FORMING

PRESS-FORMING STEEL SHEET AND STRIP

TECHNICAL BULLETIN TB-F7

Rev 2, November 2003
This issue supersedes all previous issues

1 PRESS FORMING – THE PROCESS

Press forming is a metal working process in which a flat blank, constrained between two surfaces is forced by a punch to take a required three-dimensional shape, eg. cups, gas cylinder domes. The metal may be reshaped by a combination of drawing, stretching, ironing and bending processes.

Production of some panel may require a combination of annealing, redrawing, or reverse redrawing after the initial forming operation.

A number of practical rules applies to design of dies to assist in the smooth flowing operation of the press shop. There are briefly discussed in this Bulletin and further detail can be obtained through further reading of the listed references.

2 PRESSES

Sheet metal blanks are formed in either hydraulic or mechanical presses, each type having specific advantages and applications. Shallow pressings can be completed in single-acting presses using springs or die cushions to provide the blankholder pressure. Deeper pressings and irregular shapes are generally produced in double-acting presses where consistent drawing speeds, stroke adjustment and uniformity of clamping pressure are available. Factors such as capacity requirements, die space and length of stroke are important considerations in press selection.

Most pressings require a number of stages to complete a given part design. To achieve this, separate presses can be run sequentially or automated transfer systems can be used to move a part between stages, either within the bed of a single press or between separate presses.

Various specialised press forming operations are available such as the hydroform process and the stretch drawing technique where unidirectional strain is applied to the blank prior to drawing. These specialised operations have been developed for specific demands which cannot be met by traditional presses and tools. More information on this subject is available from references listed at the end of this chapter.

3 DIES

Dies used for forming steel sheet are usually of the following basic types:

- Single-action dies
- Double-action dies
- Compound dies
- Progressive dies
- Multiple Dies

Selection of the dies and the die materials will depend on the part size and severity of the draw, and on the quantity of parts to be produced.

Section of die material will probably depend on the number of pressings required. The following die materials and surfaces, listed in order of increasing service life, are:

- Cast zinc-based alloy
- Close grained cast iron
- Inoculated cast iron (*Meehanite*)
- Close grain aluminium bronze
- Medium or high carbon steel hardened and tempered
- High carbon, high chromium steel
- Nitrided surfaces
- TD (*Toyota Diffusion*) coating
- Chrome plated surfaces
- Tungsten carbide

4 DIE DESIGN

Until recently the design of complex drawing dies has largely been an art. However, an increasing effort has been placed into the development of CAD systems for part and die design. These CAD systems are complex and most small-run dies are still designed using rules that specify factors such as punch and die radii, corner radii, depth of draw and limiting draw ratio. These are briefly discussed here; the reader is referred to basic press design books for additional detail. In setting up the die design, the part to be formed should be designed around an existing steel product and its ductility rather than attempting to fit a steel grade to the job. Following this work, decisions can be made on matters such as the number of stages and the need for any interstage annealing.

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4.1 Die Design Rules

4.1.1 DEPTH OF DRAW

The maximum depth to which a cylindrical cup can be drawn is difficult to define and depends on a number of variables such as steel grade, thickness, and allowed thinning, in addition to die factors such as die and punch radii and lubrication.

The **Limiting Draw Ratio** (*LDR*) or ratio of blank diameter to cup diameter can be used to rate the severity of the drawing operation. For small die and punch radii with minimum lubrication, the LDR shown in Table 1 should be used for the listed products.

Table 1 – Maximum limiting draw ratios for various steel products

Product	Maximum LDR*
CA5SN	2.3
CA4A, ZINCANNEAL® G3N, GALVABOND® G3N	2.2
CA3SN	2.0
CA220, HA4N	1.8
GALVABOND G2, CA260, CA2S, HA3	1.6
CM350, XF300, XF400	1.4
XF500	1.2

* LDR values can be increased by up to 0.2 with improved lubrication and increased die and punch radii.

