Some aspects of the deformation behaviour and temperature rise during instantaneous compression loading of high purity aluminium

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SYNOPSIS

The influence of deformation speed on the deformation behaviour of high purity aluminium was investigated. By varying the initial height-to-diameter ratio a considerable influence on the deformation behaviour could be noticed. Lubrication of the specimen end faces was found to have an influence on the flow behaviour and on the roughness of the specimen interface at pressing platens. The results of temperature measurements during deformation agree with work-hardening behaviour of the specimens. Flow curves calculated with the measured temperature rises do not agree with results obtained at lower strains by other workers. The possible reasons are discussed.

SINOPSIS

Die invloed van vervormings spoed op die vervormings gedrag van aluminium van hoë suiwerheid was ondersoek. Deur die oospronklike hoogte-tot-deersnee verhouding te varieer was 'n grootskaalse invloed op die vervormings gedrag waargeneem. Dit was gevind dat smering van die monster se end kante 'n invloed op die vloei gedrag en op die skurfheid van die monster interfase van die durkroller gehad het. Die resultate van temperatuur bepalings gedurende vervorming stem ooreen met die werk-verhardings gedrag van die monsters. Vloei kurwes bereken met die bepaalde temperatuurs verhoging stem nie ooreen met resultate verkryg op laer forsering deur ander werkers. Die moontlike redes word bespreek.

INTRODUCTION

During the past two decades interest in the influence of high strain rates on the deformation behaviour of metals has grown considerably. This has been due not only to the application of metals in space projects, but also in industry, where it was realised that economic advantages could be gained by using higher strain rates in such processes as forging, rolling, pressing and extrusion. Much has been published on this subject, some of which is referred to in the present paper[1-10].

In most previous investigations[5,7,9,11-15] the natural strain did not exceed 0,3 mm/mm. In the investigation described in the present paper, however, the deformation behaviour using higher strains was studied. Other parameters studied were: initial height to diameter ratios of specimens, lubrication of specimen end faces and strain rate[7,9,16].

DEFINITIONS

Loading range

The loading ranges may be classified generally into three main groups, namely, slow loading, rapid loading and instantaneous loading. The corresponding stress rates, strain rates and test durations are summarised in Table I.

According to these definitions, instantaneous loading conditions were applied in the tests described in the present paper.

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TABLE I

Loading Range	Stress rate	Strain rate	Test duration
	MN/m^2s	mm/mm s	s
Slow loading	<10	$<10^{-4}$	>30
Rapid loading	$10-10^5$	$10^{-4}-1$	$30-3\times10^{-3}$
Instantaneous loading	$<10^5$	<1	$>3\times10^{-3}$

Strain conditions

A specimen reacts to loading by deformation, which, in general, consists of a reversible (elastic) and irreversible (plastic, permanent) part. Only the plastic deformation is of interest here. It is convenient to express the deformation by the natural strain ϵ which is defined for compression as

$$\epsilon=\int_{h_o}^{h}\frac{dh}{h}=\ln(h/h_o) \qquad (1)$$

where h_o is the distance between two points in the specimen before deformation and h the distance between the same two points after deformation. For compression $h<h_o$.

Yield criterion

According to Tresca's yield criterion, plastic flow occurs when the difference between the maximum and the minimum principal stresses, a_1 and a_3 attains a critical value a_f, which is termed "yield strength":

$$(a_1 - a_3)_{crit} = a_f \quad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

The three principal stresses are $a_1 > a_2 > a_3$ and thus in uniaxial compressive loading $a_1 = a_2 = 0$ and

$$(a_3)_{crit} = a_f < 0 \quad \ldots \ldots \ldots \ldots \ldots \quad (3)$$

The difference between the applied (compressive) uniaxial stress $a_3 = F/A$, where F is the compressive load and A is the concurrent cross-sectional area, and the yield strength a_f is called the flow stress, k_f:

$$k_f = a_3 - a_f \quad \ldots \ldots \ldots \ldots \ldots \quad (4)$$

The plot of k_f versus the principal (plastic) strain ϵ, in load direction, is called the flow curve, which characterises the behaviour of the material in the plastic range[18,19]. The curve is known to depend upon temperature and stress rate.

Temperature rise during deformation

The ideal work done during deformation (in compression) is

$$A_i\hat{e} = \int_{a_o}^{h} V \, . \, k_f \, . \, d\,\epsilon = V \, . \, 2_f \, . \, \epsilon \quad \ldots \ldots \ldots \quad (5)$$

where V is the specimen volume and k_f is constant for hot deformation. Since for cold deformation k_f is not constant, a mean value k_{fm} is used in this case. Usually the arithmetic mean $\frac{1}{2}(k_{fo} + k_f)$ of k_f at the beginning and the end of the deformation process may be used as a reasonable approximation. Equating the ideal work done to the energy converted into heat in the specimen during deformation then yields:

$$V . k_{fm} . \epsilon = c . Q . W . \Delta T . V \quad \ldots \ldots \ldots \quad (6)$$

where k_{fm} is the mean yield strength during cold deformation in N/m^2, V is the volume of the specimen in m^3, ϵ the natural principal plastic strain, c the specific heat of the deformed material in Nm/kg°C (considered to be constant during deformation), Q the density in kg/m³, ΔT the temperature rise in °C and W the mechanical heat equivalent.

