PHOTOELASTIC INVESTIGATION OF METAL-FORMING PROCESSES USING NEW SAPPHIRE DIES

by S.D.K. Barbat and R.S. Rao

Sapphire dies (of single-crystal aluminum oxide) are used to obtain interfacial conditions along the contact surface of the die in a strip-drawing operation. Several solutions based on slip-line field analysis and upper-bound techniques are available for metal-forming problems. However, these solutions generally neglect elasticity and work-hardening and assume that friction is constant along the die-work interface. While these analyses are sufficient for estimating forming loads, they cannot predict residual stresses nor do they accurately define the local stresses and deformations. Furthermore, inadequate information on the frictional conditions at the die-work interface precludes quantitative predictions of the actual forming process.

In earlier research on the drawing of tin-plated mild steel with transparent dies, interfacial velocities were measured experimentally.[1,2] The velocities were then used as the prescribed boundary conditions in the finite-element analysis to provide complete information on the stresses and strains throughout the deformation zone of the strip. There were some experimental difficulties in obtaining accurate velocity profiles along the die-work interface, especially at the entry and exit regions, due to small contact length.

The photoelastic technique was applied to the study of drawing operations about 30 years ago. Since the dies in those studies were made of photoelastic materials such as epoxy resins and fused quartz, only low-strength, non-strain-hardening materials such as lead could be drawn.[3,4] Thus, the earlier work was not representative of commercial materials processing. By contrast, synthetic sapphire (aluminum oxide, Al_2O_3) is hard enough to machine and form commercial materials. The use of transparent sapphire dies in experimental studies of drawing makes the observation of tribological features at the die-work interface possible during processing commercial materials such as steel, aluminum, and copper.[5]

The moiré interferometry technique was also recently applied to the metal-forming operation. The interfacial conditions were obtained along the contact zone between a hardened tool steel die and a low-carbon steel workpiece in strip drawing.[6] Rcently, the tangential and normal stresses along the rake face in the orthogonal machining of steel were obtained using the birefringent properties of sapphire.[7] A similar photoelastic technique was applied to metal-forming processes.

In this study, photoelasticity experiments were conducted based on the birefringent properties of sapphire to reveal the isochromatic and isoclinic fringe patterns at the die-work interface. Such fringe patterns will eventually be analyzed to obtain the contact stresses (normal and tangential stresses) in the strip-drawing operation.

EXPERIMENTAL PROCEDURE AND EQUIPMENT

Sapphire Dies and Test Materials

Synthetic sapphire (aluminum oxide Al_2O_3) is an important optical material that is grown artificially as a single crystal. In order to grow a single crystal, the aluminum oxide powder is melted in an oxygen/hydrogen flame, and the small molten droplets fall on a pre-selected seed crystal which gradually grows into a large, single-crystal boule. The sapphire is then sliced with a diamond-impregnated saw, machined to size, and ground to the appropriate dimensions to form dies with a semi-drawing angle of 4 deg. Each face of the dies is then lapped with diamond compounds. The finished dies are inspected for surface finish, scratches, and surface imperfections. The sapphire dies have a nominal roughness of less than 0.05 nm on their lapped faces.

Conventional tool and die materials such as tool steel and tungsten carbide are opaque and thus preclude direct observation of the interfacial conditions and the use of some techniques such as photoelasticity to study the boundary conditions quantitatively. The physical and optical properties of synthetic sapphire, however, make it valuable for applications where conventional materials are inadequate. Sapphire has a bulk modulus of 2.07 GPa, a modulus of rigidity of 148.5 GPa, a modulus of rupture of approximately 551 MPa, a Knoop hardness of 1525-2000,

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and a Young's modulus of approximately 344.5 GPa (all depending on crystal orientation).

Sapphire can operate satisfactorily at high temperatures and it is chemically inert at temperatures below 1000°C. It has excellent optical properties such as high transmittance, a low coefficient of thermal expansion, absence of natural birefringence in the 'c' direction (optical axis), and, above all, it exhibits photoelastic properties.

