BALL-DROP PLATE BENDING: AN EXPERIMENTAL STUDY OF SOME OF ITS PROCESS VARIABLES

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SUMMARY

For the ball-drop plate bending process (analogous to orthodox peen-forming except that the balls used are very much larger and the impact speed very much less), a brief literature survey is presented. Typical results are reported of an experimental investigation concerning the effects of some variables in this impact process on the curvature acquired by initially flat strips. The experimental set-up used is described and measurements of the surface finish of the target plates after bombardment are presented.

INTRODUCTION

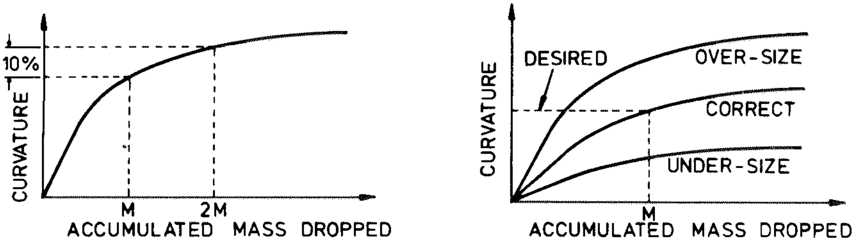
Although the peening of metallic components dates back to ancient history, one major application of this process today is the forming of flat metal sheet and plate to specified simple or compound curvature. The bombardment of a plate surface with 0.25 to 1 mm diameter shots of hardened iron, steel or glass at velocities between 20 and 300 ms^{-1} causes small plastic indentations and hence the stretching of the impacted surface layer. The mechanical action is analogous to that of hammering the surface of a metal, to relieve inherent tensile stresses and to build-up relatively large sub-surface compressive stresses. The work-hardened (and severely plastically deformed) surface layers contain high residual compressive stresses and are greatly effective in reducing troublesome fatigue failures, Fuchs (1948); they also enhance resistance to stress-corrosion, Straub (1965), - a condition particularly detrimental to aircraft structures and rotating machinery parts.

The process of peen forming is similar to shot-peening, but not the purpose; see, for example, the articles by Baughman (1970), Meguid (1978), Johnston and Daly (1975) and T. A. Johnson (1968). Whereas the fatigue strength of components is increased by the action of peening in both the latter processes, in the former the primary aim is to provide gentle and irregular contours to fairly large metal sheets. Ball-drop forming which is analogous to peen-forming uses balls that are delivered at a low velocity - usually, simply that due to fall under gravity from a small height. The multitude of impacts in this case also covers the part with a thin compressive layer (compressive stress parallel to the surface) and retards or prevents the formation of harmful tensile cracks at the surface. Ball-drop forming is a patented process, the most interesting example of its application having been to contour wing panels for the Lockheed L-1011 aircraft; see Straub (1970) and Brandel and Klass

(1971). The steel balls usually employed in this process are all of the same diameter - many times larger than those used in orthodox shot-peening. Although mostly aluminium parts have been formed very successfully by the ball-drop forming technique, other potential applications are components made of various grades of magnesium, titanium and steel, see Brendel and Klass (1971). For a detailed discussion by authors from various countries, of topics relating to peening, mechanical peen-forming and ball-forming, the reader may consult the work of Mihara and Johnson (1977), and Kopp and Hornauer (1977); see also the recent work reported by Meguid, Johnson and Al-Hassani (1977a and b), Johnson, Mamalis and Ghosh (1980), Chitkara and Johnson (1980) and Johnson (1981).

