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Deep drawing mechanism, parameters, defects and recent results: state of the art

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Abstract. Deep drawing is a sheet metal forming process which is widely used in manufacturing parts for automobile and air craft industries. In this paper, the mechanism of deformation, effect of the geometrical parameters involved and the defects encountered in the process are presented and discussed. These include: the radial clearance percentage, punch and die profile radii. Despite the number of publications on the subject, there is still a great demand for further research. Recent experimental investigation on the effect of radial clearance percentage, punch and die profile radii on their autographic records (punch load- punch displacement curves) and on quality of the produced blanks is carried out and the results are presented and discussed. It was found that the maximum drawing force decreases with increase of the die profile radius and increases by increase of the punch profile radius. Furthermore, the liability of the produced cups to wrinkle increases by the increase of both punch and die profile radii being more influenced by the die profile radius.

1. Introduction

Deep drawing is a secondary forming process which in its simplest form a cylindrical shape or alike (for example a cone or frustum) is produced from a thin disc of sheet metal by subjecting it to a compressive force (while it is held between a die and blank holder) through a circular punch which mainly on the blank thickness as illustrated in Figure 1.

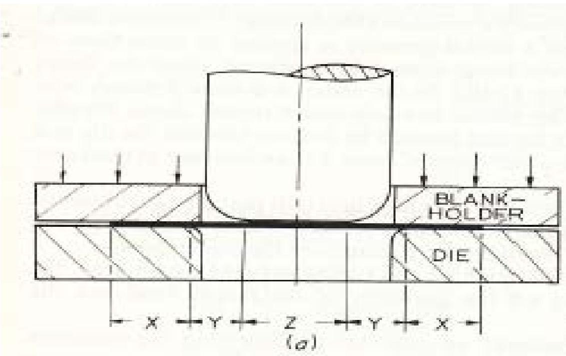

Figure 1. Deep drawing setup at start

1.1 Mechanism of deformation

The deep drawing mechanism is a complicated process particularly the different types of stresses on each region in the blank. To facilitate the understanding of the mechanism, the blank is divided into three regions X, Y and Z. The outer annual region X is sandwiched between the die at its bottom part and the blank holder at its top part. Region Y, the inner annular region is not in contact with either the punch or the die and Z the central region of the blank is only in contact with the punch as illustrated in Figure 1(a).When the compressive force is applied to the punch, the draw proceeds the material in region X starts to draw progressively inwards towards the die profile under the effect of the applied tensile stress resulting in continuously decreasing the radii in this region which causes induced compressive hoop stress which causes an increase in the material thickness at the outer part of region X. Unless holding down pressure is applied, the induced hoop stress will cause the blank to fold causing wrinkling. When the material in region X passes over the die profile it is thinned by plastic bending under the effect of the tensile stress. The net effect of the outer part of region X is increase in thickness of the material. Regarding the material in region Y, it can be readily seen that it is subjected to bending and sliding over the die profile; part to stretching in tension in the clearance region, part to stretching between the die and punch in the clearance zone and part to bending and sliding over the punch profile. Finally, zone Z is subjected only to stretching and sliding over the punch head. The above mechanism can be summarized in accordance with the above division of the blank and the type of stresses which each region is subjected to:

i. Pure radial drawing between the die and the blank holder.
ii. Bending and sliding over the die profile.
iii. Stretching between the die and the punch in the clearance zone.
iv. Bending and sliding over the punch profile radius.
v. Stretching and sliding over the punch head.

Various parts of region X may go through some or all of the processes i, ii and iii; while parts of region Y may go through some or all of processes ii, iii and iv; finally, parts of region Z may go through some or all of processes iii, iv and v.
It should be noted that process i causes thickening of the blank whereas processes ii, iii, iv and v causes its thinning.
Figure 2 shows the variation of the thickness along the wall of a drawn cylindrical cup for a flat headed punch on the right hand side.