4.1.2 THICKNESS EFFECTS

Table 2 shows the degree to which decreasing thickness reduces the LDR achievable on products such as CA3SN-E.

Table 2 – Maximum LDR for drawing round shells without flanges from CA3SN-E

Steel thickness as % of blank diameter	Maximum LDR for draw operation*				
	First	Second	Third	Fourth	Fifth
2.0	2.08	1.37	1.32	1.28	1.25
1.5	2.00	1.33	1.28	1.25	1.22
1.0	1.90	1.32	1.27	1.23	1.19
0.6	1.82	1.28	1.25	1.22	1.18
0.3	1.72	1.26	1.23	1.20	1.16
0.15	1.67	1.25	1.22	1.18	1.15
0.08	1.60	1.22	1.19	1.16	1.14

* Ratios are for die radii of 8t-15t where t is the steel sheet thickness. The ratios may decrease some 2% for die radii between 4t and 8t.

4.1.3 PUNCH AND DIE RADIUS

To draw a cylindrical cup to a maximum depth in a single operation the punch radius should be a minimum of 1.5 mm or 4t, whichever is greater. If smaller, excessive thinning will occur in the walls of the cup which will not support the force necessary to draw the blank into the die and fracture will occur at the thinnest part.

The die radius is important and if too small the wall of the cup will be reduced in thickness as the draw progresses. If this radius is too large the blank will not be supported as it leaves the blankholder and wrinkling may occur. Recommended minimum and maximum die radii are listed in Table 3 for various steel blank thicknesses.

Table 3 – Die radii for various steel thicknesses

Steel thickness mm	Die radius mm	
	Minimum	Maximum
1.5	6	9
1.2	6	9
1.0	4.5	8
0.80	4.5	8
0.70	4.5	7
0.60	4.5	7
0.50	4.5	7

4.1.4 TAPERED SIDE SHELLS

Shell or formed shapes with tapered sides are more difficult to produce than shells with parallel walls. After the blank leaves the blankholder where it is restrained by compressive forces to prevent wrinkling, it enters the die cavity unsupported and, as the draw progresses, is actually reduced in surface area. The compressive forces induced in the walls readily lead to wrinkling and can only be constrained by stretching the metal in the shell wall. Critical adjustment of blankholder pressure and metal flow is required for this type of pressing.

Where deep tapered shells are required with a height to diameter ratio of greater than one-half, a stepped shell with vertical walls should be first produced and then redrawn to provide the final shape. This shell can be produced in a single drawing operation, but medium tapered shells defined by a height to diameter ratio of between one-quarter and one-half need to be redrawn from a vertical walled shell. Refer to Table 4 (*below*).

Table 4 – Drawing of tapered shells

Shell description	Criteria	Method
Shallow	$\frac{h}{d} < 0.25$ & $t > \frac{d}{200}$	Direct drawn taper
Medium	$0.25 < \frac{h}{d} < 0.5$	Redraw from vertical wall shell
Deep	$\frac{h}{d} > 0.5$	Vertical wall stepped shell, redrawn

Key – h = tapered shell height
d = open end diameter
t = blank thickness

4.1.5 RECTANGULAR SHELLS

The depth of rectangular shells produced in a single draw is dependent on the corner radius and shell width. Table 5 gives the relationship between maximum shell heights and corner radii with shell widths.

Table 5 – Maximum height to width ratios

Radius to width	Height to width
0.4	1.0
0.3	0.9
0.2	0.76
0.15	0.65
0.10	0.50
0.05	0.30
0.02	0.12

Blank and die alterations may be required to provide a successful pressing if Table 5 ratios are exceeded.

4.2 Gap Clearances

The selection of gap clearances between punch and die depends on the part requirements. In drawing, the wall thickness if first decreased as the blank is stretched over the punch and then increased as the radial drawn progresses. For shallow draws the punch to die gap should be between 5 and 8% greater than the maximum sheet thickness, which is the nominal sheet thickness plus the maximum thickness tolerance. For deep draws where there is more wall thickening the clearances should be extended to between 8 and 12% greater than the maximum sheet thickness.