Scope of Paper

In peen-forming it is found that the curvature of a flat target plate generally increases rapidly in the early stages but that it slowly approaches an almost saturated level, see Fig. 1(a). The saturation is related to the coverage of the shot, i.e. due to the randomness in the positions of the impacts of the shot, the fraction of the target surface area that is plastically deformed increases steadily with time (but not proportionally) until the whole of it has been bombarded. The target is considered to be saturated when 98% of the exposed surface is plastically deformed. For an appropriate depth of sub-surface plastically-deformed layer and distributed stress within the target there is an optimum level of bombardment; this is approximately such that for twice the mass of shot delivered (or balls let fall in ball-drop forming) the increase in curvature is 10%. This implies that with each combination of ball size, density, hardness and drop-height there will be an optimum mass to be dropped and a certain resulting curvature for a particular target material and dimensions. Therefore, as illustrated in Fig. 1(b), for a desired curvature, and given target material and dimensions it should be possible to choose a combination of ball specifications and drop-height that is optimal; any attempt to form a specimen with over- or under-size balls (dropped from a specific height) will result in undesired shapes and qualities.



(a) (b)

Fig. 1: (a) Correct amount of bombardment and (b) correct ball size and drop-height

With a view to securing the aforementioned objectives, an experimental investigation into ball-drop forming has been carried out and the present discussion concerns the results which illustrate the effects caused by several of the variables on the curvature of components produced. These variables are: (i) the ball size and material, (ii) the height of drop of the balls, (iii) the mass of the balls dropped, (iv) the mechanical properties of the target material, and (v) the thickness of the target. Only typical results of a range of experimental data are reported here.

MATERIALS, EQUIPMENT AND PROCEDURE

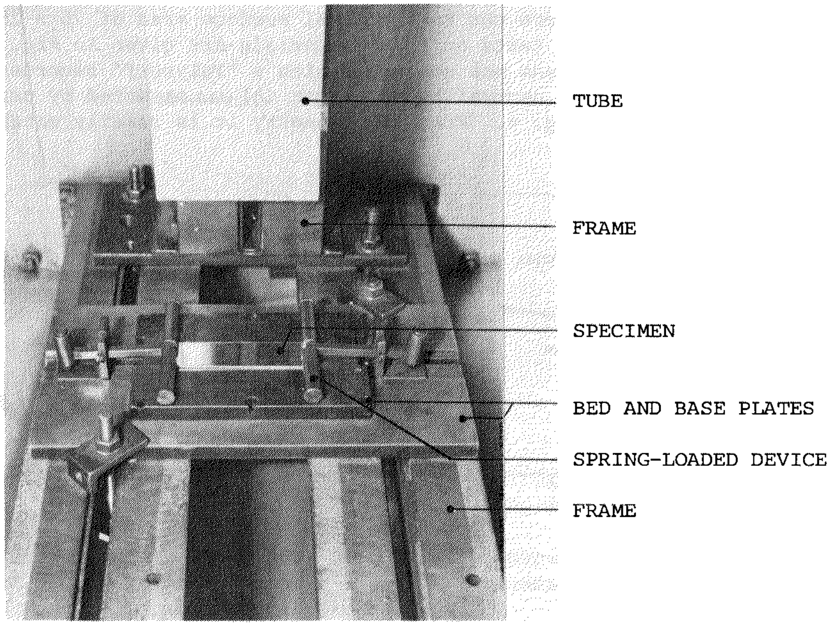


Fig. 2(a): Ball-forming apparatus

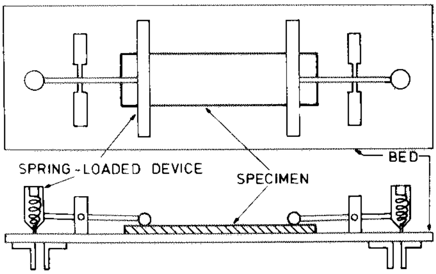


Fig. 2(b): Clamping table for targets

The ball-drop forming apparatus, part of which is shown in Fig. 2(a) is designed so that the balls are accelerated under gravity down a tube, hit the target at normal impact and are then channelled down the inclined floor of the containing box by gravity into a collecting box below. The main frame of the apparatus consists of two hardened steel beds, upon which the wooden delivery tube with its funnel is attached. Specimens in the form of rectangular strips can easily be clamped onto this bed and a base plate, by the spring-loaded device as shown in Figs. 2(a) and (b). A desired mass of balls, in multiples of 3 or 5 kg in the present tests, is poured down the tube, the curvature and surface-roughness of the specimen measured, and the process repeated until the total mass of the forming medium dropped on the specimen reached 30 or 50 kg, as appropriate. The forming 'tools' consisted of three sizes of steel balls (chrome grade ball bearings with a tolerance of 0.00125 mm, of hardness value 900 kgf mm^{-2}, and diameters (D) of 3.17, 6.34 and 9.51 mm). In addition, glass beads ($D \simeq 6$ mm) and S390 steel shot ($D \simeq 1.23$ mm) were also used.