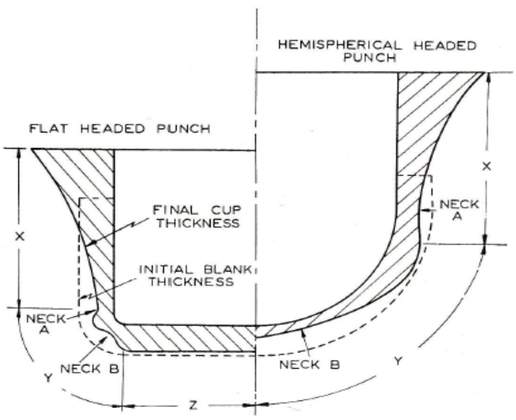

Figure 2. Sections through deep drawn flat ended and hemi spherical cups with flat and hemispherical-headed punches

In hemi-spherical punches, making allowance for bending over the punch profile radius is not essential, whereas in the more general case of drawing with a flat-headed punch, making allowance for bending over the die and punch profiles, has not yet been solved. The punch load at any phase of drawing is determined by the forming region. If the blank is held rigidly at the die to prevent radial drawing the process becomes one of pure stretch-forming. Extensive and detailed experimental and theoretical investigations of cup-drawing have been carried out by different researchers, aiming at reducing the different defects in the process and improving the quality of the produced parts, [2-35].

2. Materials, equipment and experimental procedures

2.1 Materials

The specimens were circular discs of 180 mm diameter and 0.42 mm thickness made from carbon steel with the following w.t. percentages: 0.22% C and 0.5%Mn and the remainder is Fe. They were annealed before being used. Their mechanical behavior in the annealed condition is shown in Figure 3.

2.2 Equipment and experimental procedures

The deep drawing tests were carried out using the die shown in Figure 4 which was designed and manufactured for this purpose. It consists of the following main parts: the upper and lower platens in line. They were made of galvanized steel, sleeves, blank and die holders which were all made from galvanized carbon steels. Compression springs and the punch and die which were made of X12M die steel of the chemical composition shown in Table 1.

Table 1. Chemical composition of X12M die steel

Element	C%	Mn%	Si%	Cr%	V%	Fe%
Wt. %	1.7%	0.35	0.4	0.12	0.3	Bal.

The punch and die were heat treated in accordance with the heat treatment recommended by the suppliers and the obtained hardness, as measured by Rockwell Hardness, is RC 67. All the punches and dies which were used for investigating the different parameters in this paper i.e. radial clearance percentages defined as, the radial clearance between punch and die / the blank thickness = C / to, where C is the clearance and to is the original thickness of the blank, punch and die profile radii were all made of the same material and heat treated to RC 67 and their diameters were measured using the Too Makers travelling microscope and their profile radii using shadow graph at magnification X20. The values of the used radial clearance percentages are shown in Table 2. Five punches and five dies with different profile radii were machined and ground under the same cutting conditions. Their dimensions are shown in Tables 3 and 4 respectively.

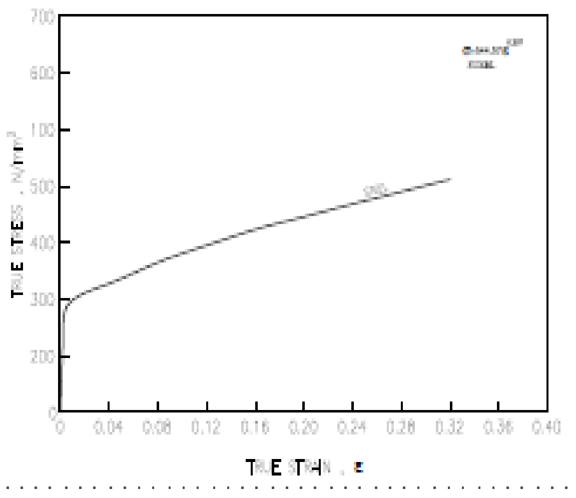

Figure 3. Mechanical behavior of blanks material

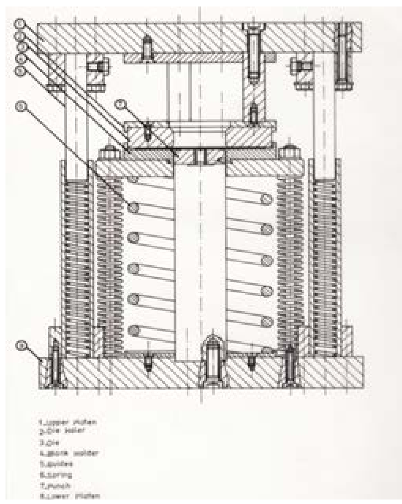

Figure 4. Th deep drawing die

Table 2. The values of radial clearance and radial clearance percentages

Symbol	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Radial clearance mm	0.3976	0.4473	0.4943	0.5450	0.5695	0.7947
Radial Clearance %	94.8	106.6	117.8	129.9	135.7	189.4