Equation 6 permits calculating the temperature rise during deformation if k_{fm}, thus the flow curve is known. Unfortunately the flow curves for slow as well as for instantaneous loading conditions were not available for the 99,995% purity Al used in the present investigation. The value k_{fm} used in evaluating the experimental results was therefore determined from the measured temperature rise ΔT, using equation (6).

TEST PROCEDURE

Specimens of different height-to-diameter ratio (between 1:1 and 2:1) were machined from high purity (99,995%) aluminium rods of 6,35 mm diameter. The mean Vickers hardness HV_{25} of the fully annealed specimens was 18,7. The two loading faces of the specimens were polished before the test.

The specimens were loaded in a device similar to the Split Hopkinson apparatus[12-17]. as shown schematically in Fig. 1. This apparatus consists of a piston which, accelerated by an air-gun, impacts an elastic weighbar.

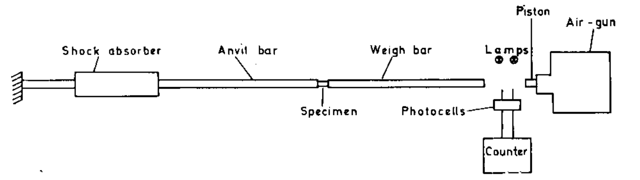

Fig. 1—Impact testing device.

The resulting stress wave travels along the weighbar and is partly reflected at the specimen end and partly transmitted through the specimen into the anvil bar and eventually absorbed by the shock absorber. The piston velocity was measured by means of two photocells and an electronic counter and was controlled within the range of 6 to 12 m/s. Stress or strain rates were not measured, but instead the piston velocity Vo was adopted as a variable. It was, however, estimated therefrom that strain rates of up to $10^3 s^{-1}$ could be achieved.

Each specimen was deformed several times. The lengths of the specimens were measured before and after each impact by means of a micrometer. With these results the strain was calculated from equation (1). The temperature rise during deformation was measured by means of a nickel-nickel/chromium thermocouple connected in a differential circuit where one point of the weld was placed in a hole drilled into the cylindrical surface of the specimens, while the other point of the weld was kept at 0°C. The temperature difference was registered with a millivolt recorder. Experiments were carried out with the flat ends of specimens unlubricated as well as lubricated with molybdenum disulphide grease.

RESULTS

Deformation behaviour

The influence of piston velocity (which is related to strain rate) on the natural strain ϵ after one and two impacts, using specimens of different lengths, is plotted in Fig. 2 for lubricated and unlubricated specimens. It will be noted that the natural strain versus piston velocity curves resulting from the first impact are linear for the piston velocity range 6 to 12 m/s corresponding to 33,3 and 133,3 J impact work respectively. The deformations are generally higher for lubricated specimens than for unlubricated specimens. The highest values of ϵ were obtained after the first impact with the shortest specimen $h_o/d_o = 1$. The values for ϵ decrease with increasing initial specimen height.

As will also be noted from Fig 2, the natural strain versus piston velocity curves resulting from the second impact are non-linear. The values reach a maximum at a piston velocity of about 9 m/s for unlubricated specimens and for lubricated specimens the maximum is estimated at about 15 m/s. This means an increase of the piston velocity above these values will always lead to a decrease in deformation during the second impact due to high degree of work-hardening of the specimens during the first impact.

The difference in natural strain between the first and second impact, $\Delta\epsilon = \epsilon_1 - \epsilon_2$, increases linearly with increasing piston velocity as shown in Fig. 3. The smallest