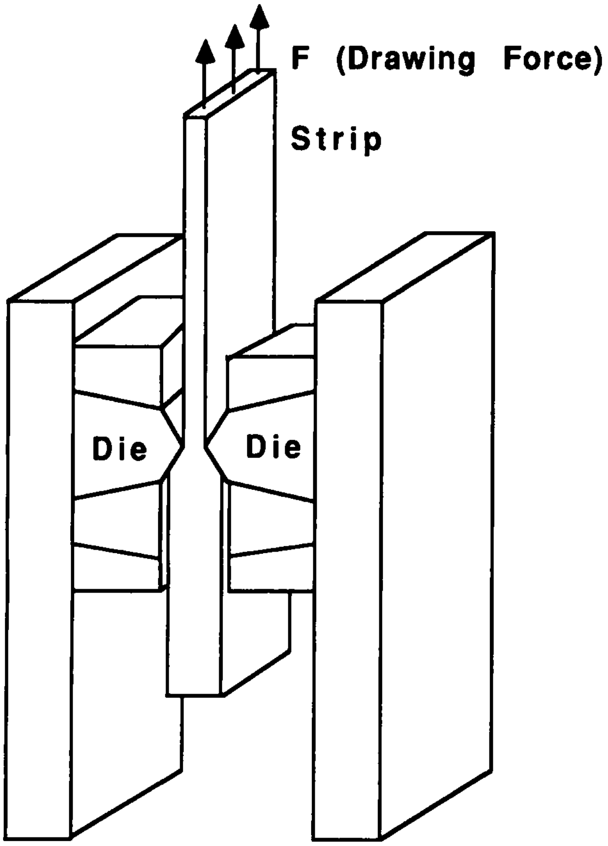

Fig. 1—*Simplified layout of the drawing apparatus and dies*

It must be pointed out that sapphire is extremely brittle and needs to be handled with care, and that its stress birefringence is relatively weak. Thus, high loads are required to produce a significant number of isochromatics in photoelasticity studies. Sapphire is transparent, exhibits photoelastic properties, and has mechanical properties comparable with those of many tool and die materials such as steels, carbide, and ceramics. Thus, sapphire is an excellent choice as the die material in this study of strip drawing. Commercial materials such as cold-rolled steel, aluminum, and copper are chosen as work materials, and light mineral oil is the lubricant for drawing.

Details of Strip-Drawing Assembly

The strip-drawing apparatus consists of a pair of identical sapphire dies fixed to the opposing faces of the steel frames. The gap between the dies can be adjusted by means of six gage blocks on the studs, one on each corner and two in the middle. The apparatus is mounted on a microprocessor-controlled Instron testing machine. The drawing speed can be varied from 0.01 to 10 mm/sec. Figure 1 shows a simplified layout of the drawing apparatus and dies.

Photoelastic Bench

The lens polariscope setup used in this study is shown schematically in Fig. 2.

The Test

The strip-drawing apparatus was mounted on a microprocessor-controlled Instron machine. The thickness of a section of the strip was reduced so it could be slipped between the dies. The exit end of the strip was clamped to the moveable cross head, and light mineral oil was used as a lubricant between the dies and the workpiece. The cross section of the strip was initially 13 × 0.915 mm, and it was reduced in thickness by 28.3 percent to 0.656 mm while the cross head speed waas maintained at 1.3 mm/min.

The fringes formed in the die were observed, and increased with the increasing load until they became stable when

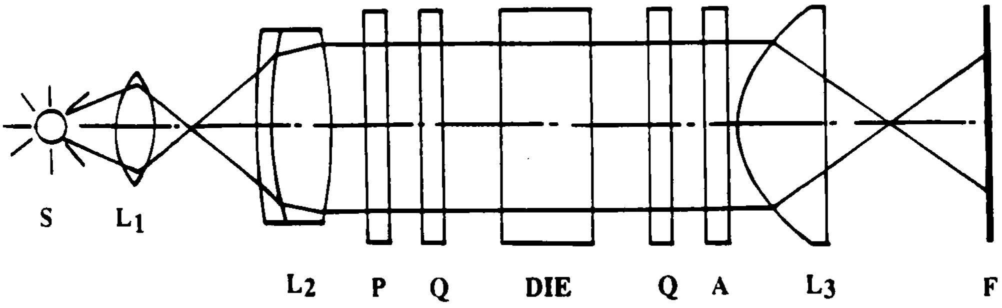

Fig. 2—*Schematic of polariscope setup*

S — Light source
L_1 — Focusing lens
L_2 — Collimating lens
P — Polarizer
Q — Quarter wave plate
A — Analyzer
L_3 — Plano-convex lens
F — Film plane