Table 3. The values of punch profile radius, (mm)

Symbol	**rp1**	**rp2**	**rp3**	**rp4**	**rp5**
Punch profile radius (mm)	2	5	10	15	20
Rpn/pr	3.34	8.34	16.67	20.0	33.34

Table 4. The values of die profile radius, (mm)

Symbol	**rd1**	**rd2**	**rd3**	**rd4**	**rd5**
Die profile radius, (mm)	2	4	6	10	15
rdn / to	4.77	9.53	14.3	23.84	35.75

All the drawing tests were carried out on the Instron Universal Testing machine of 250 KN at constant cross head speed of 10mm / minute and the autographic record was obtained for each test.

3. Theoretical considerations

3.1 Determination of the radial and hoop stresses

As the punch starts to press the blank downwards through the die opening, the outer radius of the blank decreases continuously throughout the drawing pass under the action of an induced compressive radial stress. At any instant, assuming frictionless drawing condition, for simplicity, this radial stress 6rx at any radius x is determined from the following equation:

$$6rx / 1.1 Y = \ln b / x \quad (1)$$

and the tangential stress, 6Θx is determined from :

$$6\Theta x / 1.1 Y = \ln 1 - \ln b / x \quad (2)$$

3.2 determination of the maximum height after the first draw

Consider a circular blank of diameter 2a and of original thickness to is formed into a cylindrical cup of base diameter 2b and height H. where a and b are the radii of the blank and the base of the cylindrical cup.

For simplicity, assuming there is no change in thickness which is very justified from the experimental results of the work in this paper and the work of other researchers, applying the constant volume principle in plastic deformation to get:

$$a^2 x\ to = b^2 x\ to + 2\ b\ x\ H\ X\ to \quad (3)$$

simplifying to get

$$H = b/2 (R^2 - 1) , \quad (4)$$

where R is the drawing ratio $R = 2a / 2b$ (5)

If R is taken = 2.2 which is the limiting drawing ratio, LDR, by substituting this value in eqn. (4). Then the maximum obtainable value of H is equal to 2b, i.e. it is not possible to obtain a cup whose height is bigger than its base diameter. This is very useful engineers and technicians in industry because by looking at the drawing of the required part can decide if he can produce it from the first stage or he needs a redrawing process.

4. Results and discussion

In this section, the main parameters affecting the deep drawing process are given and discussed which include: the drawing ratio, holding down pressure, radial clearance percentage, punch and die profile radii and their effect on the maximum drawing force and the defects encountered in the process are presented and discuses.

4.1 Blank holding down pressure

Normally, two types of blank-holding down pressure are commonly used: clearance blank-holding and pressure blank-holding; the object in each case is to prevent wrinkling of the blank during radial drawing, but with the minimum of interference with free drawing. In the early work of reference, [10] on mild steel blanks it was shown that with clearance blank-holding, an initial clearance of 5 per cent was sufficient for this purpose. With pressure blank-holding the medium pressure necessary to prevent wrinkling was 400 psi of blank contact area and a clearance of 0.002 in when clearance blank–holding were used .The same was adopted in this research work. It was also found that increasing the force beyond this amount had little effect on the maximum punch load or on the final thickness in the base or on the profile radius of the produced cups, though the walls were thinner with the higher loads.

4.2 Drawing ratio

Drawing ratio is defined as the ratio of blank diameter to the throat diameter of the die. It was found that for any given drawing conditions the punch load increases with blank diameter in an approximately linear manner, over the whole of the useful range with slight tendency to drop near the limiting drawing ratio. It is worth mentioning in this respect that one should differentiate between the drawing ratio which is a geometrical parameter and the limiting drawing ratio which is a material property.