Commercial purity copper (thickness, $t = 3.14$ and 1.55 mm) and aluminium ($t = 3.14$ mm), and mild steel ($t = 0.76$, 1.18, 1.59 and 3.14 mm) sheets were used as test materials. All the specimens were cut to a nominal surface area of 75 × 25 mm. Results of the uniaxial tensile tests on these materials are given in Fig. 3. The surface roughness of the specimens was measured using a 'Talysurf' recorder. The radius of curvature (R) and the central bulge height (h) was measured by using a system of three rollers, see Fig. 4. From the geometry it is readily established that $R = (2r^2/d + r)$.

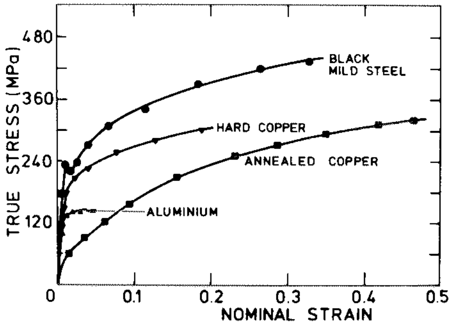


Fig. 3: True stress-nominal strain curves for target specimens from tensile test

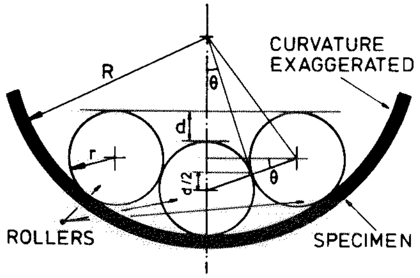


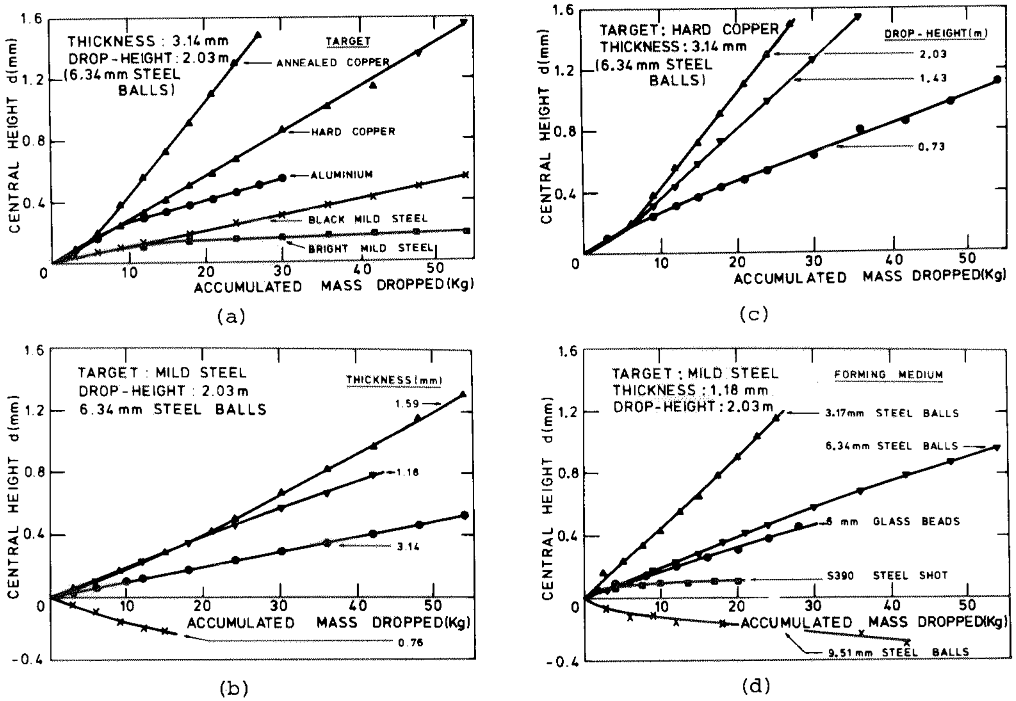
Fig. 4: The three roller system for the measurement of radius of curvature