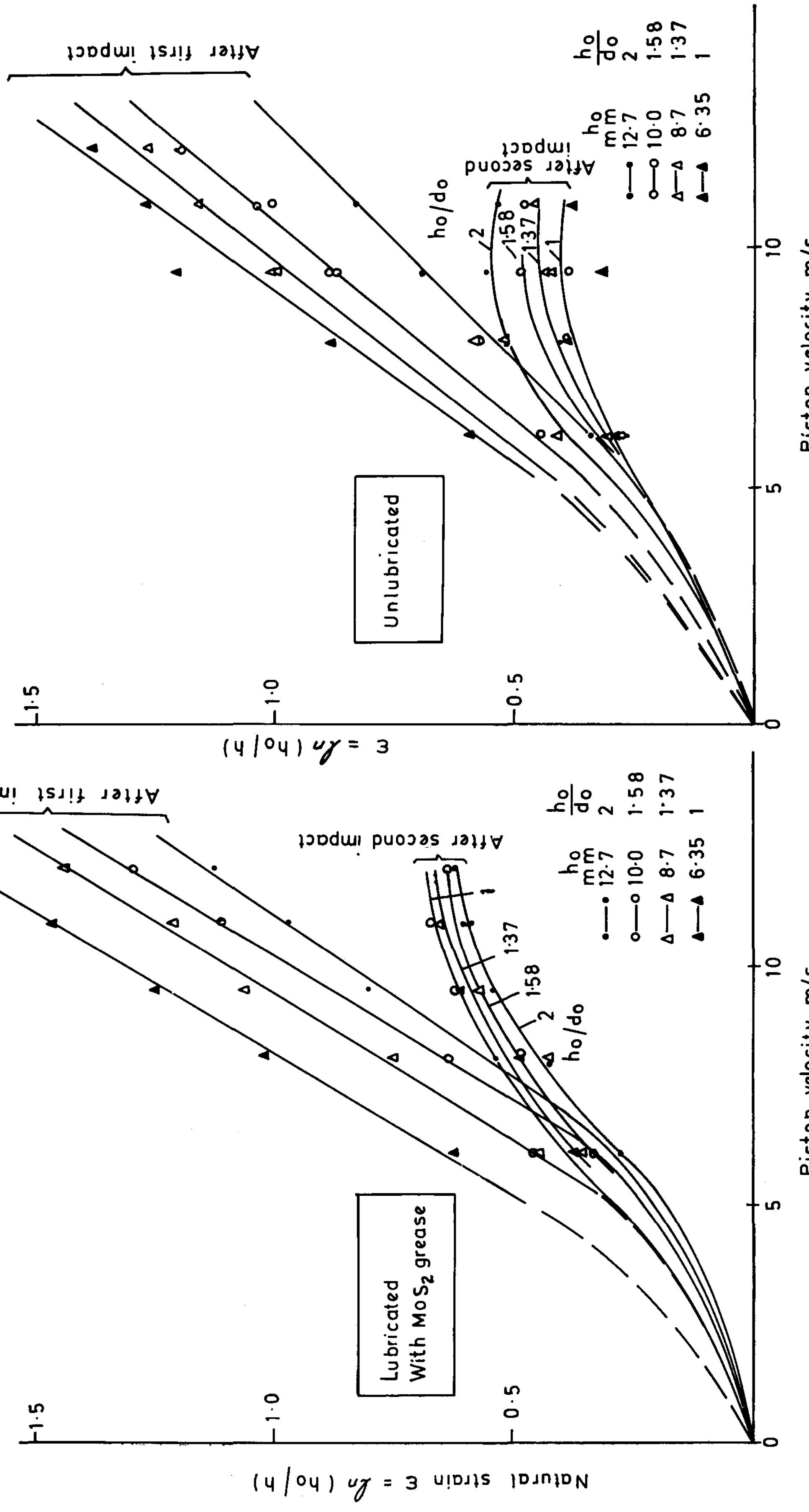

Fig. 2—Deformation versus "strain rate".

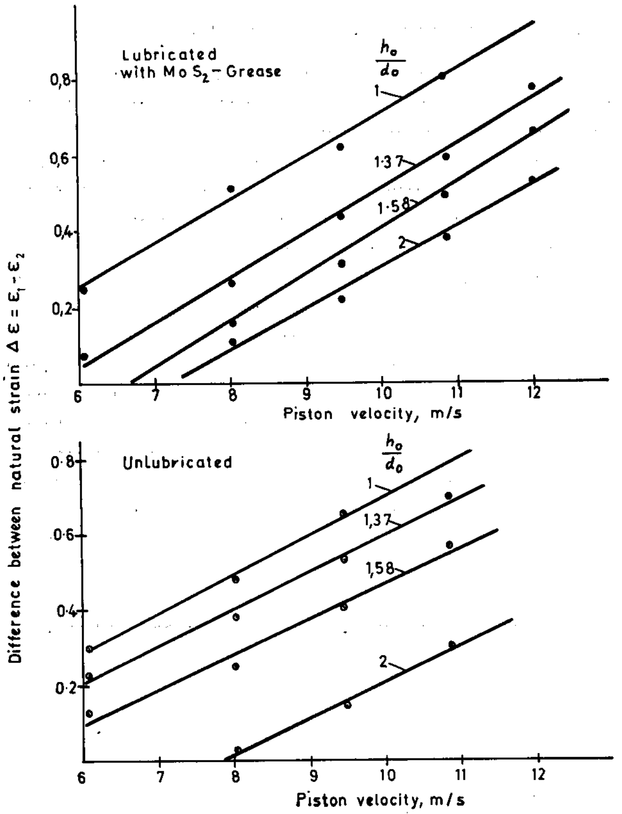

Fig. 3—Differences between natural strain after the first and second impact versus "strain rate".

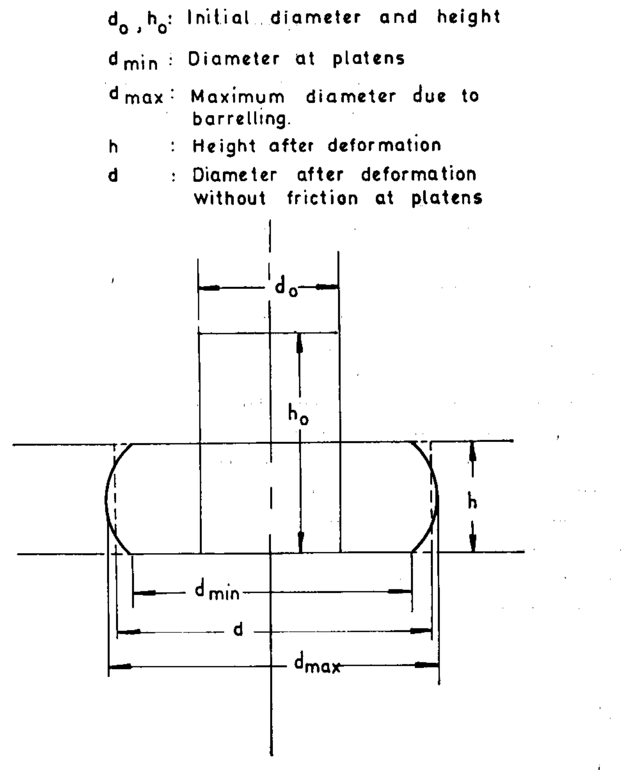

Fig. 4—Shape of a cylindrical specimen after deformation with and without friction at platens.

differences were obtained with the tallest specimens $h_o/d_o=2$ and the greatest with the shortest specimens, having initial $h_o/d_o=1$.

