To obtain fundamental data on roll forging, the actual three-dimensional unsteady flow situation is converted to a two-dimensional steady flow model and experimental and theoretical analyses of material flow are carried out for the particular case of cross rolling. An experimental rolling mill is used for the experiments with plasticine as the test material. Two-dimensional steady pseudo-plastic flow is assumed for the theoretical analysis and a finite element method is used to provide numerical solutions for lateral flow under the forming roll. The theoretical solutions for velocity and shear strain-rate distributions over transverse sections are compared with experimental measurements taken from grid patterns on the test specimens. Good agreement is obtained.

INTRODUCTION

The term roll forging can be used to describe a range of forming processes for producing components of circular section to high accuracy and with good mechanical properties. It includes such processes as cross rolling, helical rolling and ring rolling, which have each undergone substantial development in recent years. However, basic theoretical data on them is still lacking because of the complex three-dimensional unsteady flow involved, which makes analysis difficult.

In this study, to simplify the analysis, the three-dimensional unsteady flow situation is converted to a steady flow model of rolling using a rectangular-sectioned workpiece and the flow is examined two-dimensionally in a specified plane. Using this model, various roll forging processes can be simulated by applying suitable boundary conditions to the workpiece. In this paper, a cross rolling condition is employed and flow in the rectangular-sectioned workpiece is analysed experimentally and theoretically in transverse planes.

For the experimental work an experimental rolling mill is used to form sectioned plasticine test specimens, with grid patterns applied to transverse planes to indicate flow. The plasticine serves as a model material for hot steel.

For the theoretical analysis a pseudo-plastic flow model is used to represent deformation and a finite element method is employed to provide a numerical solution. The theoretical predictions are compared with experimental results.

The main purpose of the study is to enable flow in a roll forging process to be predicted by calculation.

STEADY FLOW MODEL

A schematic figure of the steady flow rolling model is shown in Fig. 1.

The rectangular-sectioned workpiece, which is considered to correspond to an element in a bar of relatively large radius, is given appropriate boundary conditions to simulate the particular process by mounting it on a flat carrier plate and applying clamping plates either on the sides or ends. For instance, for cross rolling or helical rolling, transverse flow is required and the end clamps are used as shown in Fig. 1, while for profile ring rolling, side clamps are employed allowing longitudinal flow.

The workpiece on its carrier plate is passed repeatedly through the roll gap, receiving an incremental reduction at each pass up to a certain total reduction. The material flow is examined at suitable stages in particular planes of the workpiece, e.g. two-orthogonal planes, and by superposition it is possible to indicate the three-dimensional unsteady flow.

In this paper the cross rolling condition is studied, so that the workpiece is constrained in the rolling direction by end clamps and flow is examined in the transverse plane.

EXPERIMENTAL WORK

Experimental Equipment

An experimental rolling mill, suitably adapted, is used for the experiments. Four profiled forming rolls are employed (Fig. 2), two of V form (V-type) and two of truncated V form (T-type) with semi-angles of $\alpha = 15^\circ$ and $25^\circ$. The lower roll is a plain cylinder of 74 mm diameter. The rolls are driven at 10 r.p.m.

Specimen and Procedure

Roll forging is normally a hot forming process and for these experiments the test material employed is plasticine, which is well established as a model material for hot steel.

Specimen dimensions are given in Fig. 3 together with the position of lattice points set in a transverse section for measurement of flow. The end clamps on the specimen carrier constrain flow in the rolling direction and to ensure that the bottom surface remains motionless on the
carrier, emery paper is inserted between the specimen and the carrier plate. An incremental reduction of 0.5 mm is applied by the forming roll at each pass, to a total reduction of 6 mm.

Displacement measurements of lattice points are made on separate specimens after reductions of 2 mm, 4 mm and 6 mm and the three measured displacements are superposed to give finite displacement vectors for phases R2, R4, R6, corresponding to the increments 0-2 mm, 2-4 mm and 4-6 mm.

