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V-shaped sheet forming by deformable punches

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Abstract

The technique of elastic-plastic sheet stamping has been employed extensively in the forming of a variety of engineering components. In addition to the conventional processes with unitary rigid punches and dies, a technique of sheet stamping by deformable forming tools (SSDFT) has been established and designed into a wide range of press working. Though the technique has many potential advantages over the conventional one, the process involved has not been studied carefully and proper guidelines are not available for practical manufacturing design.

The present paper describes experimental investigations into the deformation mechanisms of V-shaped sheet forming by deformable punches and rigid dies. Emphases are placed on the improvement of springback in terms of the material properties and thickness of the sheet metals, geometry and properties of the deformable punches, and geometry of the rigid dies. The study reveals that the reduction of springback ratio is mainly due to the interface actions offered by the punches. The deformation of the punch material during stamping alters the deformation mechanisms of the sheet and makes the springback ratio mainly negative. The development of the contact zone demonstrates that the plastic flow of the punch material is basically three dimensional. For a given work material, therefore, the selection of punch material is of great importance.

Keywords: V-shaped sheet forming, deformable punch, plastic bending, springback

1. Introduction

Sheet stamping process has been extensively employed in the manufacturing of a wide range of metallic engineering product components. As a result, there has been much research recently into the detailed mechanics involved in the process in order to understand and solve problems in relation to elastic springback, elastic and plastic wrinkling and material tearing [1-3].

The approaches to stamping problems, mainly of springback, have been experimental [4-7], analytical [8-11] and some have used finite element analyses [12-15]. However, despite the progress made in the past few decades, problems of large elastic springback, tendency of tearing and scratching, and inflexibility of the products using conventional rigid punches and dies still remain. Recently, a new technique of sheet stamping using deformable punches and/or deformable dies has emerged and this offers a potentially promising alternative to produce components which are otherwise difficult to make using the conventional stamping tools. In order to efficiently design the deformable tools for a desired final product, one needs to understand the mechanical process involved in a typical SSDFT. There is, however, a lack of research in this area except for some isolated studies [16-19].

The present paper describes part of our series of investigations into the SSDFT. It involves the mechanism studies of V-shaped bending of metal sheets using a deformable punch and a rigid die. Emphases are placed on the improvement of springback in terms of the material properties and thickness of the sheet metals, geometry and properties of the deformable punches, and geometry of the rigid dies. The contact features between both the sheet and punch and sheet and die are obtained systematically using Prescale Films.

2. Experimental set-up

The punch and die used for the tests are schematically shown in Fig. 1 together with the dimensions and definitions of the variables. The dies and punches' main body were made of mild steel, but the leading edge of the punches was machined into a groove and a soft wire (of lead in this case) was inserted, which made the punch deformable. In a matching set of punch and die, they both had the same value for angle θ. Lead wires of three diameters were used, i.e. 0.75, 1.5 and 3.0mm, and the rigid dies had radii of 0.5, 0.75 and 1.0 respectively. A summary of the punch and die dimensions is given in Table 1.

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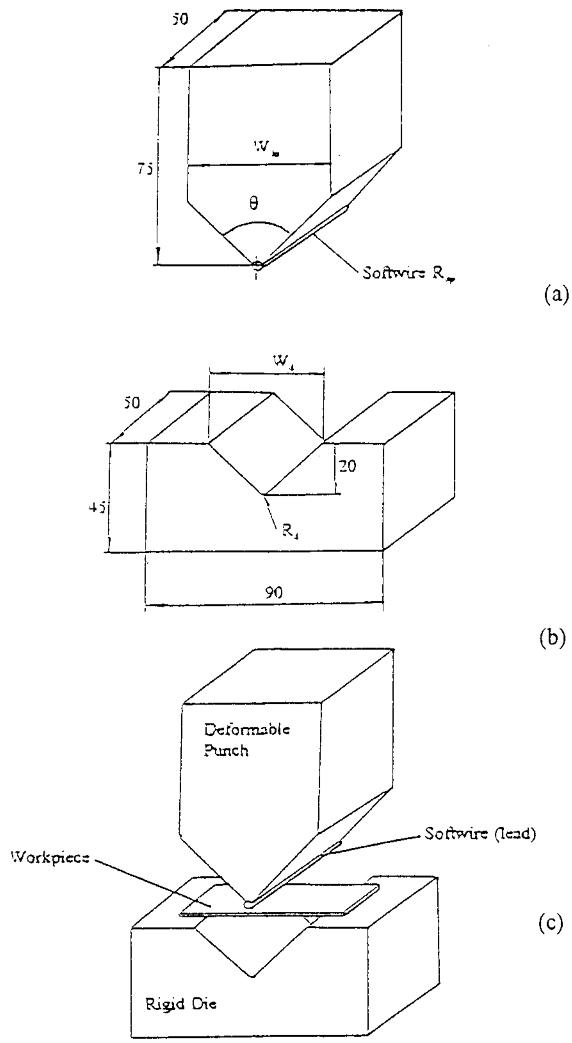