Barrelling effects

Friction at the pressure platens cannot be entirely eliminated even by lubrication. All the specimens therefore tended to become barrel shaped. A sketch illustrating the deformation of a cylindrical body after the first impact stroke is given in Fig. 4. In the ideal case with no friction between the specimen and the pressing platen, the specimen remains cylindrical after deformation, thus $d_{max}=d_{min}=d$ as indicated by the dotted contour lines.

In the case of friction between the specimens and the pressing platens, barrelling occurs, resulting in a difference between the two diameters. Curves of percentage difference between d_{min} and d_{max} versus deformation for different friction conditions are plotted in Fig. 5 and confirm that, as the friction is reduced by lubrication, the barrelling decreases. The difference between d_{min} and d_{max}, therefore, depends on the friction conditions. The curves show a maximum in the difference of the two diameters after a deformation ϵ of the aluminium specimens between 0,6 and 0,8 for the applied piston velocity of 8 m/s. For lubricated specimens the maximum difference is about 6% and for unlubricated specimens 12%. This maximum occurs at higher values of natural strain for greater initial specimen lengths. The height-to-diameter ratios h/d at these maxima are close to 0,5. With increasing further deformation the difference between d_{min} and d_{max} decreases. This can lead (as shown in Fig. 5 for slow loading of lubricated copper) to a transition from barrel to bollard shaped specimens.

Generally speaking therefore, it can be said that increased metal flow occurs at the platens with improved lubrication and that this results in a lower difference between d_{min} and d_{max} and in greater deformation during impact.

Influence of lubricant on the flow pattern of metal at the pressure platens

Lubrication also influences the surface quality of the specimen end faces. The smoothest surfaces were associated with unlubricated specimens when ground and polished platens were used. The greatest barrelling effect, however, was observed with unlubricated specimens.

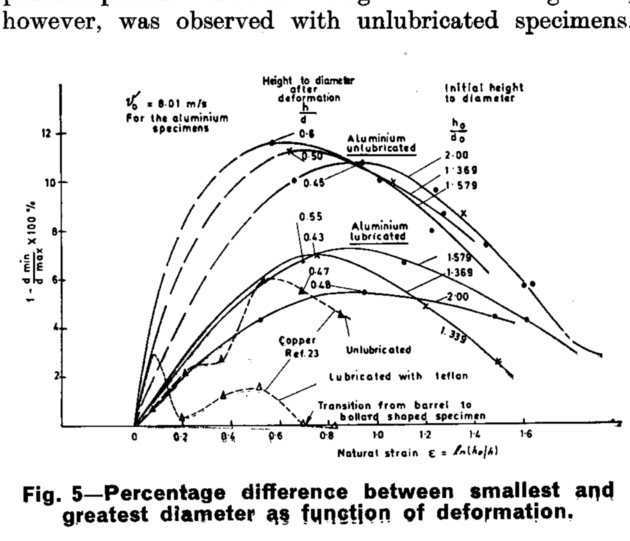

Fig. 5—Percentage difference between smallest and greatest diameter as function of deformation.

Using solid molybdenum disulphide the surface becomes much rougher; using grease the surface becomes rougher still. A roughness tester was therefore used to obtain a quantitative measure of roughness. The traces obtained are given in Fig. 6. Using solid MoS_2 the roughness is evenly distributed over the entire surface of the specimen. Using MoS_2-grease the roughness is greater in the central area of the specimen which is surrounded by a relatively smooth annular area. In contrast to the unlubricated specimens, where metal to metal contact occurs over the entire contact surfaces, those lubricated with MoS_2-grease only experience metal to metal contact over the annular area. The grease is entrapped by the ring in the central area during the shock deformation. High pressures build up so that the metal can freely deform without any contact with the platen, resulting in the higher surface roughness. In cases where rough, unpolished platens were used, it was possible even to destroy the metal surface of a specimen with grease to such an extent that 'potholes' formed on the surface as shown in Fig. 7.

Temperature rise in the specimens during deformation

Figure 8 shows the measured temperature rise during the deformation process for two of the specimens tested. Curve (b) was obtained when there was no contact between the specimen and the deforming bars of the impact loading machine after the impact. The temperature developed remained constant for about 13 seconds after which it dropped as a result of radiation to the ambient value. If the specimen remains in close contact with the impact bars, curves such as (a) in Fig. 8 were obtained. The cooling rate is much higher but the maximum temperature attained was the same as for (b). The peak temperature of the curves of the type (a), are plotted against the natural strains of successive impacts in the upper graphs in Fig. 9 for lubricated and unlubricated specimens, different piston velocities and specimens with three different initial height-to-diameter ratios.

The points for temperatures generated during the first impact versus natural strain, can, in all cases, be connected by straight lines having the same slope. Due to work-hardening of the specimens after several impacts

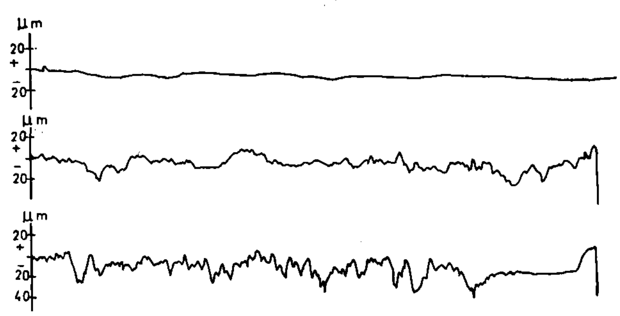

Fig. 6—Results of roughness testing of different specimens. From the top to the bottom:—Unlubricated surface—Lubricated with solid molybdenum disulphide—Lubricated with molybdenumdisulphide grease.

