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FORMATION OF TUBES BY A SIMPLE ROLLING ACTION: A NEW NORMAL-PRESSURE EFFECT

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IN the steel industry, it is known that, in the Mannesmann process[1], a red-hot rod of metal forms itself into a tube when rolled between rollers. Williamson[2] has recently described a similar phenomenon which he observed in the rolling of a certain natural Australian clay ('blue ball clay') and also with warm 'Plasticine'. He studied in great detail the microstructure of the clay with regard to its chemical constitution, water content, and particle size, shape and crystallographic orientation, and concluded that the phenomenon was specific to the microstructure and in particular to the difference in water content between the inner and outer regions of the specimen.

Weissenberg[3] has analysed the experimental observations and concludes from his theory of flow that the phenomenon should depend only on the macroscopic characteristics of the process and the material, and should be much more general than has hitherto been imagined. It should be observable as an effect of normal pressure in materials with the most varied types of microstructure and be particularly sensitive to the amount of elastic recovery present. When this amount approximates to zero, the plastic deformation caused by the rolling process should generate near the axis of the specimen a concentration of tensional normal pressures which suck in the end-planes of the specimen and open up radial cracks. This could continue under favourable conditions until a tube is formed. Tests with elastic recoveries progressively increasing from zero to large amounts should produce plastic and elastic deformations, and the latter should reduce the strength of the tensional pressures to zero and beyond this to compressions. Thus, in extreme cases, a reversion of the phenomenon of tube formation should be observed, as the compressions would tend to push out the end-planes of the specimen. The early stages of the sucking-in or pushing-out should be insensitive to changes in the initial shape of the specimen, but the completion of a tube by continued rolling should be facilitated by the choice of initial dimensions with a length to width ratio smaller than unity.

We were interested in testing Weissenberg's conclusions, particularly because it seemed unlikely that a merely macroscopic theory could predict qualitatively all the various widely differing normal pressure effects such as these and the better-known 'Weissenberg effects'[4,5] which occur under torsional shears and are almost diametrically opposed to those described here. Two series of tests were carried out.

We started the first series by reproducing and confirming Williamson's observations. We rolled tubes from warm 'Plasticine' and from an aqueous paste of a clay very similar in constitution to his 'blue ball clay'. Both materials had a macroscopic consistency which was putty-like and plastic, with no apparent elastic recovery. We then prepared a series of materials of similar macroscopic consistency but with widely differing microscopic structures by stirring liquids into aggregates of solid particles to a solid concentration of about 75 per cent (though this was not very critical). The rolling of flat-ended cylindrical specimens with a length to diameter ratio of about 0·5 produced tubes in every material of this series irrespective of the nature of the liquid phase (water, paraffin oil, or silicone oil) or whether the solid particles were coarse or fine, crystalline or amorphous, in the shape of plates (graphite), needles (asbestos), or spheres (starch). The effect of varying the dimensions of the specimen was most pronounced in cold 'Plasticine', from which Williamson failed to produce a tube. In this material we produced tubes by rolling cylindrical rods with initial length/diameter ratios equal to or smaller than 0·5, and found that the rolling of spheres and cylinders with a ratio equal to or larger than 1 (such as were used by Williamson) exhibited in the early stages a drawing-in of the ends ; but the end cavities did not meet however long the rolling continued.

The appearance of cracks during rolling allowed a rough assessment of the pressure distribution to be made. An accumulation near the axis of tensional normal pressures was indicated by the opening-up of radial cracks originating near the axis and decreasing in width from the centre outwards (see Fig. 1). The effects of varying the chemical and physical properties of the components were difficult to assess ; but, in a qualitative way, it was possible to distinguish two types. One type formed tubes by the sucking-in of the ends of the cylinder until the concavities met ; for example, smooth pastes containing, in 'Nujol' (liquid paraffin) : powders of aluminium, aluminium stearate, cement, clay, cornflour, graphite, icing sugar,

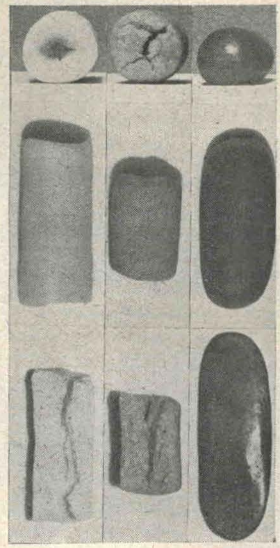

Fig. 1. Tube formation and its opposite in different types of materials. The rolled specimens are viewed in elevation (top), plan (middle), and axial section (bottom). From left to right: cornflour in 'Nujol', asbestos in 'Nujol', poly*iso*butylene with a molecular weight of about 20,000

iron, jeweller's rouge, lycopodium, polystyrene, 'Pyrex' glass, starch, and talc; in water: clay, icing sugar, lithopone; in silicone oil: graphite, icing sugar. The other type formed tubes by the opening-up of radial cracks with little or no drawing-in of the ends; for example, fibrous pastes of 'Nujol' and asbestos or of water and filter-paper pulp.

In a second series of tests, we investigated materials with a macroscopic consistency which was again putty-like but showed noticeable amounts of elastic recovery (as evidenced by bouncing or recovery from stretching) in contrast to the first group. Some extreme cases of such materials are a poly*iso*butylene with a molecular weight of about 20,000, silicone bouncing putty, and Reeves's 'putty' rubber, all of which on rolling produced elongated rods with convex ends and thus exhibited the opposite of the tube-forming phenomenon. Tests of the remaining materials in this series (Remington 'Everclean' rubber, and pastes of 'Plasticine' + rubber solution + talc, and vinyl chloride-acetate copolymer + dioctyl phthalate + china clay) showed poor reproducibility. The same material exhibited in successive experiments both drawing-in of the ends and the converse effect even with no deliberate variation of the experimental conditions. An assessment of these results has to be postponed until quantitative data are available under carefully controlled conditions of temperature, speed and pressure of rolling, etc.

Fig. 1 illustrates the normal-pressure phenomena observed in rolling. Tube formation of the two types is shown in two materials of the first series of tests and the opposite phenomenon in an extreme material of the second series.

These two series of tests do not provide sufficient information to decide for or against Weissenberg's theory. However, such indications as have been obtained are consistent with his predictions of an accumulation of normal pressures near the axis of the specimen, and of a change of the pressures from tension to compression with an increase in the amount of elastic recovery. In any event, the application by Weissenberg of the macroscopic point of view has revealed the great generality of a new set of normal-pressure phenomena occurring in the shearing movement of the rolling process.

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[May 10

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