Fig. 1. Geometries for the deformable punch (a) and rigid dies (b); and the tooling set-up (c).

Three different materials, namely mild steel, brass and copper were used and each had three thicknesses in the range of 0.3 to 0.9mm. The sheets were cut into rectangular specimens of width 30mm to be placed either on or in the die, depending on the length cut. The dimensions of the specimens are given in Table 2 and the mechanical properties of the metal sheets were obtained from standard uniaxial tensile tests.

Table 1: Parameters of the deformable punches and rigid dies

Tools	Deformable punch		Rigid die	
θ	R_{dp} (mm)	W_{dp}(mm)	R_d (mm)	W_d (mm)
60^0	0.75	40.0	0.5	23.7
	0.75	50.0	0.5	40.4
90°	1.5	50.0	0.75	40.6
	3.0	50.0	1.0	40.8
120^0	0.75	80.0	0.5	69.5

Table 2: Specimen materials and dimensions. t has three values for each material.

Material	$\theta=60^0$	$\theta=90^0$	$\theta=120^0$
mild steel	22x30xt	38x30xt	66x30xt
	30x30xt	50x30xt	80x30xt
brass	22x30xt	38x30xt	66x30xt
	30x30xt	50x30xt	80x30xt
copper	22x30xt	38x30xt	66x30xt
	30x30xt	50x30xt	80x30xt

All the tests were performed with an Instron machine (model 4302) to which the punches and dies were secured by means of adapters. The crosshead speed was set at 25 mm/min., which can be regarded as quasi-static. A 10 kN load cell with an accuracy of 1% was used. During each test, the load-displacement curve was obtained automatically. The angle bent after unloading at various stages was measured and, for typical tests, the contact area was studied by means of a Fuji Prescale film. The test program involved combinations of different punches, dies and materials.

3. Experimental results and discussion

The mechanism of sheet stamping process by a deformable punch upon a V-shaped rigid die was explored experimentally. In this section, the typical load-displacement curves are presented together with successive photographs of the specimen at various stages. The final bent angle is ultimately related to the springback of a test specimen and relevant factors are discussed; they are punch displacement, deformable punch radius, rigid die radius and rigid die angle. Phenomenon of springback and springforward is mentioned and discussed. Finally the contact area at the interfaces is shown.

3.1 Load-displacement characteristics

A typical set of load-displacement curves is shown in Fig. 2 for three materials with a deformable punch (DP90-0.75) and a rigid die (RD90-0.75). Here DP90-0.75 denotes a deformable punch with included angle $\theta=90^0$ and a radius of 0.75mm;RD90-0.75 stands for a rigid die of angle 90^0 with a radius of 0.75mm.

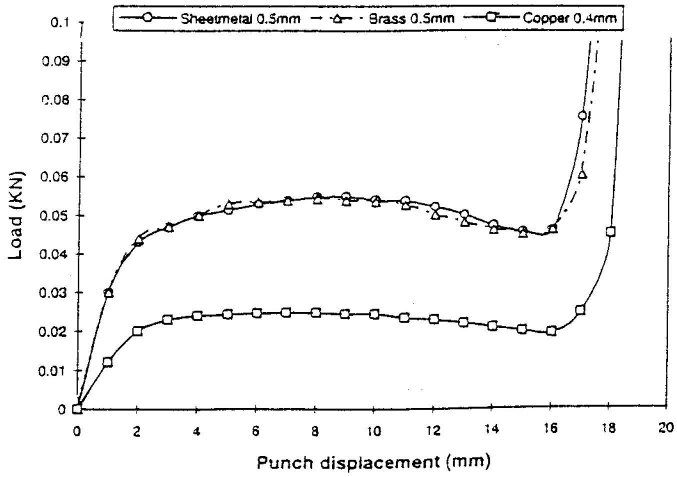


Fig. 2. Typical load-displacement curves.