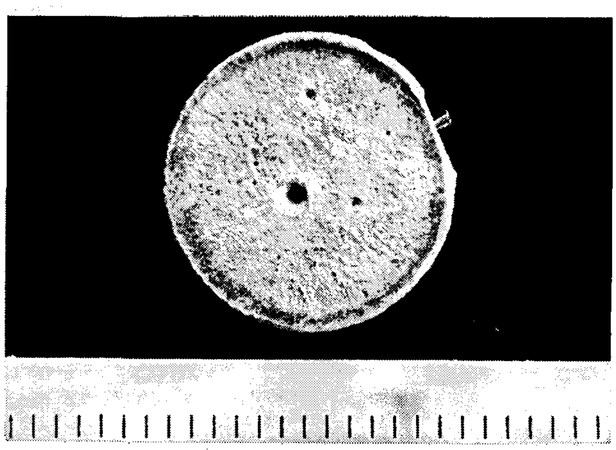

Fig. 7—Lubricated specimen pressed between rough platens resulting in "potholes" on the surface.

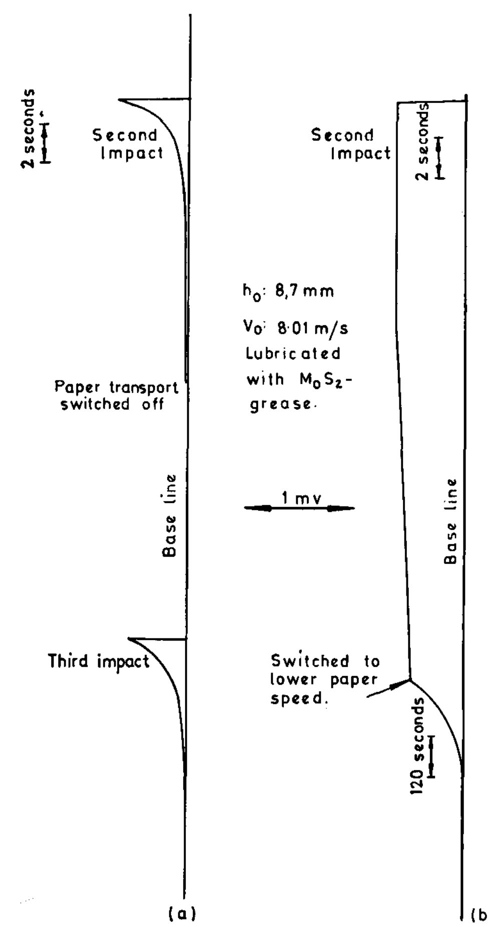

Fig. 8—Registration curves: Temperature rise versus time for:

(a) the second and third impact of a specimen remaining in close contact with the platen;

(b) The second impact of a specimen without contact with the platen after deformation.