DISCUSSION

To determine the coverage (λ), 1 kg of 6.34 mm diameter steel balls was dropped from a height of 2.03 m onto three areas of 2 cm^2 drawn on an aluminium target, and the number of indentations counted. The average number of impacts and weight of each ball was 36.2 cm^{-2} and 1.04 g respectively; the coverage (λ) was found to be $(1.04 \times 10^{-3} \times 36.2)$ or 0.038 kg cm^{-2}/kg, i.e. for each 1 kg of balls dropped, approximately 0.038 kg of balls are delivered, nominally, to every 1 cm^2.

Figure 5(a) shows the variation of the central bulge height (h) with accumulated mass of balls of 6.34 mm diameter dropped onto different targets of the same thickness, the height of drop being maintained at 2.03 m. The only specimen which showed a tendency towards a saturated height was that of bright mild steel. It may *generally* be stated that the 'harder' is the target material, the slower is the rate of increase of curvature for the same amount of mass of balls dropped onto targets having the same dimensions. However, the particular curve for aluminium is not at one with the aforementioned observation. This is surprising however, since the overall deformation behaviour of different target materials depends not only on their hardness value, elastic modulus and elastic limit but also on their strain-hardening characteristic.

Figure 5(b) shows the saturation curves for different thicknesses of mild steel sheets which were formed with 6.34 mm diameter balls dropped from a height of 2.03 m. There are two complexities which may be noted in this figure. Firstly, the curve for 1.18 mm thick specimens lies between those for 1.59 and 3.14 mm thick specimens. Secondly, the thinnest specimens tested ($t = 0.76$ mm) bulges the 'wrong' way. The latter behaviour may be attributed to the values of span to thickness ratio of the specimens; in the present case, for 6.34 mm diameter balls dropped from a height of 2.03 m, there appears to be a 'critical' thickness between 0.76 and 1.18 mm at which the curvature produced changes from convex to concave. For thicker steel sheets ($t = 1.59$ and 3.14 mm), the central bulge height decreases with increasing thickness for the same amount of mass dropped; the same residual surface stresses are balanced by smaller stresses and strains in a larger volume.



(a) (c)

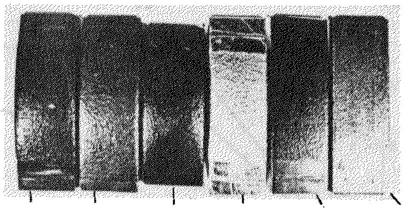
(b) (d)

Fig. 5: (a) Saturation curves for different target materials of the same thickness; (b) saturation curves for different thicknesses of mild steel target; (c) effect of height of drop on hard copper targets; and (d) effect of forming ball materials on saturation curves of mild steel targets.

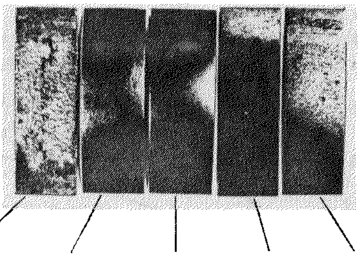
The effect of the height of drop of the balls is presented in Fig. 5(c). As would be expected, the target curvature is increased as drop-height increases. It may be noted, however, that if the curvature values were plotted against the total energy applied to the target, the reverse would be found. The above results are true for targets of finite thickness where the plastic layer generated by impact is restricted only to the surface of the target.

