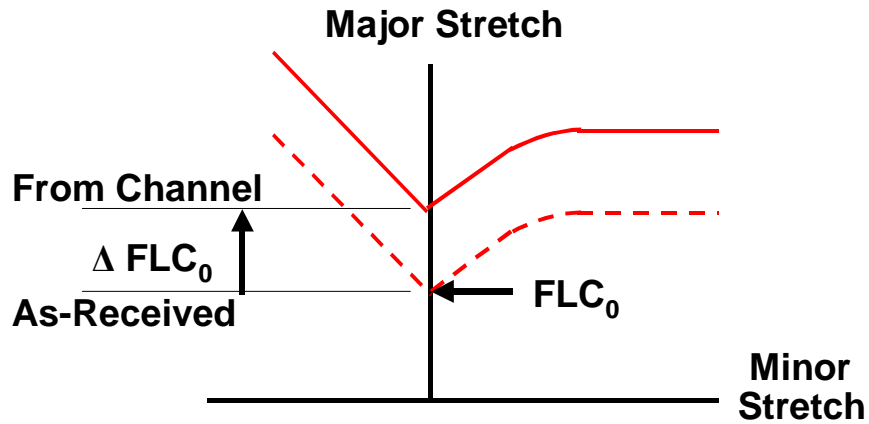


Enhanced Forming Limit Diagram

Project Team Technology Report

The Enhanced FLC Effect



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Executive Summary

The Enhanced Formability Project was initiated on the basis of press shop observations that parts with strains substantially in excess of conventional as-received forming limit curves (FLCs) could be successfully produced in large volume without breakage. In these cases, the apparent increase in the as-received FLC was observed in areas of the part that had been subjected to bending and unbending through drawbeads as steel moved off a binder. If advantage could be taken of this additional formability, higher quality panels could be produced and die modifications during press shop tryout would be reduced. This required experimental work to quantify the increase in FLCs due to bending and unbending and to provide some mechanistic basis for this behavior. This increase in an FLC after bending and unbending was described as the enhanced FLC effect, which was represented by ΔFLC_0 .

An experimental concept for quantifying the enhanced FLC effect is based on the design and construction of a channel draw die, which produced parts large enough for subsequent experimental determination of FLCs. The tooling radii and drawbead penetration primarily controlled the magnitudes of the bending and unbending strains. To increase the range of bending and unbending strains, an outboard bead system was designed to generate different degrees of back tension.

The research program generated predictive equations for use in the press shops and to provide a mechanistic basis for understanding the enhanced FLC effect. The extensive Research Report and two data CD's containing all the details and data of the multi-year research program are located on the Auto/Steel Partnership's web site.

The final phase of the program was to translate the research work into procedures applicable to press shop functions, such as die tryout, process monitoring, and FEA design of parts. The deliverables of this closing phase are a Technology Report and an in-plant training program. This document is the Technology Report.

Explaining an enhanced FLC concept to the press shops would be difficult because the research indicates that deformation and thinning of the metal going through the beads creates increased stretching limits. However, the enhanced FLC measured by ΔFLC_0 is a result of the chosen experimental program. Within the stamping the FLC is not enhanced, but remains a constant to be used for all areas of the stamping

The key to press shop application is that thinning strains created by the bending and unbending deformation through beads or over tight punch and die radii are only forty percent as damaging in terms of forming severity as uniform thinning caused by metal stretching. Thus, a Bead Correction Factor (BCF) can be applied to correct strains measured on metal exiting the bend and unbend zone before plotting them on the FLC. This procedure is described in detail in this Technology Report and highlighted by a number of case studies.

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1.0 – Introduction

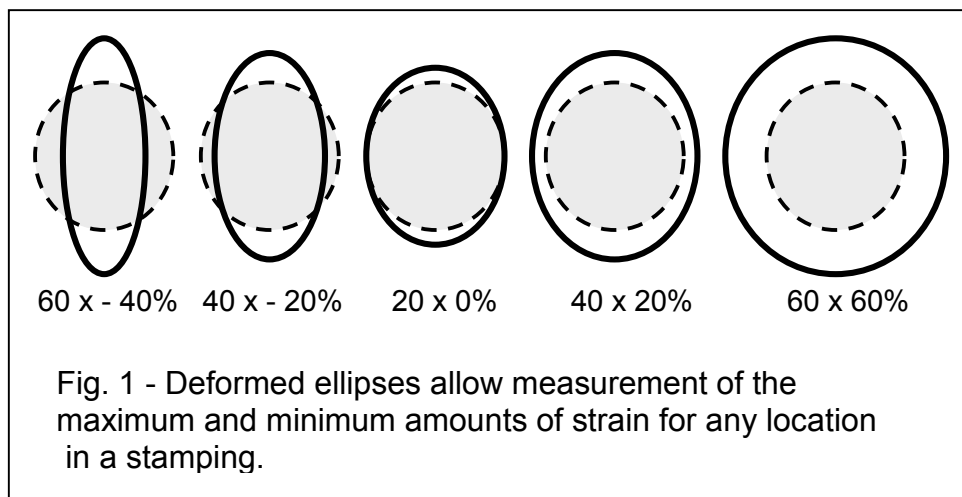
1.1 – Identifying Forming Severity

For decades, the sheet metal forming industry and its suppliers have searched for some predictive method to determine when sheet metal approached its deformation limit and was about to tear. Exceeding the limit was easy to identify - a tear or the inability of the stamping to hold water. Knowing the forming limit without encountering an identifying tear was an illusive goal.

One of the earliest methods was to produce some large number of stampings, often 250 or more, to create a statistical sample of the press performance. The inputs to the forming system encompass the general categories of part design, die design, press, sheet metal, lubricant, and operator. The final stamping is the output of all the system inputs. If failure was one part in 150, the failure rate was less than one percent. Too often this forming condition was identified as not too severe and not too conservative – just right to start production.