5 PRESS LOADS

Having selected the die design, steel thickness and type, the press forces required can be calculated and the sequencing of operations arranged to ensure that sufficient press capacity is available for both the loading force and the physical dimensions of the pressing.

Detail of the calculation of press loads is published in the literature listed at the end of this chapter.

6 BLANKS

6.1 Blank Size

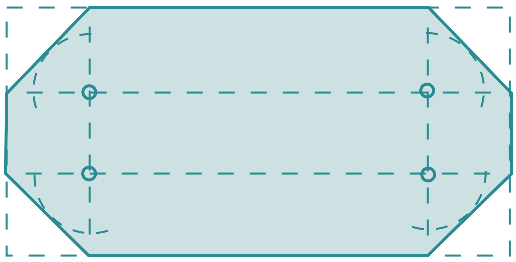
It is important to use blanks of the correct size in deep drawing to reduce stresses in the formed walls and reduce failures. The blank size can be computed from the required shape; formulae are available for this calculation from the recommended literature. Blank thickness is generally determined from the strength required in the final pressing. However, as thickness is reduced the blank becomes more prone to wrinkling in a radial draw and a larger blankholder force will be required. This increased force raises the drawing force which must be carried by the walls of the pressing and hence as blank thickness is reduced the balance between blankholder force and drawing force becomes more critical.

6.2 Developed Blanks

When drawing a rectangular shape, the additional material in the corners holds back the movement around the die radius making the pressing operation more severe. Removal of the corners prior to drawing, termed developing the blank, tends to even up the flow and can markedly reduce the severity of the pressing operation. This development can range from simple cropping of corners (*Figure 1*) to more complex kidney shaped corners, and becomes increasingly important as inner corner radii become smaller and depth of draw increases.

Ideally this technique can be extended to produce a fully shaped blank by providing constant relative movement of the blank edge around the pressing. Detail of this blank development has been recorded in many of the references listed.

Figure 1 – Simple blank development



7 PRESS OPERATION

7.1 Speeds

Maximum press speed is obtained when the material can flow across the die surface with minimum friction and is achieved when factors such as steel ductility, die surface and contours and lubrication are optimum. Speeds as high as 25 m/min can be used for the deep drawing of low carbon steels. Generally, speeds are restricted to 7 to 18 m/min for single acting presses and 13 to 17 m/min on double acting presses.

As forming conditions deteriorate slower speeds are required to obtain a successful pressing and the deterioration will be more pronounced where smaller punch radii and high blank diameter reductions are used.

7.2 Blankholder and Restraint of Metal Flow

The purpose of the blankholder in drawing is to control the flow of metal to prevent wrinkling as the blank flows into the die so that the blank is evenly stretched around the punch surface. Under certain conditions where the supported blank width to sheet thickness ratio is excessive or a conical shaped die opening (*tractrix profile*) is used, no blank holding is required. However, for most operations blankholders are used.

The simplest type of blankholder is a flat surface which is set so that restraint commences once the blank has thickened some 50% of the total increase. A more involved blankholder is tapered to allow for increasing thickness as the draw progresses. The flat surface is more common, adjusted by hydraulic pressure to provide increased holddown to the blank surface.

Thin, shimmed blankholders can be used to provide different restraints in various areas of the pressing when surface damaged by draw beads cannot be tolerated. More positive control of flow in strategic areas can be achieved with draw beads as required in odd shaped pressings where additional stretch is required. Draw beads are projections and corresponding depressions in matching die and blankholder surfaces, to constrict the flow of sheet in appropriate areas during a drawing operation. The draw bead can control the flow of the blank or provide a complete lock on the material and so allow the blank to flow at different rates as required.

8 LUBRICATION

As the blank slides over the die surface there will be areas where friction is high and the generated heat can cause welding (*galling)* of the blank and die surfaces. To continue the drawing movement an increased force will have to break the weld thus increasing the stress in the walls of the pressing. Under extreme conditions the welding effects will cause uneven flow and eventually failure.