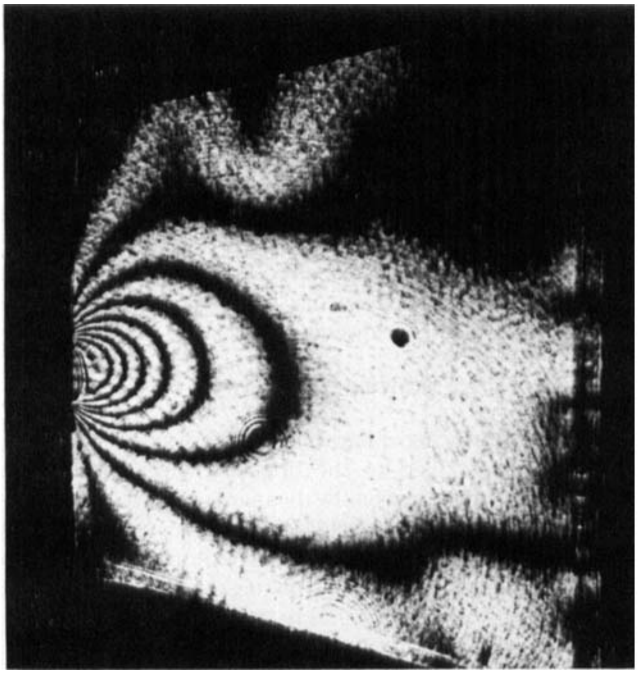

Fig. 3—*Isochromatic fringe pattern produced by drawing with sapphire die using a monochromatic light in a dark field*

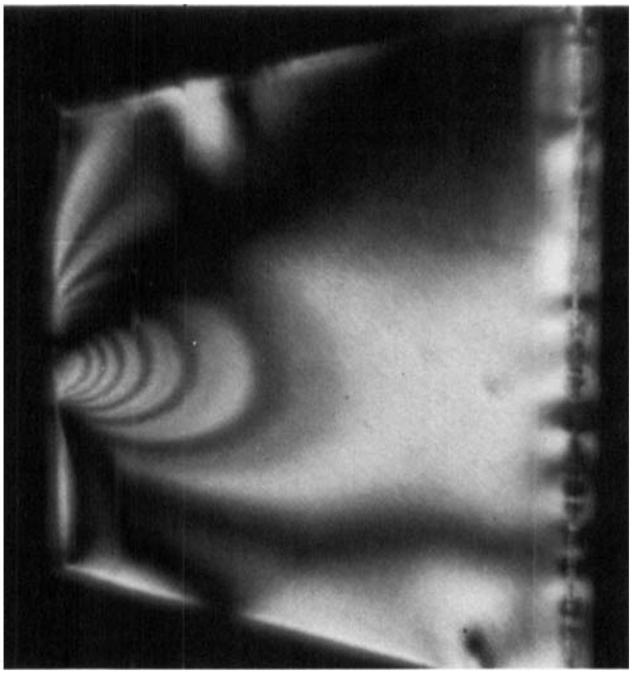

Fig. 4—*40-deg isoclinic as diffused dark bands superimposed on color isochromatic obtained from a plane polarized field of white light*

steady-state drawing conditions were achieved. The isoclinics and isochromatics were obtained simultaneously during drawing by using a plane-polariscope arrangement. White light was used to produce brightly colored isochromatics and a diffused dark isoclinic. The isoclinics were photographed at 10 deg intervals of the polarizer/ analyzer combination between 0 deg and 90 deg. The colored photographs were recorded using a 35-mm Olympus camera on a Fuji-color film. The exposure time was 1/1000 sec.

The isochromatics were recorded on a Kodak TMAX black-and-white film with the quarter wave plates in their proper locations to form a circular polariscope. The use of a circular polariscope eliminates the isoclinic fringe pattern while it maintains the isochromatic fringe pattern. Red light of 632.8 nm wave length obtained from a laser source of 15 milliwatt power was used to produce the isochromatics.

RESULTS

The isochromatic and isoclinic fringe patterns in the sapphire die itself were recorded for the first time in the case of drawing an initial strip of 13 × 0.915 mm reduced by 28.3 percent with light mineral oil as lubricant. Typical experimental data on the stress distribution in the die is shown in Fig. 3. This photograph shows the isochromatic fringe pattern obtained under the steady state condition in a dark background with a monochromatic light in a standard circular polariscope. These fringes represent contours of constant difference between the principal stresses.

Figure 4 represents the 40-deg isoclinic, i.e., the locus of all points in the die at which the principal stresses have parallel directions. The 40-deg isoclinic is obtained as diffused dark bands superimposed on the isochromatic color fringes in a plane polariscope using white light. By a systematic rotation of a polarizer and analyzer at 10-deg intervals, while keeping them crossed, a set of isoclinics was obtained. With these data, the directions of the principal stresses at all points in the die and the principal stress difference at all points can be found.

The traced photographic data of the isochromatic and isoclinic contours are shown in Fig. 5. The stress distribution in the die and along its contact surface with the work material will be found by analyzing these data by using the shear-difference method as described in Ref. 8.