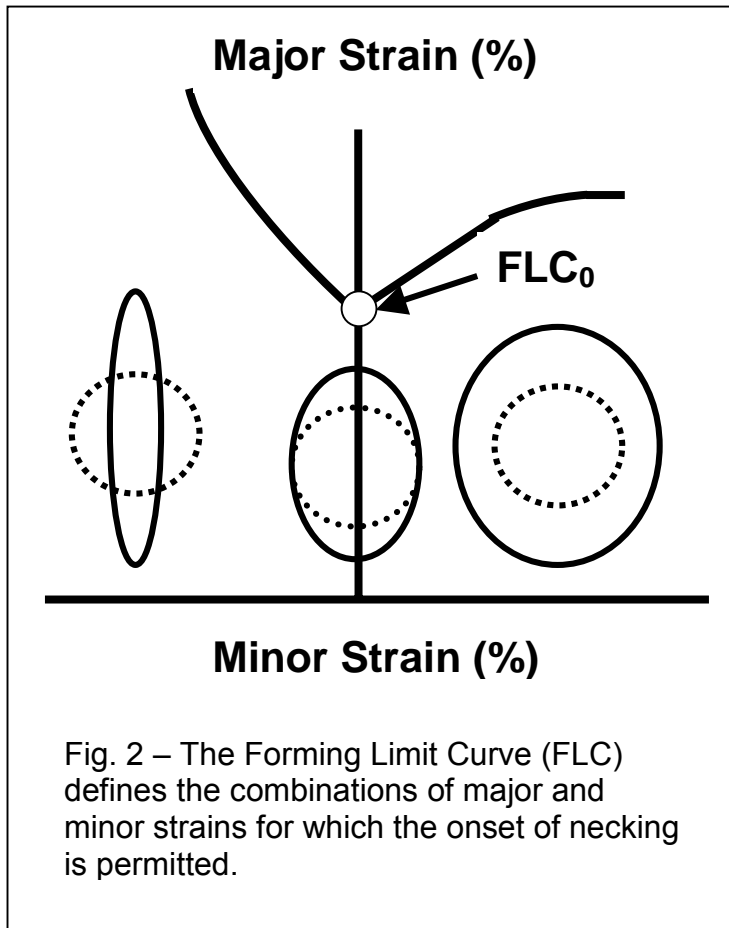
The concept of measuring the amount of deformation in the stamping provided a quantitative measure of how much the stamping had actually deformed or strained. One of the earliest recognized methods was the scribed square system. A series of one-inch squares was scribed on the blue-inked sheet metal. After deformation the percent increase in surface area was measured. While good in concept, many problems existed. All deformation within each one-inch square was averaged. Small areas of large deformation could not be identified. The squares rarely were aligned in the direction of maximum deformation, and the direction and magnitude of the largest principal strain could only be obtained through Mohr's circle calculations. Easy visualization was not possible. Even worse, tears often occurred in the scribed lines.

In the mid 60's the circle grid system solved most of the measurement problems associated with the one-inch scribed square system (1,2). Circles of small diameter (0.1 or 0.2 inch - 2.5 or 5 mm) were electrochemically etched into the surface of the blank (Appendix 8.1). Upon forming, the resulting ellipse showed the direction of the maximum and minimum deformation and allowed direct measurement of the magnitude of both strains (Fig. 1).



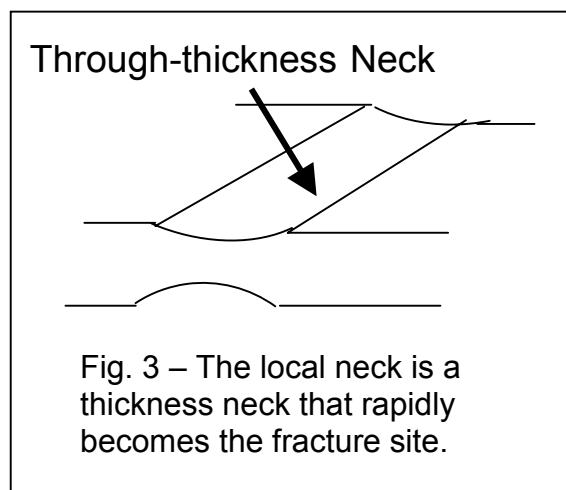
However, knowing the amount of deformation was only one-half of the information required to determine the proximity of a stamping to failure. Some measure of the limiting strains was needed. An analogy is using a map to prevent your falling off a cliff. You must be able to identify both where you and the cliff are located on the map. Only then can you keep a safe distance from the edge of the cliff. Only then can you track your journey to determine whether you are going toward, parallel to, or away from the edge of the cliff.

1.2 – Forming Limit Curves



Circle grids identified how much the sheet metal had deformed. The Forming Limit Curve or FLC identified the edge of the cliff (Fig. 2). The FLC defines the major - minor strain combinations at the onset of a local or thickness neck (Fig.3) in stampings (Appendix 8.2). The FLC in sheet metal stampings is not associated with the onset of the diffuse (width) neck observed in the tensile sample and is not limited by the tensile strength or uniform elongation measured during tensile testing. In a tensile test specimen, this local neck occurs just prior to specimen fracture.

Basic research on the FLC was conducted during the 60's (1-3). This research on steel defined the basic shape and values of the FLC for low carbon steel in the laboratory (Fig. 2) and showed that onset of local necks in production stampings could be predicted.



During the 70's additional research on steels expanded the application of FLCs to higher strength steels and a wide range of sheet metal thickness (4). Improvements in ultrasonic thickness measurement devices in the 80's increased the use of FLCs in monitoring sheet metal deformation for troubleshooting and production control. To complement this work, FLCs based on thickness strain were created. The tremendous growth of computer simulation of sheet metal forming in the 90's has found new applications for FLCs, which is the primary method to determine when a sheet of metal is expected to fail.

One major benefit of utilizing FLCs for steel applications is that most production steels (including higher strength steels) are considered one alloy (low carbon) and one temper (dead soft or light temper pass). Application of FLCs to non-ferrous metals also has taken place but at a slower rate. For these metals, each alloy and temper requires determination of a unique FLC.