4.3 Radial clearance between punch and die

Radial clearance between punch and die throat may affect the drawing process directly by controlling the freedom of the walls either to thicken or to taper and pucker. It can be seen from Figure 4b that the maximum drawing force is greatly influenced by the radial clearance particularly when its value is less than the blank thickness i.e. the case known as ironing condition where it increased more than three folds. As the clearance increases above the blank thickness it becomes less affective until it reaches a constant value e.g. it can be seen that. The best radial clearance percentage for the steel used material was the difference in the maximum drawing force all C / to % above 100 % within the tested range does not exceed 10 %, however at 130 % the produced cups have least wrinkling and ears height. This is in agreement with the results reported in reference [10] for mild steel. Hence a net radial clearance of about 30 per cent is suitable for general purposes, with free drawing and a reduction of 50 per cent, and this has the sanction of practical experience. However, increasing it beyond this value may allow a bell-mouth to persist near the rim of the cup, which would be practically objectionable if the deep drawn products are required to undergo a re-drawing operation. A more important feature than the drawing force is the local strain in the blank, which may lead to local necking and finally to cracks and fracture. Radial stresses tends to thicken the blank at its rim, while bending and sliding over the die profile and the punch head tends to thin it. The most serious thinning arises from the stretching over the punch head and particularly between the punch head and the die to reduce the thinning as much as possible it is required to maintain high frictional condition on the punch while maintaining low friction everywhere else similar to mandrill drawing.

The effect of radial clearance percentage on the thickness strain distribution on the used steel is shown in Figure 5. It indicates that the maximum thinning is 6 % which occurred at 106 % radial clearance percentage. In general, there is not a great difference between the values of thinning among the investigated values of C / to %. It is worth noting from Figure 5 that all the thinning occurs at punch profile zone of the blank which is subjected to bending and tension.

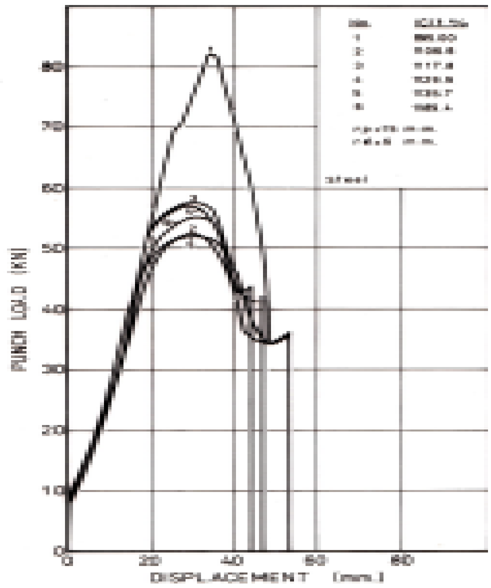

Figure 4b. Autographic records of different C/ t %

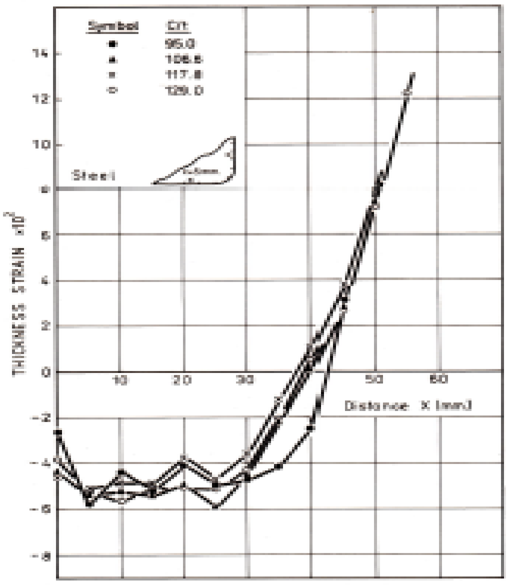

Figure 5. Thickness strain distribution

4.4 Die profile radius

In this section the die profile radius was varied between 2 and15 mm, as shown previously in Table 4, section 2, while keeping the punch profile radius constant. This was carried out on five punch profile radii namely: 2, 5, 10, 15 and 20 mm. as shown previously in tables. The autographic records for all the combined values of dies and punches were obtained from which the maximum drawing force was determined for each test. It was found that the maximum drawing force decreases with increase of the die profile radius, rd, whereas its liability for wrinkling increases. The optimum value for the used steel material was found at rd = 6 mm i.e. about 15 to. Also the sharper is the die profile radius, the greater is the maximum punch load, because of the increased process work due to plastic bending under tension. Consequently, decreasing the profile radius below 15 times the blank thickness lowers the limiting drawing ratio, (LDR). The effect of die profile on the essentially practical problem of success or failure of the drawing is shown in Figure 6. Each point near the critical range represents four tests. It was also found that the more generous is the punch radius, the more gradual is the rise of punch load and the longer is the punch travel and the maximum punch load is almost unaffected. This is an indicator of the limit of consistency in the cup-drawing.