The effect of balls of different material on the variation of curvature with accumulated mass dropped, is presented in Fig. 5(d). It is interesting to note that the S390 shot truly saturated the target with a total mass of around 4 kg. Also, the use of the target steel balls (D = 9.51 mm) gives rise to concave-shaped specimens as opposed to those obtained employing smaller steel balls. From Figs. 5(b) and (d) it is clear that for a given drop-height, the attainment of greatest curvature and convex shape depends on the ball size, in addition to the thickness of target, its strength characteristic, and the span to thickness ratio.

Some of the specimens for which the results are plotted in Figs. 5(a) to (d), are shown in Fig. 6. Figure 7 presents a comparison of close-up views of the surface of copper targets when formed with different diameter steel balls, steel shot and glass beads. The general pattern of the surfaces formed with steel balls is similar, although the chordal diameter of indentation decreases, and is almost proportional to the diameter of the steel balls. The surface of the targets formed with steel shot and glass beads, see Figs. 7(d) and (e), respectively, appears to be much 'smoother'; both the jagged nature of the shot and the partially broken glass beads give rise to indentations which are irregular but flatter in shape.



Different target materials



Different balls

Fig. 6: Typical specimens

(a) 9.51 mm steel balls drop height 2.03 m
(b) 6.34 mm steel balls
(c) 3.17 mm steel balls
(d) S 390 steel shot
(e) 6 mm glass beads
(f) 6.34 mm steel balls drop height 1.43 m

Copper target: thickness 3.14 mm

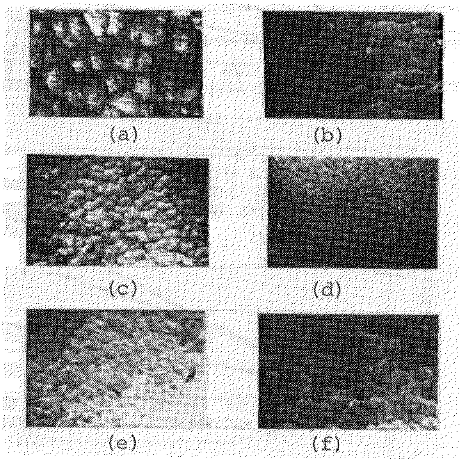


Fig. 7: Surface finish of 3.14 mm thick copper targets (magnification ×10)

The surface profiles of some of the mild steel targets, presented in Figs. 8(a) to (f), clearly demonstrate how the chordal diameter and depth of indentation increase with increasing ball size, Figs. 8(a) - (c). The relatively smoother surfaces obtained using steel shot and glass beads may also be seen from the profiles of the hardness of the target material; the roughness decreases as the values of the latter increase.

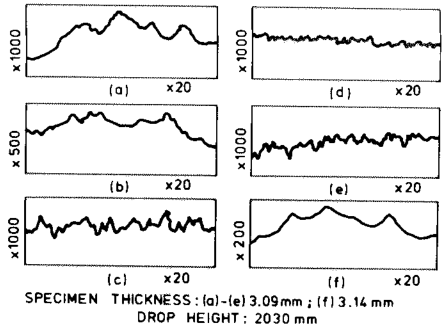


Fig. 8: Some surface finish profiles of 3.14 mm thick mild steel specimens, where the forming media are: (a) 9.5 mm, (b) and (f) 6.34 mm, (c) 3.17 mm steel balls, (d) S390 steel shot, and (e) 6 mm glass beads

CONCLUSIONS

The critical observations reported here pertain to the effects on the curvature of components introduced by the finite thickness of the target, the ball size, the target material properties and the drop height. For a given target, a critical ball size appears to exist, below which there will be 'convex' curvature and above which a 'concave' curvature is obtained. For a given drop-height, the surface roughness increases with increasing ball size and decreasing target strength. Additionally, if the drop-height is raised so that the same final curvature is produced, the roughness will decrease with increasing ball size. In general, however, the rate of increase of curvature increases with: (i) increasing ball size and drop-height, and (ii) decreasing target thickness and hardness.

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