Factors such as the blank and die surface conditions, the die material and lubrication all affect this problem.

Lubrication of the blank is used to separate the tool and blank surfaces and prevent welding while still allowing control of the blank flow by variation of holddown pressure.

This separation protects the die against wear and the blank surface against damage in addition to allowing easier flow of the blank over the die surface.

The lubricant must be easily applied and removed and afford some corrosion protection to the surface after pressing. Some deep drawing lubricants contain chloride additives; these should never be used with BlueScope Steel Limited metallic coatings as rapid corrosion will result. All lubricants should be checked for compatibility with steel or coating surface by contacting the lubricant manufacturer and BlueScope Steel State Sales Offices.

8.1 Coatings

Coatings of various types can have a significant influence on the press forming process as they can modify the frictional characteristics of the surfaces involved. These changes must be considered during the die design stage or if a change in part material in contemplated.

Galvanized coatings, such as on GALVABOND® G2 can cause pick up on draw beds or die radii. Hard coatings, eg. on ZINCANNEAL® G2, are not prone to galling but can result in powder build up in tools. Control is achieved by regular cleaning of dies during a press run as well as routine maintenance of the die surface. Recurring problems associated with powdering, especially in deep drawing operations, can be alleviated by chrome plating the die surface and utilising a lubricant with effective boundary or extreme pressure additives.

9 PRESS PERFORMANCE

In many ways the performance of a die can be evaluated by determining accurately the reject rate resulting from split or otherwise defective pressings and it is recommended that performance records be kept for each run of every reasonably severe pressing. An increase in the rejection rate will indicate a change has occurred in the process; it may be mechanical, lubrication or material or may suggest that die maintenance be improved.

For specific press failures careful examination of the part can often provide a lead to the cause of the failure. For instance, shiny areas on the flange probably result from excessive or uneven holddown pressure; shadow marks show that failure is imminent.

These observations can provide the experienced eye with a reasonable indication of the problems but a further technique, termed **Grid Strain Analysis** (*GSA*) will provide a quantitative measure of performance. The technique can be readily applied by press shop personnel with comparatively inexpensive equipment.

9.1 Grid Strain Analysis

In many press shops, decision-making for die alterations and maintenance is based on the visual appraisal of a pressing and die. Such evaluation is subjective and success depends on the experience and skill of the appraiser.

While having its place in a press shop, this method can be supplemented by GSA, a technique which can provide a quantitative assessment of the pressing. GSA allows measurement of the maximum strains in any area of the pressing so that it is possible to estimate how close a pressing is to failure. Alternatively, the effects of die modifications

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can be accurately determined to show whether the severity of a pressing has been eased or not.

GSA has provided many shop operators with the means to improve profitability through reduced die development and die setting times, the ability to select the most economic combination of material thickness and quality and more rapid fault finding.

9.2 Forming Limit Diagrams

The GSA technique is based on the measurement of strain (*percentage change in dimensions*) in any area of the pressing. It is necessary to measure the maximum or major strain and the minor strain or the strain at right angles to the major strain in the same area.

These measurements are obtained from small circles electrochemically etched on to the blank surface before drawing. When drawn or stretched a circle becomes an ellipse with the major axis of the ellipse denoting the magnitude and direction of the maximum strain and the minor axis allowing calculation of the minor strain. Thus the direction of the magnitude of strain can be determined for any area of the pressing.

The **Forming Limit Diagram** (*FLD*) is a graph relating the minor and major strain conditions applying at the onset of local necking for various combinations of strain. An FLD has been reproduced in Figure 2 where the negative minor strain side indicates strain conditions applying in drawing operations, and the positive minor strain indicates conditions occurring during stretching.