4.5 Punch profile radius

The effect of the punch profile radius was investigated by using five different profiles: 2, 5, 10, 15 and 20 with constant die and constant radial clearance percentage, as was shown previously in table 3. The autographic record was obtained for each test. The effect of the punch profile radius on the thickness strain distribution is shown in Figure 9.

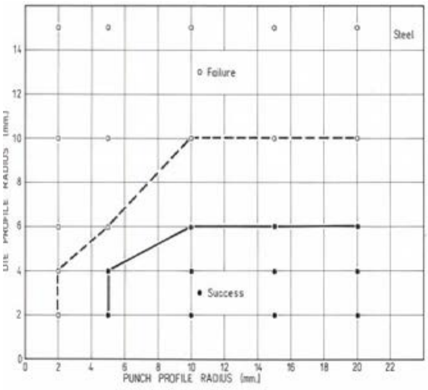

Figure 6. Effect of die profile on drawing capacity

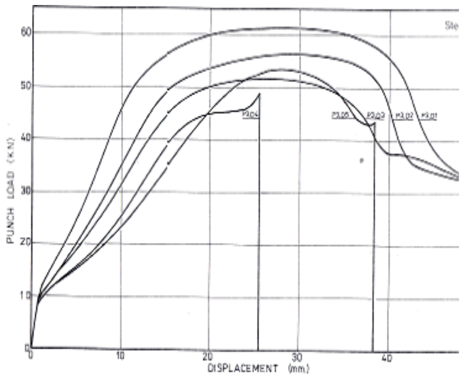

Figure 7. Effect of die profile radius on the autographic records at constant punch profile

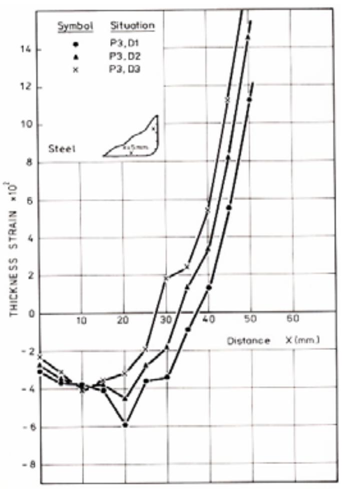

Figure 8. Effect of die profile radius

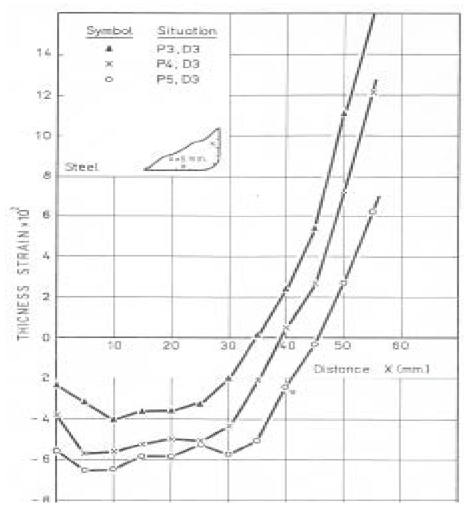

Figure 9. Effect of punch profile radius on the thickness strain distribution on the thickness strain distribution

4.6 Defects encountered in deep drawing

The following defects might take place in the deep drawing process

4.6.1 Ironing

Iron consists principally in reducing the wall thickness of the cup by restricting the clearance between the punch and the die to a value less than the blank thickness. The punch load is of primary importance in ironing because it determines the tension in the cup walls and hence the maximum reduction possible for a given punch load. A theoretical study of ironing has been reported in reference [21] and an experimental investigation was carried out using hemispherical heade punches for different condition of wall thinning, die profile and lubrication [22].