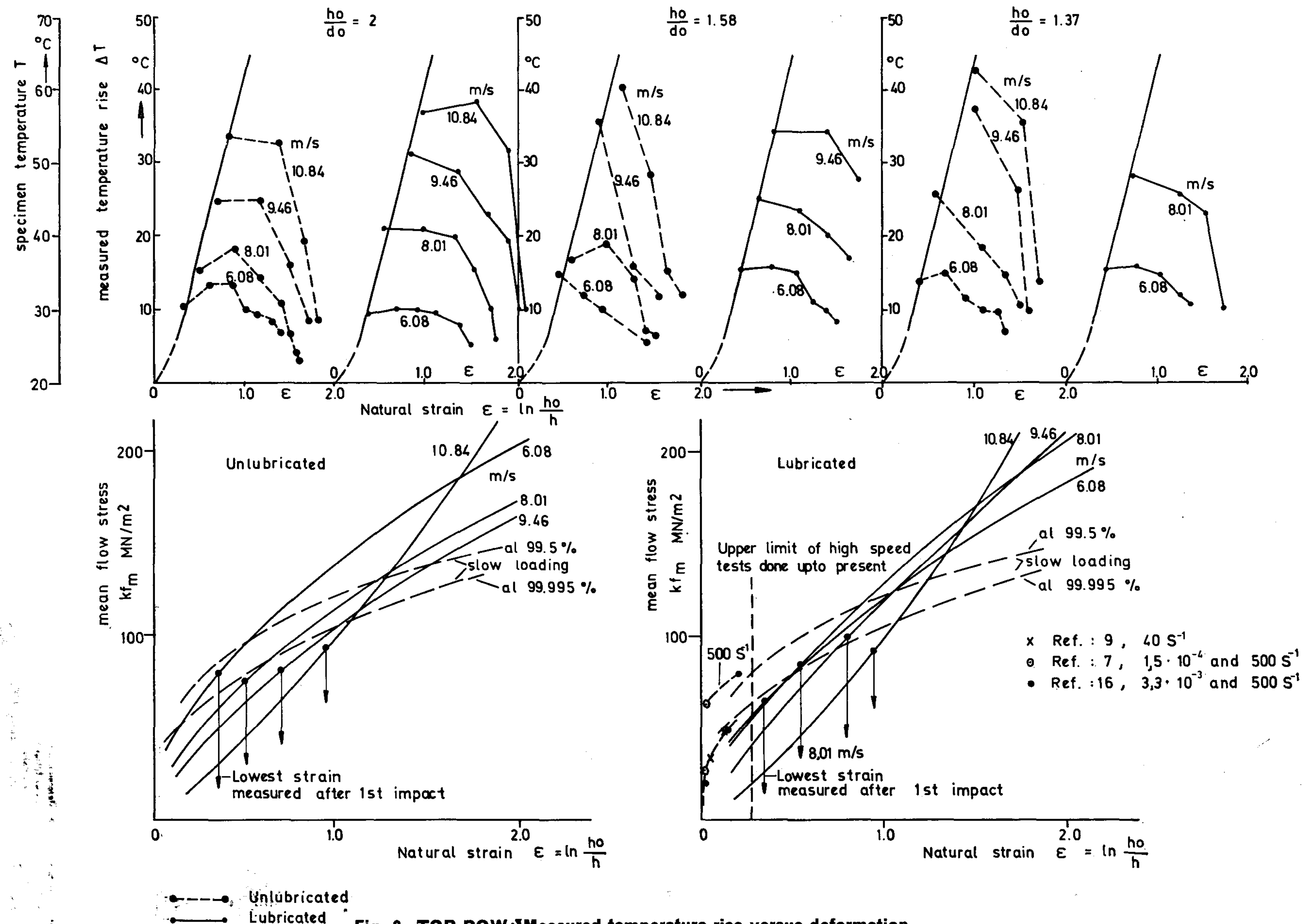

Fig. 9—TOP ROW: Measured temperature rise versus deformation.
BOTTOM ROW: Flow curves kf_m versus deformation—calculated using equation (6).

the temperature generated in the specimens decreases with increasing natural strain. In some cases, particularly for "taller" specimens with an initial h_o/d_o ratio of 2 and for some lubricated specimens, the decrease of temperature started after a period of constancy which is more extended for lower piston velocities. The lubricated specimens showed, in general, higher temperature rises than the unlubricated specimens.

Using these measured temperature rises, the mean yield strength k_{fm} was calculated using equation (6). By plotting these k_{fm} values versus the natural strain ϵ flow curves were obtained as shown in the lower graphs of Fig. 9. The first measured values are indicated by an arrow at these curves. As a result of the greater work-hardening during instantaneous loading, the slopes of the curves are greater than for slow loading conditions as indicated by the two curves for Al 99,5 and Al 99,995 which were separately determined and also shown in Fig. 9.

DISCUSSION

The determination of the influence of strain rate (presented by the piston velocity in the present investigations, and the friction on the deformation behaviour and temperature rise in the material was the main purpose of the tests.

It was confirmed that friction between the platens and the test specimens is one of the major factors influencing the results obtained in compression tests. Thus the absence or presence of lubricants at the interface of the platens and the specimens can create different frictional states. In the case of the absence of a lubricant almost complete surface contact at the interface occurs in the resulting dry friction condition as shown in Fig. 6. This high friction causes a barrelling effect which occurs at all strain rates.

As a result of this friction the flow and thus the resulting deformation of metals at unlubricated platens is less than at lubricated platens, see Fig. 2. This is in accordance with the results from other investigations[26].

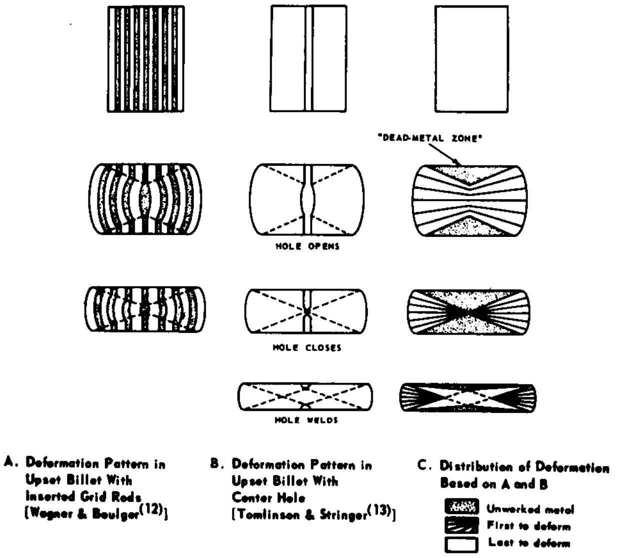

Fig. 10a—Deformation patterns of cylindrical specimens forged between flat platens, according to ref. 26.

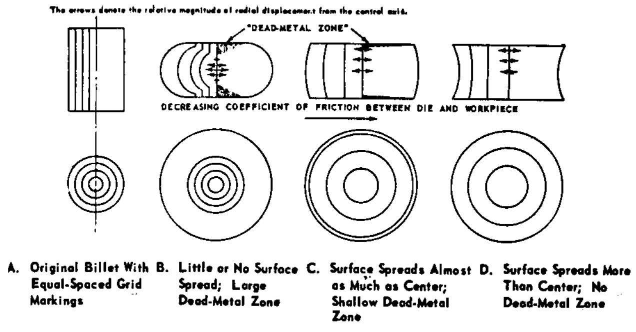

Fig. 10b—Inffuence of decreasing friction on the stress distribution during forging, according to ref. 26.