Fig 3 presents the photographs of a specimen of mild steel taken during a test for DP90-0.75 and RD90-0.75.The angle of V shaped specimen during loading, α, was measured. The specimen was unloaded at each stage in order to measure the angle of specimen after unloading, β. Thus before a test the flat specimen has a value of 180° for α.

All the load-displacement curves for the different tool combinations exhibit similar characteristics, as shown for example in Fig 2. In general, a load-displacement curve can be divided into three zones, namely, the primary zone, the secondary zone and the coining zone as illustrated in Fig. 4.

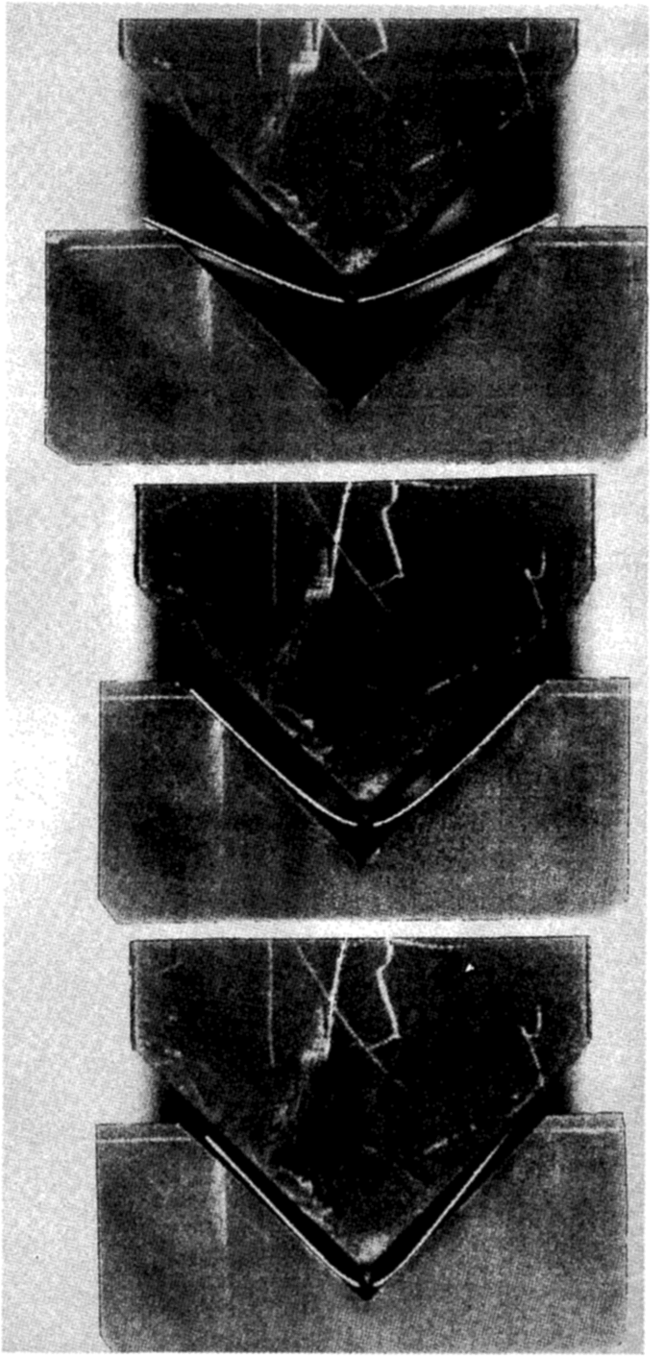


Fig. 3. Photographs of a specimen during test at a displacement of 8, 16 and 18mm, respectively.