THEORETICAL ANALYSIS
Pseudo-Plastic Flow Model

A steady pseudo-plastic flow model is used to represent the deformation of the hot steel and the plasticine model material. Governing equations for the pseudo-plastic (viscous incompressible) flow are given in the Appendix.

A viscosity coefficient \( \mu \) is used in the equations, which is a function of the second invariant \( J_2 \) for non-Newtonian flow following a power law in the relationship between stress and strain rate.

Hence, for pseudo-plastic flow the relation between stress and strain rate is

\[
\sigma_v = 3 \mu (J_2) \dot{\varepsilon}_v
\]

(1)

\( \dot{\varepsilon}_v \) is the equivalent strain rate, given by

\[
\dot{\varepsilon}_v = \sqrt{4J_2/3}
\]

(2)

where

\[
4J_2 = 2 \left( \frac{\partial u}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} \right)^2
\]

for the plane strain condition. The relationship between stress and strain rate for plastic flow of hot steel can also be written as

\[
\sigma_v = K (\dot{\varepsilon}_v)^{n-1} \dot{\varepsilon}_v
\]

(3)

\( \sigma_v \) is equivalent stress, \( n \) and \( K \) are material constants.

Combining equations (1) and (3)

\[
\mu(J_2) = \frac{K}{3} (\dot{\varepsilon}_v)^{n-1} = \frac{K}{3} (4J_2/3)^{n-1}
\]

(4)

Consequently the plastic flow of hot steel can be represented by pseudo-plastic flow using equation (4).

Values of \( n \) and \( K \) used in the calculations are

\( n = 0.156 \)

\( K = 9.6 \) (Kg. sec\(^{-n}\)/mm\(^2\))

for S55C at 900\(^\circ\)C and \( \dot{\varepsilon}_v < 0.2 \).

Numerical Calculation Method

Good correlation between theory and experiment is normally achieved using finite element methods and a single programme can be used to represent a range of forming situations. In the theoretical analysis, to simplify the calculation, the flow is assumed plane strain in a transverse section and velocity vectors in the section are calculated by the finite element method. Finite element formulations of the governing equations for pseudo-plastic flow model are given in the Appendix.

The calculations are performed for the same conditions as the experiments.

For the boundary conditions a mean vertical velocity is given to the material in contact with the roll, obtained from the rolling reduction and the roll speed. The roll contact surface is assumed frictionless and material at the bottom surface is motionless relative to the carrier plate.

RESULTS AND DISCUSSION

Finite Displacement Vectors

In Figs.4a-d are shown distributions of experimentally determined finite displacement vectors for phases R2, R4, R6 on transverse sections of the specimens for the different roll forms. Because of symmetry only half-sections are necessary.

These results can be compared with calculated results, but it must be acknowledged that the experimental results are subject to slight errors because of the superposition of the three measured displacements from the three different plasticine specimens, in spite of the careful handling and measurement. However, it is considered that the results are sufficiently accurate in showing general trends.

Calculated Velocity Vectors

Velocity vectors in the transverse plane calculated by the finite element method are shown in Figs. 5-6. These can be compared with the finite displacement vectors obtained experimentally.

Figs. 5a-c give results corresponding to stages R2, R4 and R6 using the V-25° roll. At R2 the vectors are small except near the roll contact surface. Upward movement is indicated at the upper free surface and it results in the pile-up of material at the free surface, as observed in the experimental results. At R4 the vectors have extended down to the middle section and the pile-up is increasing. At R6 the vectors have increased further except in lower region, mainly in the transverse direction and there is no further pile-up.

These results agree well with the experimental result in Fig. 4a. Movement of the side of the specimen agrees also with experiment, although there are differences in the directions of the experimental and calculated vectors.

Figs. 6a-c give results at stage R4 for V-15°, T-25° and T-15° rolls to illustrate the effects of roll shape. Pile-up at the upper free surface is observed for the V-25° roll but not for the others, thus agreeing with the experiments.

For the V-15° roll the trends are generally similar to those for the V-25° roll, but the magnitudes are greater in the upper and middle regions and the directions incline more to the vertical in