As illustrated in Fig. 10(a), the metal in contact with and adjacent to the flat platens is unworked. The unworked regions at the ends remain unworked with a 120 degree cone reaching into the specimen, until they meet at the centre and then begin to deform. The meta near the specimen centres is deformed more severely than indicated by the simple reduction of height. The metal at the specimen centres flows outwards until the zones meet. At this stage the metal flow reverses. This occurs at a height-to-diameter ratio of approximately 0,5. The same value is reached at the maxima of the curves in Fig. 5 for a piston velocity of about 8 m/s and indicates that after reaching this value the "dead-metal" zones begin to deform and increased metal flow is observed at the platens. The difference of the two diameters d_{min} and d_{max} begins to decrease. It can therefore be understood why the maxima occur and that they were shifted to higher values of natural strain for greater initial heights because the cones meet later in the taller specimens.

Application of lubricants between the flat platens and the specimens alters the friction conditions and the strain distribution patterns considerably. The mechanism of transferring the load into the specimen depends on the lubricant used, the grain size of the specimen and the strain rate[28]. When solid lubricants or greases were applied, a roughness similar to that of "freely deforming" surfaces of the cylindrical sides was developed. In case of solid lubricants the resulting roughness was evenly distributed over the entire flat surface of the specimen. Where grease or fluids were used the lubricants were entrapped and a bright annular peripheral contact area was usually formed at the specimen's pressed surface. This effect occurs according to Butler[27] with even the lightest lubricant. It resists expulsion, and compression occurs mainly via the entrapped fluid film. The shape of the compressed specimens can change with decreasing friction as indicated in Fig. 10(b). The increasing diameters of the concentric rings show that decreasing the surface friction causes increasing amounts of surface metal to flow. This produces a more uniform strain distribution and, in turn, more uniform metal flow. This is the reason why the natural strain for lubricated specimens is always higher than for unlubricated specimens. When friction is almost completely eliminated, conditions can be such that the surface metal spreads more than the centre material[23].

The work done by deformation appears mainly in the form of heat. This heating-up during deformation has been studied at intervals during the past 40 years[20,21,24,29,31]. According to Farren and Taylor[21] the percentage of the work converted into heat depends upon the materia and can amount to 85% to 95%. The rest remains in the lattice as latent energy. Results recently obtained by Dillon[22] indicate that as much as 95% to 100% of the work done was converted into heat. As a result of these investigations it was found that the temperature rise is limited to the front of migrating dislocations[29].

With every impact stroke the material work-hardens resulting in a decrease of the mobility of dislocations and thus reducing the number of centres where heat is generated. This must lead to the drop in temperature generated. Measurements of the ratio of stored to expended energy during deformation of copper also showed close relationship between the different slopes of the flow curve and the energy[32].

From the temperature measurements shown in Fig. 9 and from deformation measurements shown in Fig. 2, it can be seen that taller specimens ($h_o/d_o=2$) work-harden more slowly than shorter specimens. This is also indicated by the more extended horizontal part of the $\Delta T-\epsilon$ curves in Fig. 9, especially at lower piston velocities of 6 and 8 m/s for lubricated specimens. With smaller initial height-to-diameter ratios the temperatures generated in the specimens immediately drop at the second impact. Unlubricated specimens always gave lower temperature rises than lubricated specimens due to different amounts of metal flow.

The flow curves shown in Fig. 9 which were, for instantaneous loading determined by means of equation 6 using the measured temperature rises and by direct recording of stress and strain for slow loading, are in good agreement with results from other investigations only in the slow loading range. For instantaneous loading there is a considerable discrepancy in the slope of the curves. A reason for this could be that the present results were obtained under non-uniform deformation conditions, resulting in lower ΔT-values, from which lower k_{fm}-values were calculated. The limit for uniform conditions used in other papers is indicated by the vertical dotted line, which shows that all measured first points of the present results are outside this limit.

CONCLUSION

The work-hardening of high-purity aluminium specimens depends on the initial h/d ratio and increases with decreasing initial h/d ratio. The deformation under compression leading to large strains of more than 0,5 is non-uniform. For the deformation behaviour the "dead-metal" zones formed at the pressing platens are important as they influence the flow behaviour of the metal at the pressing platens. Strains in the centre of the specimens become entirely compressive once the "dead-metal" zones meet. This occurs at a height-to-diameter ratio of approxmately 0,5 leading to a maximum in the $d_{min}-d_{max}$ versus ϵ curves. Lubricated and unlubricated specimens have the maxima at the same h/d ratio but the difference between $d_{min}-d_{max}$ is smaller for lubricated specimens. The metal flow of lubricated specimens is more uniform and the resulting strains for each impact are higher. This results in a higher temperature generated in the specimen during deformation. Short specimens give higher temperature rises during the first impact but due to higher work-hardening, show steeper temperature drops during the following impact. Flow curves calculated from the temperature measurement do not agree with direct measured values.