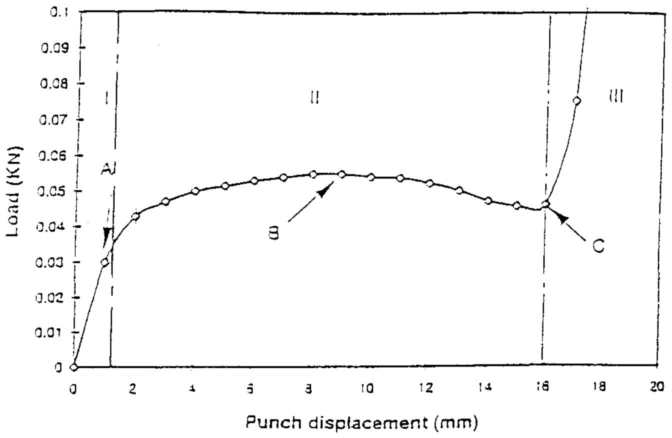


Fig. 4. Three stages of a general load-displacement curve.

In the primary zone, the force rise rapidly from zero to point A at an initial small punch travel of 2 mm. This mainly corresponds to the elastic behaviour of the material where the load increases almost linearly with the punch displacement until the onset of the plastic deformation.

In the secondary zone, the bending force somehow rises to point B and then gradually falls until it reaches point C as indicated in Fig. 4. The increase in load is due to the developing and spreading of the plastic zone while the decrease results from the relatively large rigid-body displacement and the lower deformation resistance of the specimen in this stage. Point C can be considered as an onset point of coining.

In the coining zone, the force rises sharply with the movement of the punch. This is the final process of the V-die bending. In the case of bending with a rigid punch and die, the specimen has full contact with the punch and die surfaces. With a deformable punch, however, the specimen has almost full contact with die surfaces (depending on the radius of the die) and the punch surface is separated by the deformed softwire (lead), see Fig 3. The contact zone will be illustrated later in the section.

Generally, the force magnitude required for V-bending varies with the material parameters and tool geometries. From the load-displacement characteristics shown in Figs 2 and others obtained for different tool combinations, the following general observations can be made, though some of them may be expected:

1. Bending force increases with the material thickness and its Young's modulus. In general, for the same material, the greater the material thickness, the higher is the plastic bending moment of the cross section, hence a higher bending force is required.

2. Bending force increases with large radius. This is due to the changes in the contact condition which leads to a change in the lever arm. The present experimental results are in good agreement with those from a finite element study by Lange *et al* [12] where it was found that the force increases with punch radius.

3. Bending force decreases as the die opening W_d increases. This is evident as the lever arm is getting longer for a larger W_d, which for a given specimen leads to a smaller force.

4. The bending force prior to the coining process is not affected by the die radii ranging from 0.5 mm to 1.0 mm. This is due to the fact that there is no contact between the specimen and the curved die region.

The load-displacement curves are particularly useful as a guide to determine the force capacity requirement of a stamping machine.

3.2 Influence of displacement on α and β

The influence of the punch displacement D on the bent angles can be illustrated in Fig. 5. where α and β are plotted against D for a deformable punch and a rigid die. The difference between the two angles represents the angular springback. From the plots, the springback value reduces with the increase of punch displacement until point B where the angle after unloading, β, is less than that before unloading, α. Further increase of punch displacement leads to an increase of both α and β with α being larger than β. For a rigid punch, the maximum punch travel is 20.00 mm limited by the die opening depth. For bending with a deformable punch, the punch travel can be more than 20.00 mm, depending on the extent of deformation on the softwire lead. Similar experiments were conducted for brass and copper sheets.

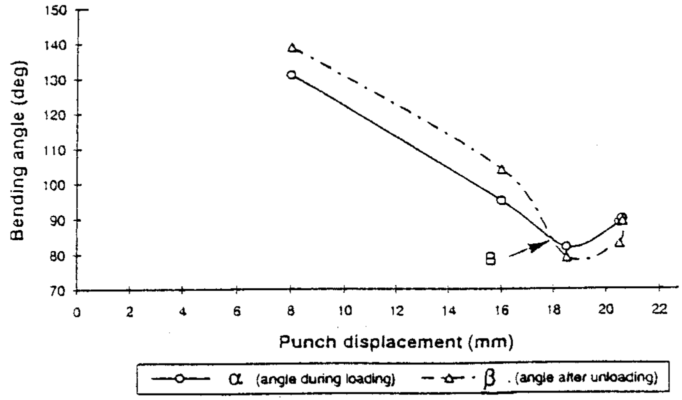


Fig. 5. Angle bent during loading and after unloading: DP90-0.75, RD90-0.75. mild steel, t=0.5mm.