Forming Limit Curves are used during the complete life cycle of a sheet metal stamping – from forming of the stamping on the computer through die tryout to production monitoring. A few specific applications are:

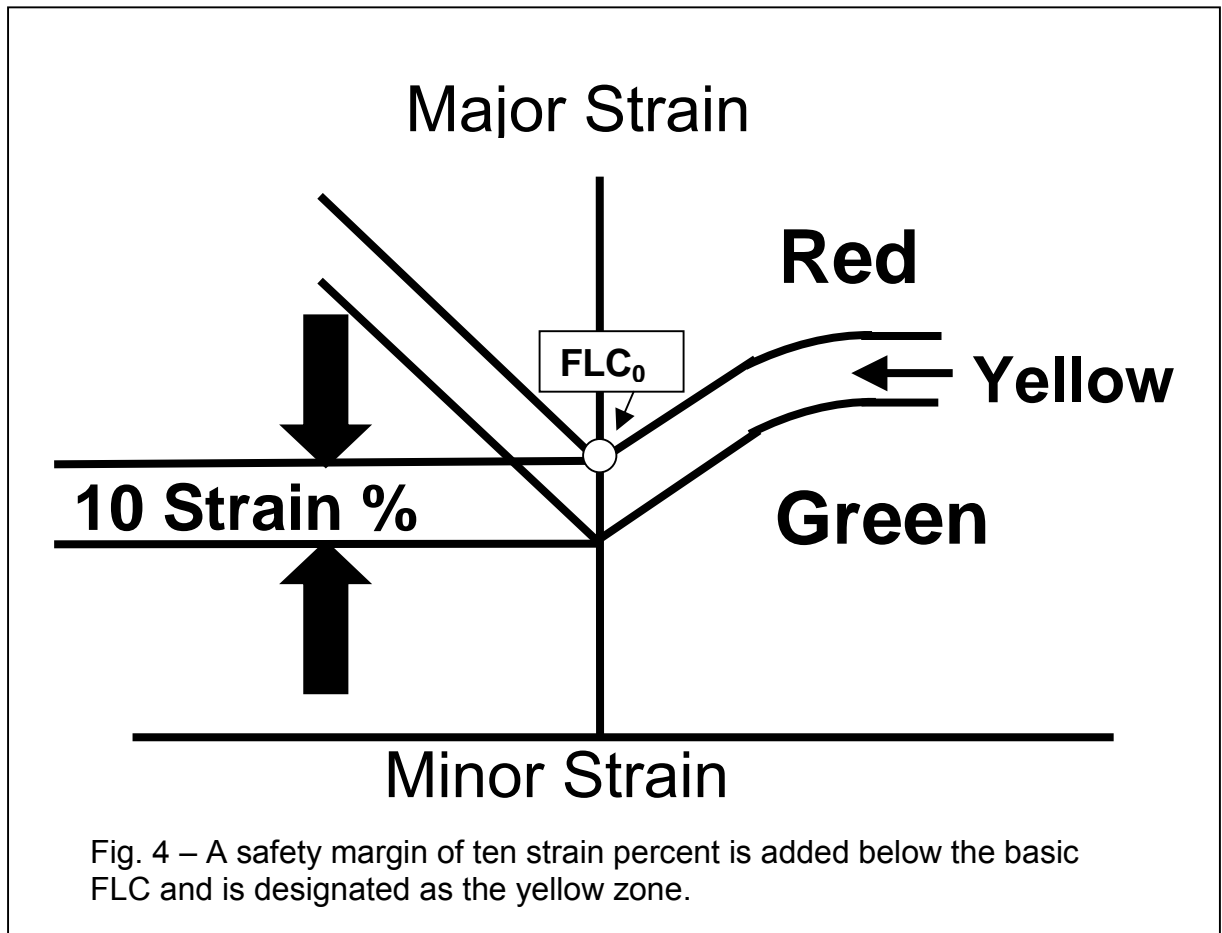
1. Establish die tryout severity – soft and hard tooling
2. Provide quantitative data for die buyoff
3. Evaluate engineering changes
4. Monitor process changes
5. Set forming limit for FEA forming analyses
6. Assess die transition repeatability
7. Create extended forming severity control charts
8. Assist as a troubleshooting tool

The key benefit of utilizing the FLCs is rapid determination of the maximum amount of strain a piece of sheet metal can withstand before failure – locating the edge of the cliff on the deformation map. The FLC shows that no single value of stretch can be used as the forming limit (Fig. 2). Different values are applicable depending on the strain state or combination of major and minor strains.

The sheet metal can always be forced to fail in the press by increasing the deformation for the purpose of obtaining a forming limit. However, this procedure only identifies the maximum allowable stretch for one combination of major and minor strain. Even worse, this may not be the actual strain state controlling the particular stamping under investigation. Exceeding production values of force can alter the deformation mode within the stamping and distort the production conditions.

A safety factor or safety margin can be obtained by comparing the actual deformation in the stamping to the allowable deformation defined by the FLC (Appendix 8.3). This assessment can be obtained with only one stamping and is extremely important during die tryout when time is very limited. One cannot afford to make 500 or 1000 stampings to see if a percentage of breakage will occur.

Another key press shop use of circle grids and forming limit curves is to require stampings to have a specified safety margin before acceptance for production. This safety margin usually is a ten strain percent band before the failure or red zone is reached (Fig. 4). This safety margin or yellow zone provides an allowance for normal production variations without exceeding the forming limit.



In many press shops, drawbeads are used in an attempt to create a specified minimum strain in the flat or least deformed portion of exposed stampings. Often restraint of the metal traversing the beads is increased until either the minimum strain is attained or the wall of the stamping tears. Historically the FLC has not been used in assessing the proximity to failure for metal pulled through the drawbeads.

1.3 – Concept of Enhanced FLC

Since the early introduction of FLCs, metal that underwent bending and unbending through drawbeads has been excluded from any FLC forming severity analyses. This was based on the argument that the deformation was not constant from one surface to another (tensile on the outer fiber and compression on the inner fiber for each bend) and that the surfaces underwent several complete reversals of deformation.

When press shops evaluated metal that had been deformed through drawbeads, areas of high strain were observed to be in the failure or red zone (negative safety margin) of the FLC but did not fail. At the same time, pressure was being placed on die builders and die tryout staffs to certify that the entire stamping was in a safe or green zone condition. The Auto/Steel Partnership created a project team to study this problem.

An extended research program was initiated to evaluate the FLCs of sheet steel that had been bent and unbent moving through drawbeads. A channel die was designed and constructed to deform metal through drawbeads to different degrees of forming severity.

Samples of the deformed metal were removed from the sidewall of the channel and FLCs were measured on the deformed metal. The deformation of metal through the drawbeads caused an increase in the measured FLCs – thus the term Enhanced FLC was created to describe the research program.