CONCLUSION

This research reports the first observations and recordings of the isochromatic and isoclinic fringes in sapphire dies during drawing of commercial metals. The fringes in the contact region, between the die and the workpiece, and in its vicinity are crowded and distinguishable. In comparison with previous work,[3,4] these photoelastic experiments using new sapphire dies are believed to have provided the data closest to the contact region in strip drawing.

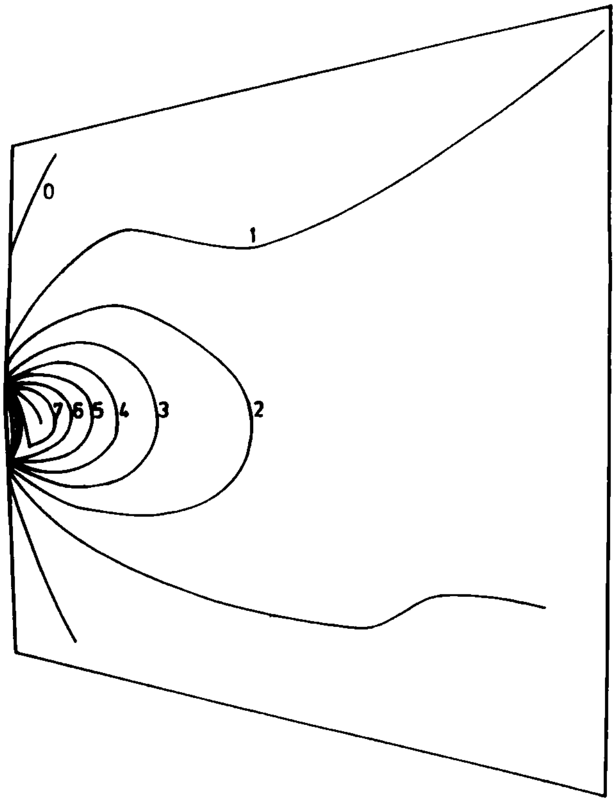

Fig. 5a—*Isochromatics*

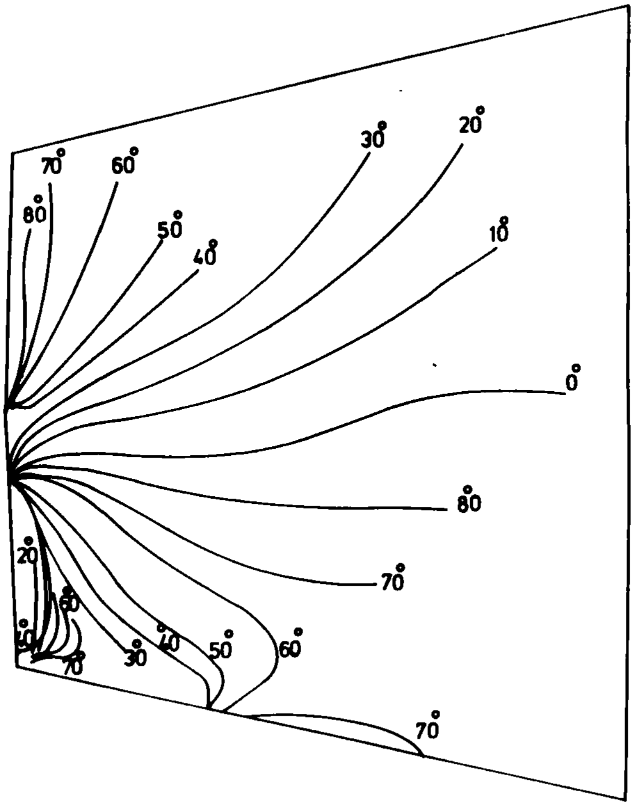

Fig. 5b—*Isoclinics obtained during drawing a low-carbon steel strip at 1.3 mm/min speed for the 28.3-percent reduction*

Thus, synthetic sapphire is found to be strong enough to withstand loads that arise in processing commercial metals such as low-carbon steels, aluminum, and copper. Transparent sapphire seems to be the only practical material that exhibits birefringent properties suitable for photoelasticity investigation, and its mechanical properties are comparable with conventional die materials such as tool steel and tungsten carbide.

FUTURE WORK

Several process parameters are now being investigated, and different light sources and lenses are being tested to improve the quality of fringe patterns. Stress distributions in the die will be determined from the isochromatic and isoclinic patterns using the shear-difference method and the model fringe constant. The normal and shear stress components, σ_x, σ_y, and τ_{xy} on the contact surface of the die, given by the above analysis, will be used to determine the contact pressure and the frictional stress. Such tractions can lead to the determination of the distribution of the frictional behavior in strip drawing.

ACKNOWLEDGMENTS

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