Comparing the final bent angle from the two processes, it can be seen that V-bending with deformable punch is more accurate than the conventional method. This may be due to the more distributed force transmitted due to the lead deformation. The negative springback, or springforward, after points A and B in the two plots is discussed in detail later in the section.

3.3 Influence of deformable punch radius on β

The influence of the deformable punch radius on angle β can be seen from the experimental results plotted in Fig 8 for three different materials; β value was obtained at the end of each test. Here the included angle θ for both the punch and die is 90^0 with a die radius of 0.5mm.

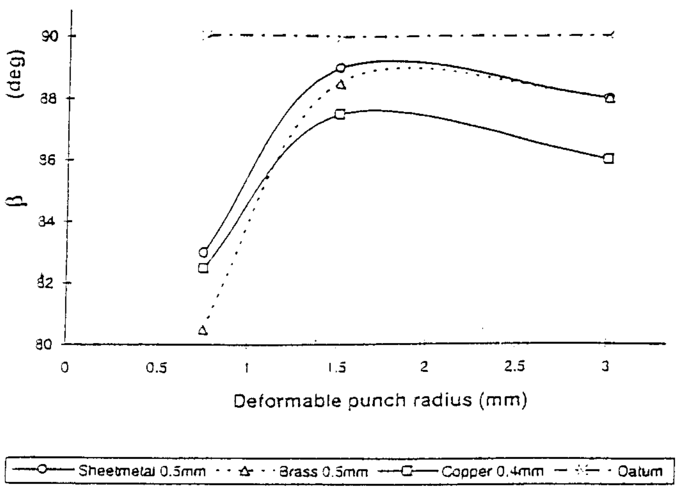


Fig. 6. Influence of deformable punch radius on β: θ =90°.

The curves show a similar trend for all the materials studied. The accuracy of the bent component is largely affected by the deformable punch radius. From Fig 6, the optimum value for the deformable punch radius is about 1.5 mm for all the three specimens.

3.4 Influence of rigid die radius on β

Fig. 7. shows the plot of β versus die radius R_d with punch DP90-0.75. This indicates that β is little affected by the rigid die radii between 0.5 mm to 1.0 mm.

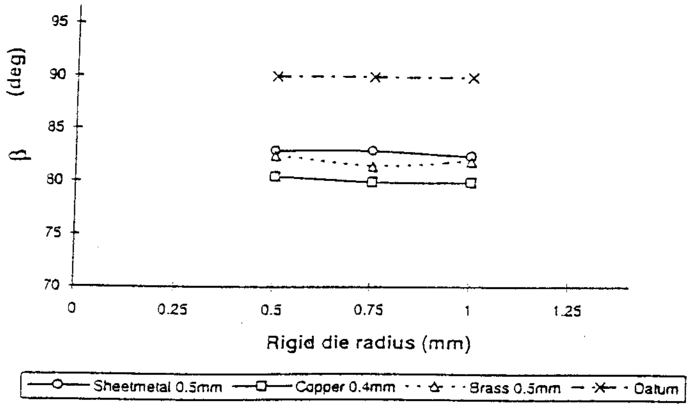


Fig. 7. Effect of rigid die radius on β: θ=90°.

3.5 Influence of punch and die angle θ on β

In Fig 8 β is plotted against punch and die angle θ with R_p=0.75mm and R_d=0.5mm. The datum line represents the ideal case where the springback is zero. The region above the datum line is springback region while below this is the springforward region. It is evident that springforward occurs for all the cases studied. The difference between the datum line and the final angle β increases as angle θ increases and this implies that springforward becomes larger as θ increases.