1.4 – A/S-P Research Program

The A/S-P research program covered four years of experimentation at the Industrial Research and Development Institute (IRDI) in Midland, Ontario. The research was directed and reviewed by the A/S-P Enhanced FLC Team. The detailed results of the research are contained in an extensive Research Report written by B. Levy and D. Green (5) plus two CDs containing data spreadsheets and drawbead deformation videos. All three items can be accessed from the A/S-P web site located at www.a-sp.org. The Introduction for the Research Report is reprinted here as a general overview of that extensive research effort.

Introduction

The Enhanced Forming Limit Curve Project was initiated on the basis of press shop observations that parts with strains substantially in excess of the conventional as-received forming limit curve (FLC) could be successfully produced in large volume without breakage. In these cases, the apparent increase in the as-received FLC were in areas of the part that had been subjected to bending and straightening as steel moved off a binder surface or off a post (punch). It was recognized that if advantage could be taken of this additional formability, it would be possible to produce higher quality panels and/or eliminate unnecessary die modifications in press shop tryout. This required experimental work to quantify the increase in FLCs due to bending and straightening and to provide some mechanistic basis for this behavior. The increase in an FLC after bending and straightening is described as the enhanced FLC effect.

The experimental concept for quantifying the enhanced FLC effect is based on a channel draw die that produces parts large enough for subsequent determination of an FLC using the Marciniak double blank method. Since drawbeads and die and punch entry radii are the predominant source of bending and straightening in stamping dies, considerable attention was given to a system for using inserts for the drawbead and the die entry radius so that a range of geometries could be evaluated. In order to provide back tension at the drawbead, the die was designed with outboard drawbeads. This unconventional approach was selected because of its low cost.

With the basic experimental approach determined, several experimental methods were developed to obtain the needed data quality. The first requirement was developing a more accurate system for determining FLCs because determining the enhanced FLC effect requires comparing an experimental enhanced FLC with the experimental as-received FLC. Since accurate predictive relations were needed, stringent requirements for accuracy were established.

Since the original experimental planning had identified back tension and actual bending radius as key variables, experimental methods were developed for determining these variables. For back tension, a hydraulic cylinder with a load cell was added as an auxiliary

to the channel draw die. Determining actual bending radius was more difficult. Initial attempts to measure radii from the channel draw test pieces provided accurate measurements, but it was not possible to account for springback. As a result, considerable work was done to successfully develop an in-situ system for measuring the actual radii in drawbeads. For the die entry radius, it is assumed that the actual bending radius equals the tooling radius.

Planning for the experimental work was done by the Project Team based on available funding. The experimental work was done over four years. Work was planned on a yearly basis, and each year's work was based on what had been learned and changing needs as determined by the Project Team. Many of the ideas and analytic methods included in this report are the direct result of input from the Project Team.

Initially, work was planned using AKDQ steel and round drawbeads. As work progressed, square, double round, and double square drawbeads were included in the program. Another key change was the design and use of variable penetration drawbeads so that different drawbead conditions could be evaluated more economically. Also, in the last year of the program it was decided to evaluate BH210, HSLA and DP600 steels.

Since the project objective was developing quantitative relationships for predicting the enhanced FLC effect, considerable effort was devoted to determining the experimental variability of all measured quantities used in its prediction. This information is used to evaluate the reliability of the predictive equations.

Since the results of the project are for industrial use, the work is reported in two parts. This report describes the quantification of the enhanced FLC effect and discusses its fundamental basis. A companion report, which includes cases studies, describes how the enhanced FLC effect should be applied in press shops and is intended for use by press shop personnel. Thus, the Applications section of this report describes in technical terms, some of the factors that must be considered for press shop work. This report also includes some discussion of the use of the enhanced FLC effect in FEA work.

1.5 – Technology Report Sections

The purpose of this Technology Report is to translate the results documented in the Research Report into procedures that are feasible in the press shop. For this particular program, the recommended press shop procedures are quite different from the approach adopted by the basic research program. This Technology Report contains the following additional sections:

- Section 2 – Describes the evolution of Enhanced FLC study
- Section 3 – Technology details from the Research Report
- Section 4 – Case Studies from the press shop
- Section 5 – Drawbead Correction implementation issues
- Section 6 – Techniques for using the Drawbead Corrections
- Section 7 – References
- Section 8 – Appendices for additional information

2.0 – Evolution of Enhanced FLCs

This section details the history of the Enhanced FLC program from early observations in the press shop to the very detailed research program that proved and quantified the enhanced FLC effect.

2.1 – Early Observations in Stamping Plants

A primary use of FLCs is to evaluate the severity of the stamping during the die tryout. This is accomplished by comparing the actual strain state in the stamping (major and minor strains) to those allowed by the FLC (Appendix 8.3).

If the actual strain state is above the FLC, the die has negative safety margin and is said to be a “red zone” die (Fig. 4). A safety margin between 0 and 10 strain percent is marginal and represents a “yellow zone” die. The goal is to achieve a safety margin greater than 10 strain percent, which is defined as a “green zone” die.

Many companies, especially automotive related, have specifications stating that new dies must be in the green zone before buyoff. Additionally, many companies require that dies be kept in the green zone during the entire production history.

Traditionally two areas of deformation in stampings have eluded FLC analysis. One is metal subjected to major changes in strain path. These changes in deformation mode can range from balanced biaxial strain followed by uniaxial tensile strain to uniaxial tensile strain followed by balanced biaxial strain and can cause major changes in the level of the FLC. While these types of changes can occur within a single die, they are more common when a stamping progresses from one die to the next die. Recent research (6) has allowed these multiple FLC levels due to strain path changes to be eliminated. Instead of using the traditional strain-based FLCs shown in Fig. 4, the recent research has shown the strain-based FLC can be converted into a single stress-based FLC that is independent of strain path. Press shop application of stress-based FLCs is still pending, but their use in FEA forming simulations is strongly encouraged.

The second area of deformation that has eluded FLC analysis is metal that has been deformed going through drawbeads and ends up in the walls and corners of the panel. These areas are noted for having strain levels well above the traditional FLC and yet do not experience failures. Because of the high strain levels without failure, press shop personnel have said FLCs do not apply to metal deformed through drawbeads and have ignored these areas in stampings.