4.6.2 Galling

It is the transfer of some particles from the cup wall into the part of the die in contact with it. It causes damage to the die surface. It depends on the hardness o the blank and the lubricant effectiveness. It can be avoided by keeping the die surface in very good surface quality and using efficient lubricants to reduce friction between the cup and the die surface in contact with it.

4.6.3 Orange peeling
It occurs at the outer surface of the cup when the grain size of its material is large it can be avoided by reducing the grain size prior to drawing either by heat treatment or by adding grain refining the grains by the addition of the appropriate refiners.

4.6.4 Earing
It is caused by the planar anisotropy which is due to variation in the mechanical behavior of the sheet from its plane to any other direction inclined or perpendicular to it they are normally even in number 2 or 4 or 6. The worst number is 8 in case of brass blank. They appear on the upper part of drawn cup and is treated by trimming. The photograph of Figure 10 clearly shows the ears on the steel specimen.

4.6.5 Tearing
It might take place at the inner region of the anular part of the rim near the die profile if the holding down pressure is high which stops the blank from sliding and bending over the die profile radius, or it might take place in the maximum thinning region in the clearance region near the punch profile which is subjected to bending and stretching as clearly indicated in Figure 11.

4.6.6 Wrinkling
This defect starts in the rim region of the blank and travels towards the middle region, the clearance zone between the punch and die profiles, by the continuation of the deep drawing process, as indicated in Figure 11. Examination of the available literature reveals that experimental research work on this important defect is relatively little compared to the analytical and theoretical work, [23-27]. The critical dimensions of the rim at the onset of wrinkling was given in reference [23] where it was stated that wrinkling depends on properties of the blank thickness and its mechanical properties in addition to the shape and dimensions of the die set and the method by which the holding down pressure is applied. The experimental work of reference, [24] revealed that the resistance to wrinkling increases with the increase of strain percentage; which explains the use of the draw-beads in the deep drawing process to reduce the liability to wrinkling. The authors of reference [25] found the critical values of stress and thpunch displacement at which wrinkling starts to occur. They also agree with authors of reference [26] that both the critical stress and displacement increase with the increase of strain in the process.

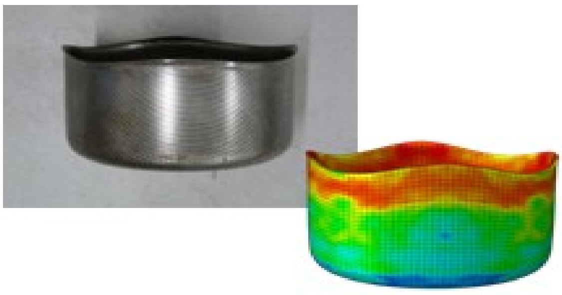

Figure 10. Photograph showing ears

Figure 11. Tearing and wrinkling

5. Conclusions
Within the experimental limitations, regarding the investigated geometrical errors the following points may be concluded:

i). The maximum drawing force is greatly influenced by the radial clearance between the punch and the die, particularly when it is less than the blank thickness i.e. the case known as ironing condition, it increased more than three folds the clearance increases above blank thickness it becomes less affective until it reaches a constant value. The best radial clearance percentage for the steel used material was found at 130 % which produced least wrinkling and ears height. However increasing it a beyond this value causes bell shaped cup.

ii). The maximum drawing force decreases with increase of the die profile radius, rd, whereas its liability for wrinkling increases. The optimum value for the used steel material was found at rd = 6 mm which equals about 15 to.

iii). The maximum drawing force increases with increase of the punch profile radius, rp , up to rp = 15 mm then it starts to decrease. However, it was less affected by rp compared to rd.

iv). Although the research on the deep drawing process has been going on for more than nine decades, it is far from being complete and further work is required to get rid of the defects encountered in the process and renders it cost effective.