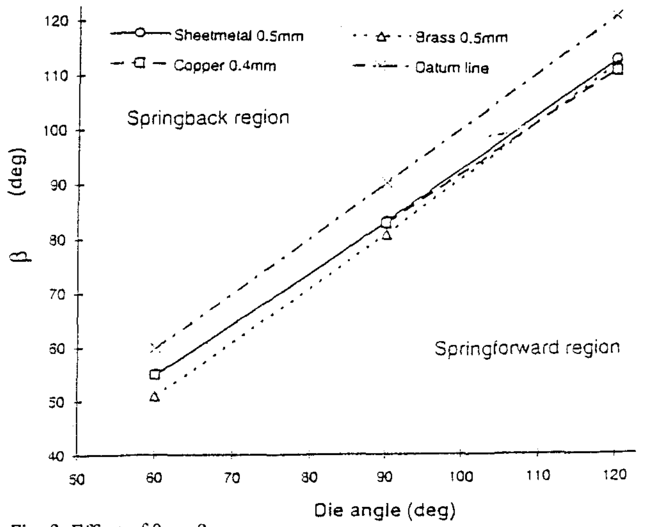


Fig. 8. Effect of θ on β.

3.6 Springback ratio K

The above results of springback/springforward have been presented in terms of the values of α and β individually. It can also be expressed in terms of the ratio of the two angles, or springback ratio, defined as $K=\beta/\alpha$. Springback ratio of less than unity is denoted as "springback" and that of more than unity is termed as "springforward". A unity springback ratio means that the workpiece is perfectly bent without any springback or springforward.

It would be straightforward to re-plot the previous figures on the effect of various parameters in terms of this new parameter K. Fig 9 shows the effect of specimen. It may be seen that K is always larger than unity and a thicker material possesses a lower value of K. All the three materials exhibit a similar trend

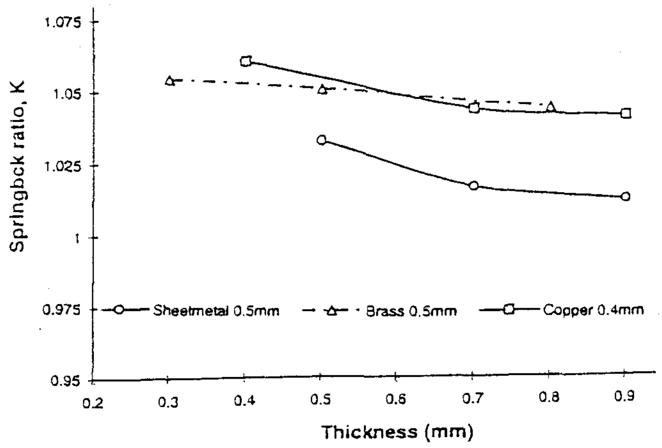


Fig. 9. Effect of thickness on springback ratio K.

3.7 Mechanism of springback and springforward in V bending

It is well known that springback/springforward is caused by the elastic recovery of bending deformation in metal sheets upon unloading and the permanent bending is caused by the plastic deformation. From the experimental results, it was observed that a specimen could experience either springback or springforward when unloaded at different stages in the process of V bending, see Fig. 7. This may be difficult to understand at first glance. However, one can explain this by carefully following the bending process of the specimens observed.

Refer to the photographs in Fig 3. The sheet is initially under 3 point bending with the both support ends and the punch loading being point up to say 18mm. During this period, the plastic zone develops only in the central region and the rest of the sheet remains elastic. Upon unloading, most of springback occurs in the central plastic zone where the bending moment is maximum. This causes a positive springback.

Further loading from this point leads to the both ends of the sheet to lose contact with the die and the contact points between the sheet and die move substantially towards the centre. This corresponds to the increase of the punch force as the lever arm is reduced. As the punch moves down further, the two ends of the specimen move toward the punch faces, a result of rotation in the support points of the specimen. This is still a case of 3 point bending and the springback is also positive.

Two additional loading points appear when the two ends of the specimen contacts the faces of the punches. The specimen now is under deformation similar to a 5 point bending. As the punch pushes down, the two ends of the specimens are forced towards the die surfaces. At this stage, plastic deformation may occur in the two contact regions of the specimen with the die. Therefore, upon unloading the elastic recovery there may result in an apparent negative springback, see the last photo in Fig. 3. This explains, qualitatively, the forming of the springback and springforward. This experimental observation is in good agreement with the velocity field of a V bending obtained from a finite element analysis for rigid punch cases [13].