However, the push for more product consistency in terms of springback, strain distribution, maximum thinout, and in-service capabilities has elevated the priority for more understanding of deformation of metal pulled through a drawbead. Specific drivers for this improved understanding are:

1) Green zone die status is being required for all areas of the stamping. The large thinning strain of metal pulled through drawbeads often is in the red zone. Additional die adjustments, steel with different mechanical properties, or different lubricants would be initiated first in an attempt to reduce the severity of the deformation. In many severe cases, the primary reduction in forming severity would have to come from product redesign or major tooling modifications. The latter would reduce the severity of the drawbead through less penetration, greater radii, or other modifications that would allow more metal to flow into the body of the part. Unfortunately, this usually also reduces the amount of stretch in the face of the part, which probably is already too low to meet ideal specifications for dent resistance, minimum in-panel strength, minimum stretch for outer body panels as required by exposed surface quality, minimum stretch for panels made from bake hardenable steels to trigger bake hardening effect, and other in-service performance requirements.

2) If the press shop makes a decision to ignore the high strain region with the feeling that breakage will not occur in that area, then many additional stampings will have to be made to validate that decision. The reduced time between concept and production does not allow for extended tryout time to determine if an area is actually safe or not. If only a few stampings are made and breakage never occurs, the press shop still does not know what safety margin can be assigned to the highly strained metal.

3) Some press shops allow breakage in metal pulled through drawbeads if the tear does not extend into product and will be trimmed out. However, this breakage in the offal or engineered scrap can be a major source of dimensional variation in the product. As dimensional variation requirements are tightened, no tears or necks in any portion of the blank will be allowed. Therefore, even the offal will have to be in the green zone.

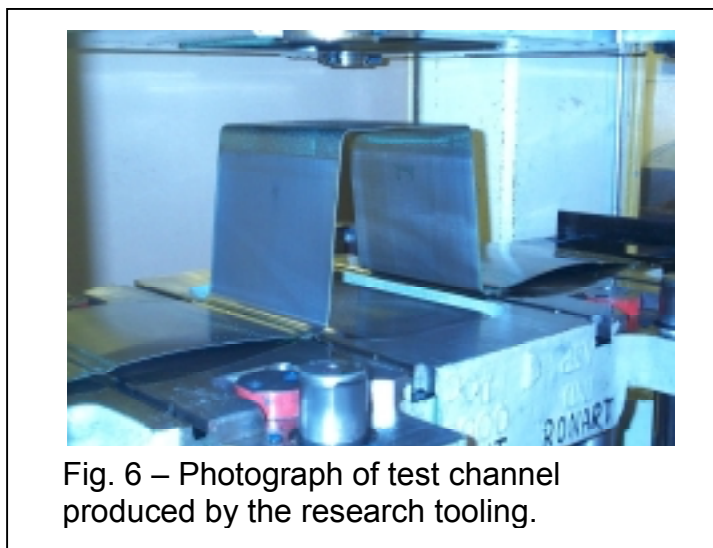
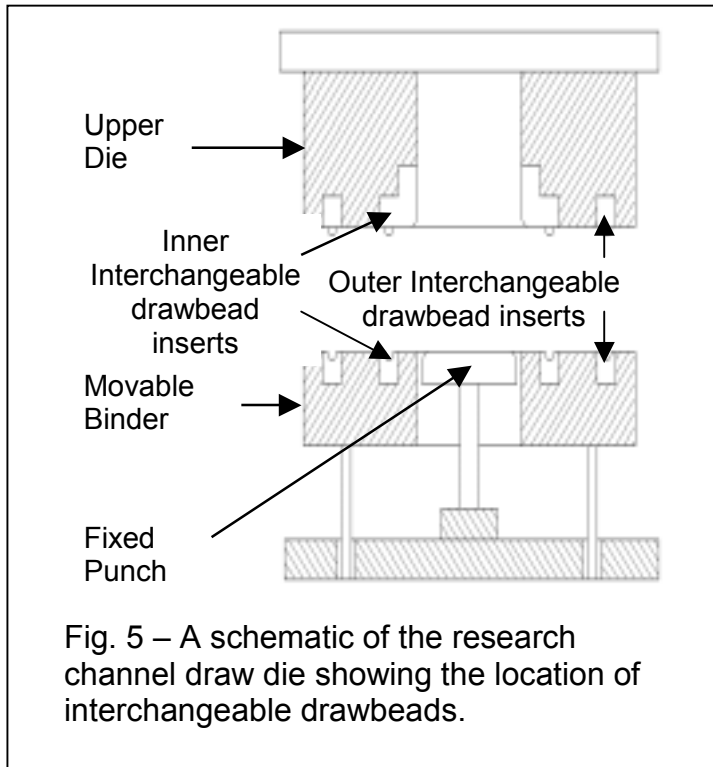
2.2 – Auto/Steel Partnership Team Formed

The inability to assign a valid forming severity to metal pulled through drawbeads became a priority issue with the Auto/Steel Partnership and a team was assembled in April 1997 to investigate this issue.

Some early measurements at Chrysler and Ford verified that higher levels of strain could be obtained without breakage in the plane strain (no width strain) condition when the severity of the deformation through the drawbeads was increased.

The team's first assignment was to design a research tool that would have the following capabilities:

- 1) Magnify the effect of the drawbead deformation.
- 2) Allow measurement of the FLC for the sheet metal prestrained through drawbeads.
- 3) Provide a change in the deformation severity generated by the drawbead through changes in drawbead configuration (geometry, penetration, and back tension).
- 4) Permit direct measurement of the restraining force developed by each drawbead configuration.
- 5) Minimize tooling costs while still achieving the desired number of research tests.



A channel draw die was designed for the research portion of the program (Fig. 5). The channel was 10 inches wide and 10 inches deep (Fig. 6). The inner beads created the prestrain in the metal, while the outer beads created the back tension. Design of the die was completed and the build contract was awarded to Ronart Company – Detroit, Michigan on June 12, 1997. Tooling was completed and accepted by the team on October 15, 1997.

The tooling was delivered to Industrial Research and Development Institute (IRDI) of Midland, Ontario for the majority of the research work. The work by IRDI included forming the channels, determining the FLCs for the as-received steel and for steel samples taken from the wall of the channel, and measuring the actual restraining force created by each drawbead configuration. An added feature of the research was videotaping the profile of the sheet steel as it was pulled at press speeds over the different drawbead configurations.