Figure 2 – Forming limit diagram

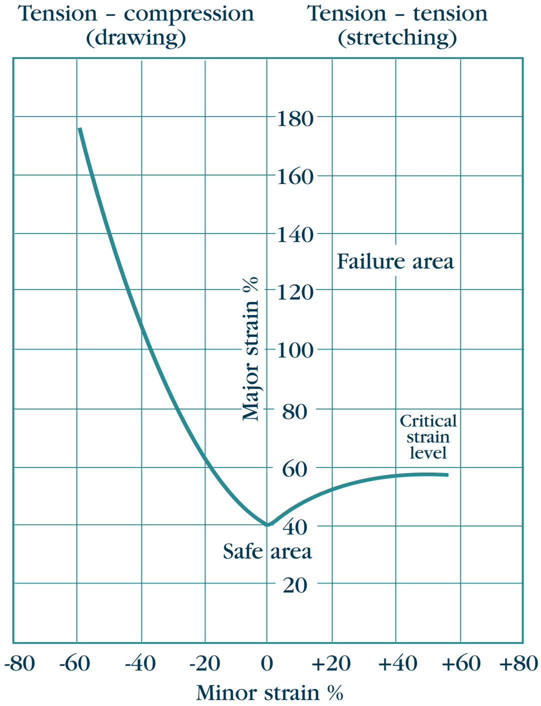
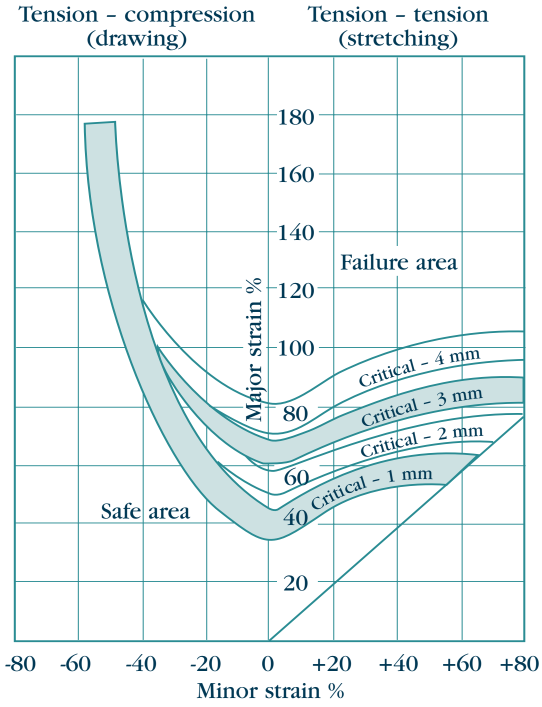


Figure 3 – Forming limit diagram for various steel thicknesses



The curve indicates the strain conditions which will produce local necking and hence an unacceptable pressing. In practice this curve becomes a narrow band but for simplicity the curve shown is equivalent to the lower limit of the band.

9.2.1 EFFECT OF STEEL THICKNESS ON FLD

Increased thickness gives a larger major strain for the same minor strain as indicated in Figure 3 (*above*).

9.2.2 EFFECT OF VARIOUS STEEL TYPES ON FLD

For practical purposes, all plain low carbon steels, both coated and uncoated and the various grades of Interstitial Free (*IF*) steels will have the same FLD, with the different characteristics of each grade causing the major-minor strain intersection point to occur at different positions on the diagram in a similar way to the steels in Figure 4.

High strength steels with reduced ductility will have a lower FLD curve than indicated in Figure 3.

The FLD for high strength steels is shown in Figure 4.