3.8 Contact area

As mentioned earlier, springback is caused by the elastic redistribution of the internal stresses upon unloading. The elastic redistribution of the internal stresses is in turn dependent on the magnitude and direction of forces acting on the specimen during bending. In order to determine the manner and amount of force acting on the specimen, Fuji Prescale films were used. The working principle of Prescale films is as follows. Once applied with pressure, the chemicals within the film reacts and this turns the colour of the film into red. The intensity of this colour (red) is a unique function of the value of the pressure applied.

A deformable punch ($\theta=90^{\circ}$) with a radius of 3.0 mm (DP90-R3.0) was used together with a rigid die (RD90-RO.5) to bend a 0.5mm thick brass specimen. The shape and size of the contact area between the deformed softwire (lead) and specimen as well as between the specimen and die surfaces were attempted during the bending process utilizing both the medium and high pressure Prescale films. Fig 10 shows the deformation of both the specimen and the lead. The Prescale films are illustrated in Fig. 11.

The contact area increases as the deformation proceeds. On the top surface of the specimen, there is full contact with the deformed lead. However, the contact zones at the bottom surface of the specimen gradually spreads with the central region untouched. The deformation may be likely caused by the interaction between the bending and stretching due to the frictional effect. An interesting feature is that for both top and bottom surfaces of the specimen, the overall contact zone size is similar. Thus, to a large extent the pressure applied to the specimen via the lead may be directly transmitted to the die faces just underneath the same region of the specimen. The deformation of lead is not in a plain strain condition with a proportion around the end region being "squeezed" out.

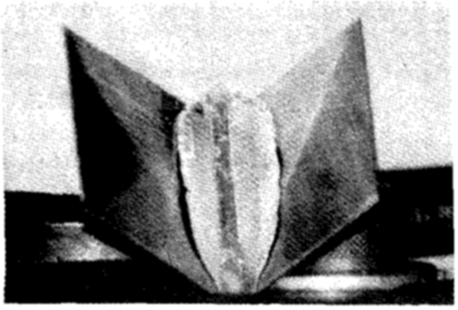
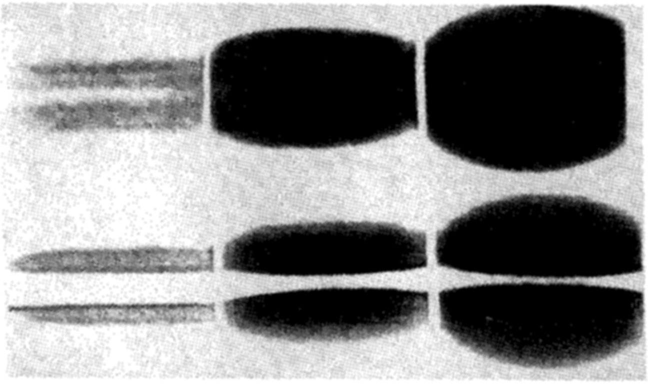


Fig. 10. Photograph of deformed lead and specimen.



D=20mm D=21mm D=22mm

Fig. 11. Impression of contact area obtained from film; top: between lead and specimen; bottom: between specimen and die. D: punch displacement.

It is evident that the shape and size of the contact area changes as the punch displacement increases. At punch displacements greater than 18 mm, a slight increment in punch travel will cause a significant increase in punch force. This force is in turn transmitted onto the specimen via the deformed lead. Hence from the shape, size and the colour density of the Prescale film, pressure distribution on the specimen can in principle be determined. However, because the films got saturated easily due to the high pressure involved, accurate systematic pressure distribution is difficult to obtain. nevertheless, the results give reliable information on the size and shape of the contact zones.

4. Conclusions

A large number of experiments have been performed and detailed observations have been carefully made in this study of V-shaped bending using a deformable punch. Especially, the global deformation process of the specimen, load-displacement curves, and size and shape of the contact zones in the interfaces have been investigated. Much attention has been paid to the measurement of springback or springforward values and the effect of the relevant parameters on it has been thoroughly studied. The obtained clear physical understanding of the problem will be good guidelines for engineers and it will form a solid base for our further theoretical studies.

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