2.3 – Research Report

An extensive Research Report compiled all the research data into a comprehensive summary of the research conducted, the results,

conclusions, and applications. Dr. Bernard Levy of B.S. Levy Consultants Ltd. and Dr. Daniel Green of IRDI compiled this report entitled *Enhanced Forming Limit Diagram – Project Team Research Report (5)*. A copy of this report is available on the Auto/Steel Partnership web site www.a-sp.org.

All the raw data generated by the project and the videos of the steel moving over the drawbeads are recorded on two CD's, which are also available on the Auto/Steel Partnership web site.

2.4 – Technology Report

The mission of this Technology Report is to extract sections from the Research Report that are applicable to production applications – both for utilization on the press shop floor and computer simulations. The research results are then combined with practical press shop knowledge to generate operational procedures for evaluating the forming severity of sheet metal that has undergone bending and unbending cycles while being drawn through drawbeads.

Five case studies are presented. These case studies not only illustrate how the operational procedures are applied, but also serve as illustrations of actual applications. Several case studies confirm the accuracy of the operational procedures on production parts.

2.5 – Training Manual and Seminar Presentations

An important requirement of the Enhanced FLC project is to generate a training manual for broad distribution and conduct several training seminars for the members of the Auto/Steel Partnership. The training manual, entitled *The Bead Correction Factor (7)*, is available on the Auto/Steel Partnership web site www.a-sp.org.

3.0 – Technology information from the Research Report

The foundation for the operational procedures for the press shop and the computer simulation of forming is the Research Report (5). Therefore, appropriate sections or parts of sections from the Research Report are included here and then modified for better implementation in the production environment.

3.1 – Key Information for Press Shops

The research program subjected different grades of sheet metal to deformation through different configurations of bead design and back tension. The purpose was to create a wide range of prestrain (the bending and unbending cycles) to duplicate possible press shop conditions.

FLCs were used to define the sheet metal forming capabilities. The FLC from the as-received steel defined the base capabilities. The FLC from the wall of the formed channel defined the forming capabilities after the bending and unbending prestrain cycles. The difference between the two levels of the FLC, as measured by the FLC₀ intersections, was defined as ΔFLC_0 .

Comparing the prestrained FLC to the as-received FLC was an excellent, but tedious, method of quantitatively defining the affect the drawbead and die radius deformation had on the residual formability of the metal in the addendum and/or body of the part.

The ΔFLC_0 was always positive for the conditions studied in the project. This indicated that the deformation through the drawbeads appeared to “enhance” the allowable stretchability of the metal. Thus “Enhanced FLC” became the project and team name.

The key results of the research were three equations that allow predicting the change of ΔFLC_0 as a function of i) the computed bending and unbending severity or ii) sheet thinning through the drawbeads and die radii. These equations are:

$$\text{Equation 1) } \quad \Delta FLC_0 = (41.7 + 104 \text{ BTR}) \text{ BSF}^{1.54}$$

$$\text{Equation 2) } \quad \varepsilon_t = (0.624 + 1.20 \text{ BTR}) \text{ BSF}^{1.27}$$

$$\text{Equation 3) } \quad \Delta FLC_0 = 59.7 |\varepsilon_t| - 1.24$$

where BTR is the Back Tension Ratio, BSF is the Bending Strain Factor, and ε_t is the absolute value of the thinning strain created while going through the drawbead or drawbead / die radius combination.

The first two equations are best suited to computer simulation were the variables BTR and BSF are known or can be computed. These variables are very difficult to obtain in the press shop. The third equation is ideal for press shop utilization. It describes the increase in ΔFLC_0 as a function of incremental thinning through the drawbead. The amount of thinning can easily be measured in the press shop using an ultrasonic thickness gage.

Equation 3 shows that for each one strain percent increment in net thinning strain due to bending and unbending, ΔFLC_0 only increases by 0.6 strain percent. Thus, the loss in ΔFLC_0 from thinning due to bending and unbending is 40% and not 100%. This difference is the basis for the enhanced FLC effect.

3.2 – Development of the Bead Correction Factor (BCF)

The concept of enhanced FLC or ΔFLC_0 was an excellent method to quantify the effect of the bending and unbending deformation through drawbeads. Unfortunately, it does present some problems in press shop applications.

Explaining the shape of the FLC is difficult as best (Fig.4). The left side of the curve is a constant thickness or pure shear line. This condition is created when the negative true minor strain generates the increased levels of positive true major strain. This mode of deformation allows for very high major strain levels on the left side of the curve and is relatively easy to understand.

The right side of the curve is more difficult to explain and is limited to experimental data without theoretical derivation. The fact that the allowable major strain increases as the positive minor strain increases is extremely hard to comprehend. It indicates that tensile strain in both the major and minor strain direction allows for greater stretching before failure. The right side of the FLC has to be accepted on experimental evidence alone.

Unfortunately, the enhanced FLC research suggests that one can additionally increase the amount allowable stretch (the FLC moves higher by the factor of ΔFLC_0) by increasing the amount of cold work, work hardening, and thinning as the metal undergoes bending and unbending deformation while traversing the drawbead and die radius. This makes acceptance difficult for researchers and even more so for the press shop.

The use of ΔFLC_0 was a good experimental procedure. However, the results of the research do not demand that the height of the actual FLC increase by ΔFLC_0 . The research results actually showed that for each one strain percent increment in net thinning strain due to bending and unbending, the ΔFLC_0 only increased by 0.6 strain percent. This suggests that a strain correction factor is a better procedure for the press shop. Instead of using the actual major strain (or thinning strain) to plot on the FLC to determine the safety margin, a corrected major strain (or corrected thinning strain) should be plotted.

Such a procedure has been in use for many years when analyzing the severity of a simple bend. The outer fiber tensile strain is a combination of the bending strain and the through thickness stretch. In pure bending, the outer fiber tensile strain is balanced by the inner fiber compressive strain. The thinning strain is zero and therefore the bending strains do not contribute to FLC severity. Only the through thickness tensile stretch causes thinning and is important relative to FLC severity. Thus, a corrected strain value (with the bending component removed) is used for plotting the strain state of a bend on the FLC.