Figure 4 – Forming limit diagram for various 1 mm thick steels

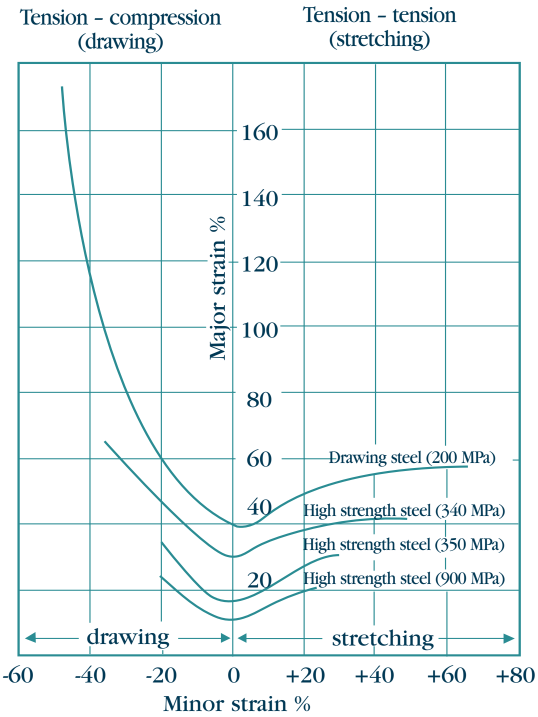
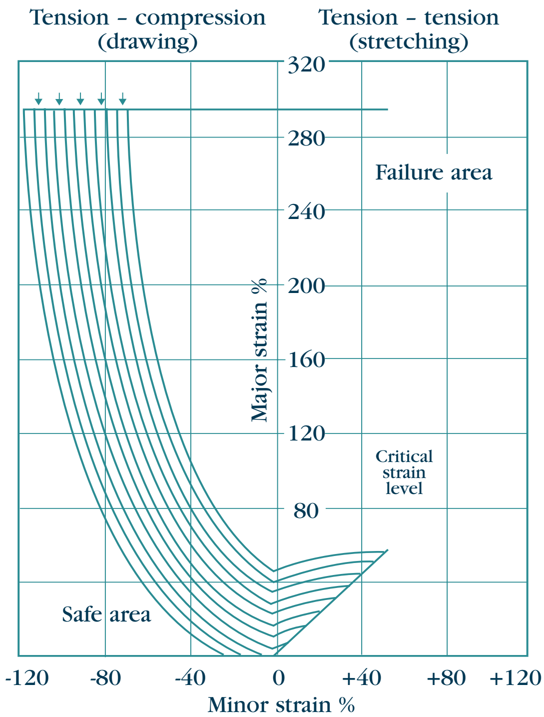


Figure 5 – Forming limit diagram severity zones



9.2.3 SEVERITY ZONES

Several users of the GSA technique have proposed adding to the FLD a series of severity zones as shown in Figure 5.

If a (*major-minor*) strain intersection point falls into severity rating 10 (*Figure 5*) the strain is only fractionally below the critical strain and any deterioration in tool performance, material quality or factors such as lubrication may result in panel failure once the tool has been placed in production.

Several press shops specify a severity rating of 8 or lower to reduce press shop problems. This gives a factor of safety to minimise the risk of failure.

9.3 Using the Forming Limit Diagram

The major strain possible from a blank, before the pressing shows signs of local necking, will depend on the biaxial strain conditions applying to the pressing. For instance, if the minor strain is allowed to decrease, and equivalent increase in major strain is obtained before the pressing shows signs of local necking. This type of deformation occurs in radial drawing conditions. Contrary to expectations under stretch forming conditions where the minor strain is increased, a high major strain is required to produce local necking.

By measuring the major and minor strains in critical areas it is possible to determine not only the areas of high strain but also to estimate how close each area of the pressing is to failure. This estimation uses the Forming Limit Diagram.

9.4 Use of GSA

Grid Strain Analysis (*GSA*) is a practical tool for use in the press shop whereby the opinions of an experienced die fitter can be quantified and used to demonstrate his problems and preferred solutions. The technique may be used for die development, steel selection and assessment of press conditions.

9.4.1 DIE DEVELOPMENT

Setting up the die and selection blank quality and press conditions can be a lengthy process

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involving die alteration, blank development and alterations to factors such as draw beads or holddown pressures.

The GSA technique allows the measurement of the effects of each alternation so that the beneficial changes or those giving a safer major strain can be incorporated into the design. Several press shops have found that die development work on critical panels can be reduced by up to 50% when using GSA.