6. Acknowledgment

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7. References

[1] Johnson W, Mellor P B 1980 Engineering Plasticity, The Camelot Press Ltd., Southampton, U.K
[2] Sommer M H 1925, Machinenbou, 4, 1171
[3] Eksergian GL 1926, Trans. ASME,48, 609
[4] Eksergian GL 1927, Metal Industry, 23, 483
[5] Siebel E and Pomp A 1929, inst. Eisenfforsch, 11, 139
[6] Sachs G 1934-1935, Proc. Inst. Of Automobile Eng., 29, 588
[7] Oehler G 1939, Metallwistschaft, 16, 1059
[8] Swift H W 1939-1940, Proc. Inst. Of Automobile Eng., 34, 361
[9] Jevons J D 1945 The Metallurgy of Deep Drawing and Pressing, 2nd Ed, Chapman & Hall.
[10] Swift H W 1948, Engineering, 166, 333 and 357
[11] Chung S Y, Swift H W 1951 Cup-drawing from a Flat Blank, Proc. Inst. Mech. Engrs.165. 199.
[12] Hesenberg W C F 1954 A simple Account of some of Professor Swift Work on Deep Drawing, B.I. S.R.A. Report MW/1954
[13] Alexander, J M 1960, Metal Review5, No 19
[14] Chiang D C, Kobayashi 1966, J. Engng. Industry, 88, 443
[15] El-Sebaie M G, P B Mellor 1972, Int. J. Mech. Sci.,14, 535
[16] El-Sebaie M G, P B Mellor 1973, Int. J. Mech. Sci., 15, 485
[17] Panknin W 1976, Sheet Met. Ind. 53
[18] Gransow W G 1979, Sheet Met. Ind., 56, 561
[19] Gotoh M 1980, Int. J. Mech. Sci., 1980, 22, 367
[20] Yu X T, Johnson W 1982, Int. J. Mech. Sci., 24, 175. Lee S H, Kobayashi S 1974, Proc. 15th Int. M. T.D. R. Conf., Birmingham, UK
[21] Fukui S, Hansson, Analytical Study of Wal Il Ironing, Considering Work-hardening. Annls of C.I.R.P., 18, 593
[22] Freeman P, Leeming H, Ironing of Thin-walled Metal Cups-the Distribution of the Punch Load, B.I.S.R.A. Report No.MW/E/46/53
[23] Lange K, Dalhaimer R, 1967, Proc. 18th. M.T.D.R. Conf., 221
[24] Geckeler J.W, Angew, 1928, Math. Mech., 8, 341
[25] Senior B. W 1956, J. Mech. Phys. Solids, 4, 235
[26] Naziri H, Pearce R 1969, La Metallurgia Italiana, 40, 727
[27] Triantafyllidis N, Needleman A, 1980, J.Engng.Mat.Tech.102, 241
[28] Chen F K, Huang T B 2003 Formability of stamping magnesium-alloy AZ31 sheets J. Mater. Process. Technol. 142643–647

[29] Zhang H, Huang G, Kong D, Sang G, Song B 2011 Influence of initial texture on formability of AZ31B magnesium alloy sheets at different temperatures J. Mater. Process.Technol. 211 1575–1580

[30] Zhang H, Huang G, Fan J, Roven H J, Pan F, Xu B 2014 Deep draw ability and deformation behavior of AZ31 magnesium alloy sheets at 473 K, Mater. Sci.Eng.A608 234–241

[31] Liu C Y, Jing R, Wang Q, Zhang B, Jia Y Z, Ma M Z, Liu R P 2012 Fabrication of Al/Al3Mg2composite by vacuum annealing and accumulative roll-bonding process Mater. Sci. Eng. A 558 510–516

[32] Liu C Y, Wang Q, Jia Y Z, Jing R, Zhang B, Ma M Z, Liu R P, 2012 Microstructures and mechanical properties of Mg/Mg and Mg/Al/Mg laminated composites prepared via warm rollbonding Mater. Sci. Eng. A 556 1–8.

[33] Jafarian M, Khodabandeh A, Manafi S 2015 Evaluation of diffusion welding of 6061aluminumand AZ31 magnesium alloys without using an interlayer Mater. Des. 65160–164.

[34] Zhao Y, Lu Z, Yan K, Huang L 2015 Microstructural characterizations and mechanical properties in underwater friction stir welding of aluminum and magnesium dissimilar alloys Mater. Des.65675–681

[35] Yan J, Xu Z, Li Z, Li L, Yang S 2005 Microstructure characteristics and performance of dissimilar welds between magnesium alloy and aluminum formed by friction stirring Scripta Mater. 53585–589