References

1. Nadai, A. and Manjoine, M. J. High-speed tension tests at elevated temperatures. *J. Appl. Mech.* 8(1941), pp. A-77/A-91.
2. Manjoine, M. J. Influence of rate of strain and temperature on yield stresses of mild steel. *J. Appl. Mech.* vol. 11 (1944), pp. A-211/A-218.
3. Clark, D. S. and Wood, D. S. The time delay for the initiation of plastic deformation at rapidly applied constant stress. *ASTM Proc.* vol. 49 (1949), pp. 717/737.
4. Krafft, J. M., Sullivan, A. M. and Tipper, C. T. The effect of static and dynamic loading and temperature on the yeild stress of iron and mild steel in compression. *Royal Soc. Proc.* Ser. A. 211 (1954), pp. 114/127.
5. Alder, J. F. and Phillips, V. A. The effect of strain rate and temperature on the resistance of aluminium, copper and steel to compression. *J. Inst. Met.* vol. 83 (1954-55), pp. 80/86.
6. Chalupnik, J. D. and Ripperger, E. A. Dynamic deformation of metals under hydrostatic pressure. *Experim. Mech.* vol. 6 (1966), Nov., pp. 547/554.
7. Karnes, C. H. and Ripperger, E. A. Strain rate effects in cold worked high purity aluminium. *J. Mech. Phys. Solids.* vol. 14 (1966), no. 2, pp. 75/88.
8. Davidson, D. L., Lindholm, N. S. and Yeakley, L. M. The deformation behaviour of high purity poly-crystalline iron and single crystal molybdenum as a function of strain rate at 300°K. *Acta Met.*, vol. 14 (1966), no. 6, pp. 703/710.
9. Revsin, B. and Bodner, S. R. Experiments on the dynamic tensile strength of metals and plastics. *Israel J. Technol.*, vol. 7 (1969), no. 6. pp. 485/493.
10. Rinehart, J. S. and Pearson, J. *Behaviour of metals under impulsive loads.* Dover Publications, Inc., New York, 1965.
11. Davies, E. D. H. and Hunter, S. C. The dynamic compression testing of solids by the method of the split hopkinson pressure bar. *J. Mech. Phys. Solids.*, vol 11 (1963), pp. 155/179.
12. Chiddister, J. L. and Malvern, L. E. Compression impact testing of aluminium at elevated temperatures. *Experim. Mech.*, vol. 3 (1963), April, pp. 81/90.
13. Maiden, C. J. and Green, S. J. Compressive strain-rate tests on six selected materials at strain rates from 10^{-3} to 10^4 in/in/sec. *Trans. ASME* (1966), Sept., pp. 496/504.
14. Lindholm, U. S. and Yearkley, L. M. High strain-rate testing: tension and compression. *Experim. Mech.*, vol 8 (1968), Jan., pp. 1/9.
15. Lindholm, U. S. Some experiments with the split hopkins pressure bar. *J. Mech. Phys. Solids.*, vol. 12 (1964), pp. 317/335.
16. Lindholm, U. S. and Yearkley, L. M. Dynamic deformation of single and poly-crystalline aluminium. *J. Mech. Phys. Solids.*, vol. 13 (1965), pp. 41-53.
17. Davies, R. M. A critical study of the hopkinson pressure bar. Phil. Soc. London, *Phil. Trans.*, vol 240 (1948), Jan., pp. 375-457.
18. Heinemann, H. H. Formänderungsfestigkeit verschiedener Aluminium- und Kupferlegierungen bei hohen Formän. derungsgeschwindigkeiten und Umformtemperaturen-Schloemann Druckschrift. pp. 2-611 (1962).
19. *Fliesskurven Metallischer Werkstoffe.* VDI-Arbeidsblatt 3200, (1964).
20. Taubert, P. Über die Erwärmung von Zerreiss-stäben infolge plastischer Verformung. *Z. Aangewandte Phys.*, vol 6 (1954), no. 3, pp. 108/112.
21. Farren, W. S. and Taylor, J. F. The heat developed during plastic extension of metals. *Proc. Royal Soc.* Ser. A-107 (1925), Jan./Apr., pp. 422/451.
22. Dillon, O. W. jr. Plastic deformation waves and heat generated near the yield point of annealed aluminium. In:

Mechanical behaviour of materials under dynamic loads. U.S. Lindholm, Editor. Spring-Verlag, Berlin/Heidelberg/New York- (1968) pp. 21-60.

23. Hsü, T. C. A study of the compression test for ductile materials. *Materials Res. & Standards.*, vol. 9, (1969), no. 12, pp. 20-25 and 47-53.
24. Podszus, E. Energie-Verhältnisse und Umsetzungen bei Verformung und Bruch. ½. *Metallkde.*, vol. 41 (1950), pp. 23-31.
25. Winkler, E. 'Forgeability' and its correlations to the mechanical properties of metals. *Canad. Metallurg. quarterly.*, vol. 7 (1968), no. 1, pp. 49-54.
26. Sabroff, A. M., Boulger, F. W. and Henning, H. J. *Forging Materials and Practices.* Reinhold Book Corp., New York, Amsterdam, London (1968), pp. 129-133.
27. Butler, L. H. The effect of interposed lubricants on the surface deformation of metals during plastic working. *J. Inst. Met.*, vol. 88 (1959/60), pp. 337-343.
28. Wiegand, H. and Kloos, K. H. Der Kaltstauchversuch als Modellumformverfahren zur Erfassung der Reibungs- und oberflächenvorgänge. *Werkstattstechnik.*, vol. 56 (1966), pp. 129-137.
29. Spath, W. *Fliessen und Kriechen der Metalle.* METALL-Verlag GmbH, Berlin, Germany (1955), pp. 13 and 45.
30. Lippmann, H and Johnson, W. Temperature development based on technological analysis: fast rolling as an example. *Appl. Sci. Res.*, Sect. A, vol. 9 (1960), pp. 345-357.
31. Schonert, K. and Weichert, R. Die Wärmetönung des Bruches in Eisen und ihre Abhängigkeit von der Ausbreitungsgeschwindigkeit. *Chem. Ing. Techn.*, vol 41 (1969), no. 5 and 6, pp. 295-300.
32. Wolfenden, A. The ratio of stored to expended energy during the room-temperature-deformation of copper single crystals. *Scripta Met.*, vol. 4, (1970), no. 5, pp. 327-332.