The recommended press shop practice therefore is to convert the ΔFLC_0 factor into a strain correction factor. To do this, equation 3 is reversed from an additive factor to the FLC and changed to a subtractive factor to the measured major strain. In addition, equation 3 is simplified within experimental error to make application easier for the press shop. The equation now becomes:

$$\text{Equation 4)} \quad BCF = 60 \epsilon_t$$

where BCF is the Bead Correction Factor and ϵ_t is the increment of change in true thickness strain as the sheet metal passes through the drawbead or the drawbead and die radius combination.

For easier computation, the natural log of the ratio of the metal thickness exiting the bead divided by the metal thickness entering the bead is substituted for the true thickness strain.

$$\text{Equation 5)} \quad BCF = 60 \ln(t \text{ bead exit} / t \text{ bead enter})$$

For actual use in the press shop, equation 5 can be converted into a graph for those uncomfortable with natural log calculations (Fig. 7). A table lookup also can be created.

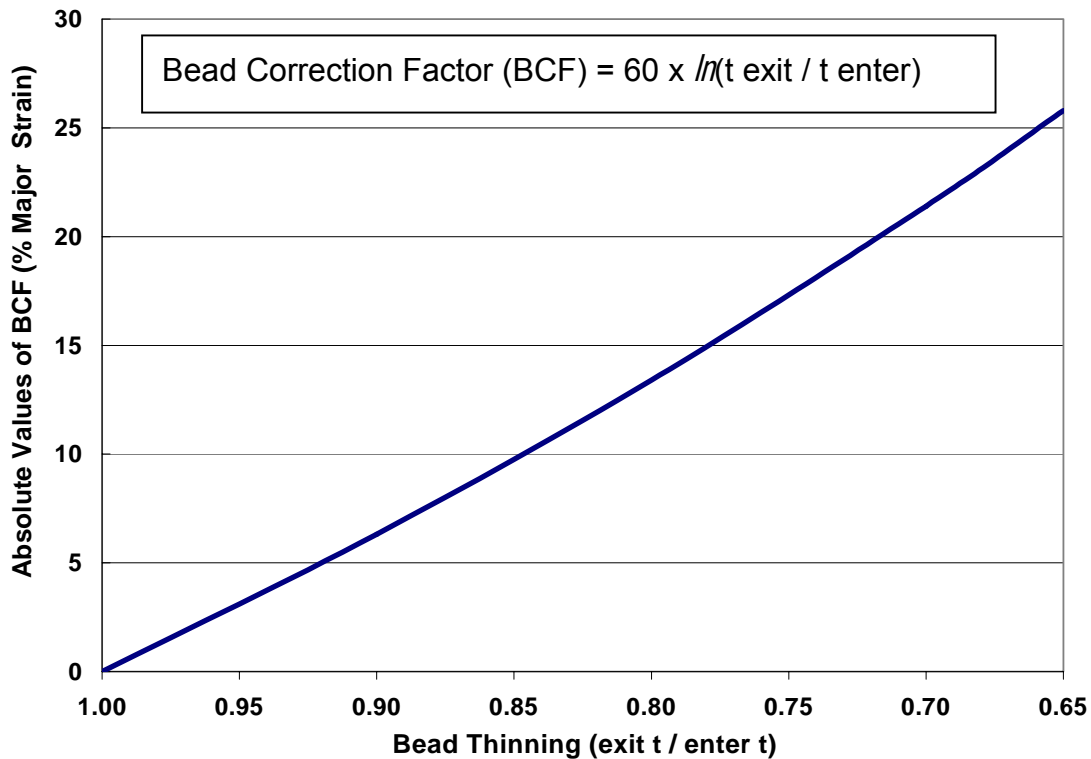


Fig. 7 – Bead Correction Factor (BCF) versus metal thinning through the drawbead.

3.3 – Suggested Procedure for Utilizing the BCF

The following procedure can be used for correcting the forming severity of the measured bending and unbending strain.

Preparation: Obtaining the raw data.

It is important to first verify that the metal location to be analyzed (called the analysis point) has been pulled through the complete bead and/or a die/punch radius. This usually can be accomplished by locating the analysis point relative to the bead or radii impact lines.

The required raw data are:

A) The amount of strain at the analysis point. This can be obtained from:

- 1) The engineering major and minor strains from a gridded part
- 2) The thickness strain if the minor strain is zero
- 3) The thickness and minor strain if the minor strain is not zero

B) The as-received sheet metal thickness and the work hardening exponent. The work hardening exponent usually is computed for the strain range between 10 percent strain and uniform elongation or between 10 percent to 20 percent strain.

C) The metal thickness at the entry and exit sides of the drawbead location (or exit side of the die radius if included in the metal flow path) that created the bending/unbending deformation experienced by the analysis point.

Step 1: Compute FLC₀ for the steel used

One of two equations can be used to calculate FLC₀:

FLC₀ = (23.3 + 14.2 t) n/0.21, where t is as-received sheet thickness in mm

FLC₀ = (23.3 + 360 t) n/0.21, where t is as-received sheet thickness in inches

Step 2: Obtain the as-measured engineering major strain at the analysis point

A) The engineering major strain can be measured directly from the gridded stamping

B) The ultrasonic thickness measurement can be used to calculate the true thickness strain. If the minor strain is zero, the true major strain is the negative value of the true thickness strain, which then is converted to engineering major strain. The necessary equations are:

True thickness strain = $\ln(\text{ultrasonic thickness} / \text{as-received metal thickness})$

True major strain = - (True thickness strain)

Engineering major strain = $(e^{\text{true major strain}} - 1) 100$

C) The ultrasonic thickness measurement and the minor strain can be used to calculate the true thickness strain. However, this is not a common occurrence. Most areas of concern are approximately straight stamping walls or addendum areas that have undergone plane strain deformation. The equations are:

Engineering thickness strain = $(\text{ultrasonic thickness} / \text{as-received metal thickness}) - 1$

Use the constancy of volume equations (Appendix 8.4) to convert engineering thickness strain and engineering minor strain to engineering major strain.

Step 3 (Optional): Compute as-measured Safety Margin

Subtract the as-measured engineering major strain (step 2) from the allowable engineering major strain value (Appendix 8.3). For plane strain (minor strain equals zero) conditions, the allowable engineering major strain value is equal to FLC₀ (step 1). If the minor strain is not zero, the appropriate allowable engineering major strain values must be obtained from the FLC (Appendix 8.3).