9.4.2 DIE MAINTENANCE

The effect of die wear on the severity of the pressing can be determined and correction made during maintenance. This evaluation may not be required on the majority of panels, but there will be critical panels requiring GSA to maintain low rejection rates.

Maintenance of records is important in these instances so that wear and the necessary corrections can be predicted and corrected before problems are encountered in production.

9.5 Material Selection

As the die performance is improved by the use of GSA, the possibility of using a less costly, less ductile steel grade increases. Experience indicates that some pressings are produced from CA5SN-E or CA3SN-E because of die problems whereas with improved die set-up and strain distribution the use of a less expensive steel may be possible.

9.6 Lubrication

The influence of a lubricant on the press forming ability of a blank can be difficult to predict. Use of the GSA technique will allow evaluation of the effects on the pressing severity. Other factors such as die wear and panel protection also need to be considered and these have been more fully covered in the Technical Bulletin TB-F1 Lubrication of Steel Sheet and Strip for Forming.

9.7 Training

Die setting has been an art acquired by long exposure to the various problems and in many instances die alterations will be made because of opinions rather than specific quantified evidence.

GSA can be used to train people involved in die work and reduce the dependency on experience and guesswork, often the means of reaching decisions in this work.

Information on the method of use and applications of GSA to press problems has been more fully covered in several BlueScope Steel reports which are available from BlueScope Steel State Sales Offices. These reports have sufficient detail to allow purchase and use of the required equipment.

Further technical assistance is available on request and additional information can be obtained from references 5 and 6 listed at the end of this chapter.

10 CORRECTION OF PROBLEMS DURING PRESSING

In the event of metal splitting during pressing the following factors should be carefully considered.

10.1 Blank Material

Steel Thickness

Ensure that the blank thickness is within the accepted tolerance for the ordered thickness.

Steel Grade

Grade mixes can occur within the steelmakers plant and within the press shop. The steel cannot be confirmed without involved testing procedures. Relative comparison can be made by pressing panels from other packs.

10.2 Dies and Press

Areas that need attention to ensure maximum performance of pressing operations include:

a) Draw radii, draw beads, die ring and blankholder surfaces must be clean and smooth. In critical pressings these surfaces may need to be highly polished. Any grinding marks should be in the direction of the metal flow.

b) When the draw radius is too small, excessive thinning or fracture results at the bottom of a panel and at any stage of the operation. This can be corrected by increasing die radius or blank development to allow easier metal flow.

c) Burnished areas on the sides of a pressing indicate that clearances between punch and die are too small, excessive or uneven.

d) Excessive blankholder pressure will be indicated by bright burnished patches on flanges. Uneven pressure may hold back areas of the blank, causing undesired blank flow patterns.

e) If a small radius is required on final pressing, draw a larger radius and restrike rather than use an excessively small punch radius.

f) Check limiting draw ratio (*blank diameter to cup diameter*); this may be too high for the steel used, causing pressing failures

g) Inadequate or unsuitable lubrication can be another cause of high failure rates in pressing operations

h) If the flange of a pressing is wrinkled or the wrinkles have been pulled into the walls the following may be responsible:
   - blankholder pressure too light.
   - draw radius too large. The blank

cannot be controlled by holddown pressure once the edge enters the draw radius.
- punch radius too large.
- uneven blankholder pressure or burr on one edge when wrinkles are on one side.

i) An uneven top rim or flange in a drawn cup can result from the following:
- the formation of ears around the edge of a cup usually occurring as a result of the blank having different properties in various direction (*normal anisotropy*).
- uneven holddown pressures or incorrect positioning of blankholder which permit uneven flow into the die. This uneven flow can be caused by burrs or damage to the edge or surface of the blank.
- inaccurate location of punch, die or blank.

ACKNOWLEDGMENT

BlueScope Steel wishes to acknowledge the assistance of Harrington GA & L Pty Ltd of Padstow NSW in the preparation of this document.

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