technique is a very effective tool.

ACKNOWLEDGEMENTS:

The author wishes to thank Prof. Cao Qixiang (Institute of Metal Forming, Dept. of Mech. Engg., Tsinghua University, P. R. China) for his supervision for the last 6 years.

VI. REFERENCE

- [1]. Cao Qixiang, Ye Shaoying, Xie Bing, Ma Xiteng, The Theory and Application of Moiré Method (in Chinese), Tsinghua University Press, 1983,5.
- [2]. Cao Qixiang, Xie Bing, Zhong Yuexian, The Engineering Applications and Automatic Fringes Processing of Moiré Method (in Chinese), China Railway Press, 1990,4.
- [3]. Wang Shunlong, Modelling FM(Free from Mannesmann effect) Heavy Forging Process by Moiré Method, Ph.D thesis, Tsinghua University, 1991,1.
- [4]. P.S. Theocaris, Moiré Fringes in Strain Analysis, 1969.
- [5]. A.J.Durelli, V.J.Parks, Moiré Analysis of Strain, 1970.