Step 4: Compute the Bead Correction Factor (BCF)

The BCF is determined by the amount of thinning experienced by the sheet metal as it moves through the drawbead or drawbead and die radius.

$BCF = 60 \ln(t_{\text{bead exit}} / t_{\text{bead enter}})$ for drawbead deformation only

$BCF = 60 \ln(t_{\text{die radius exit}} / t_{\text{bead enter}})$ for drawbead and die radius deformation

These measurements and equation also can be used for bending and unbending over a punch or die radius if the r/t (radius to sheet thickness ratio) is less than five (5).

Note that the BCF usually is a negative number since the sheet metal becomes thinner after going through a draw bead or over a die radius.

Step 5: Compute the corrected engineering major strain

Before the safety margin can be calculated for metal that was deformed by flowing through a draw bead (and die radius if present), the as-measured engineering major strain must be corrected by the BCF. The corrected engineering major strain is equal to the as-measured engineering major strain (step 2) plus the BCF (step 4).

Step 6: Compute corrected Safety Margin

The corrected safety margin is obtained by subtracting the corrected engineering major strain (step 5) from the allowable engineering major strain value (Appendix 8.3). For plane strain (minor strain equals zero) conditions, the allowable engineering major strain value is equal to FLC_0 (step 1). If the minor strain is not zero, the appropriate allowable engineering major strain values must be obtained from the forming limit curve (Appendix 8.3).

Optional Computation for Thinning Strain Severity

Step 7: Compute thinning strain for different severity levels

Compute FLC₀ for the as-received steel (or obtain from step 1)

FLC₀ = (23.3 + 14.2 t) n/0.21, where t is as-received sheet thickness in mm

FLC₀ = (23.3 + 360 t) n/0.21, where t is as-received sheet thickness in inches

Compute the thinning strain for start of red zone (assuming minor strain = 0)

1. The engineering major strain for the start of the red zone is equal to the FLD₀.
2. The engineering major strain is converted to true major strain by the equation:
True major strain = $\ln(1 + \text{Engineering Major}/100)$
3. For plane strain (minor strain = 0) the true thickness strain is equal to the negative value of the true major strain.
4. Finally, the true thickness strain is converted to the red zone engineering thickness strain using the equation:

$$\text{Engineering thickness strain} = (e^{\text{true thickness strain}} - 1) 100.$$

Compute the thinning strain for start of yellow zone (assuming minor strain = 0)

1. The engineering major strain for the yellow zone is equal to (FLD₀ % – 10.0%).
2. Perform the same calculations numbered 2 through 4 as written for the red zone above.

Step 8: Determine severity of as-measured engineering thickness strain

Compute as-measured engineering thickness strain

$$\text{As-measured engineering thickness strain} = [(\text{ultrasonic thickness} / \text{as-received metal thickness}) - 1] 100$$

Determine if the as-measured thickness strain is greater than the start of red or yellow zone

Label the severity zone of the as-measured engineering thickness strain

Step 9: Determine severity of corrected engineering thickness strain

Obtain corrected engineering major strain (step 5)

Convert the engineering strain to true major strain = $\ln(1 + \text{Engineering Major}/100)$

True thickness strain is equal to the negative value of the true major strain

The corrected engineering thickness strain is equal to $(e^{\text{true thickness strain}} - 1) 100$

Determine if the corrected thickness strain is greater than the start of the red or yellow zone

3.4 – Typical Example of Using the BCF Procedure

Record Raw Data:

As-received steel: $n = 0.218$ $t_0 = 0.0321$ in.

Panel thickness at study location = 0.0213 in.

Bead deformation: t (enter) = 0.0305 in. and t (exit) = 0.0213 in.

Step 1: Compute FLC₀ for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0321 \text{ in.})] 0.218 / 0.21 = 36.2\%$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0213 in.

True thickness strain: $\epsilon_t = \ln(0.0213/0.0321) = -0.410$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.410$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $(e^{0.410} - 1) 100 = 50.7\%$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 36.2%

Subtract as-measured major strain (step 2) = (-) 50.7%

As-measured Safety Margin = -14.5% (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0213/0.0305)$

BCF = -21.5%

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +50.7%

Add BCF (step 4) = -21.5%

Corrected major strain = +29.2%

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 36.2%

Subtract corrected major strain (step 5) = (-) 29.2%

Corrected Safety Margin = +7.0% (Yellow Zone)

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC₀

FLC₀ = (23.3 + 360 t) n/0.21 for thickness in inches

FLC₀ = [23.3 + 360 (.0321 in.)] 0.218/0.21 = 36.2%

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 36.2 %

True major strain = $\ln(1 + 36.2/100) = 0.309$

True thickness strain = -True major strain = -0.309

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.309} - 1) 100 = -26.6\%$

Compute thinning strain for yellow zone (assuming minor strain = 0)

Engineering major strain = 36.2 % -10% = 26.2 %

True major strain = $\ln(1 + 26.2/100) = 0.233$

True thickness strain = -True major strain = -0.233

Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.233} - 1) 100 = -20.8\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = [(0.0213/0.0321) - 1] 100 = -33.6%

Red zone start line (step 7) = -26.6%

As-measured thickness strain is above red zone line (Red Zone)

Step 9: Determine severity of corrected thickness strain

Corrected major strain (step 5) = +29.2%

True major strain = $\ln(1 + 29.2/100) = 0.256$

True thickness strain = -True major strain = -0.256

Engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.256} - 1) 100 = -22.6\%$

Yellow zone start line (step 7) = -20.8%

Corrected thickness strain is above the yellow zone line (Yellow Zone)

4.0 – Case studies from press shops

The case studies were press shop stampings with areas of the stamping that had been cold worked by bend and unbend deformation through drawbeads to a level that exceeded the FLC and yet did not show any failures. The BCF (bead correction factor) was applied to each of the case studies to show the actual damage done by the bend and unbend deformation. Five of the case studies are discussed here to highlight different production applications of the BCF.

Note: The computational work sheets for each case study are located in Appendix 8.5.

4.1 – Case Study #1 – Hood Outer at Press Show

The hood outer was being evaluated at the press show. To check the binder pressure window, the binder pressure was increased 20 percent. A split now was observed in the panel at location C (Fig.8).

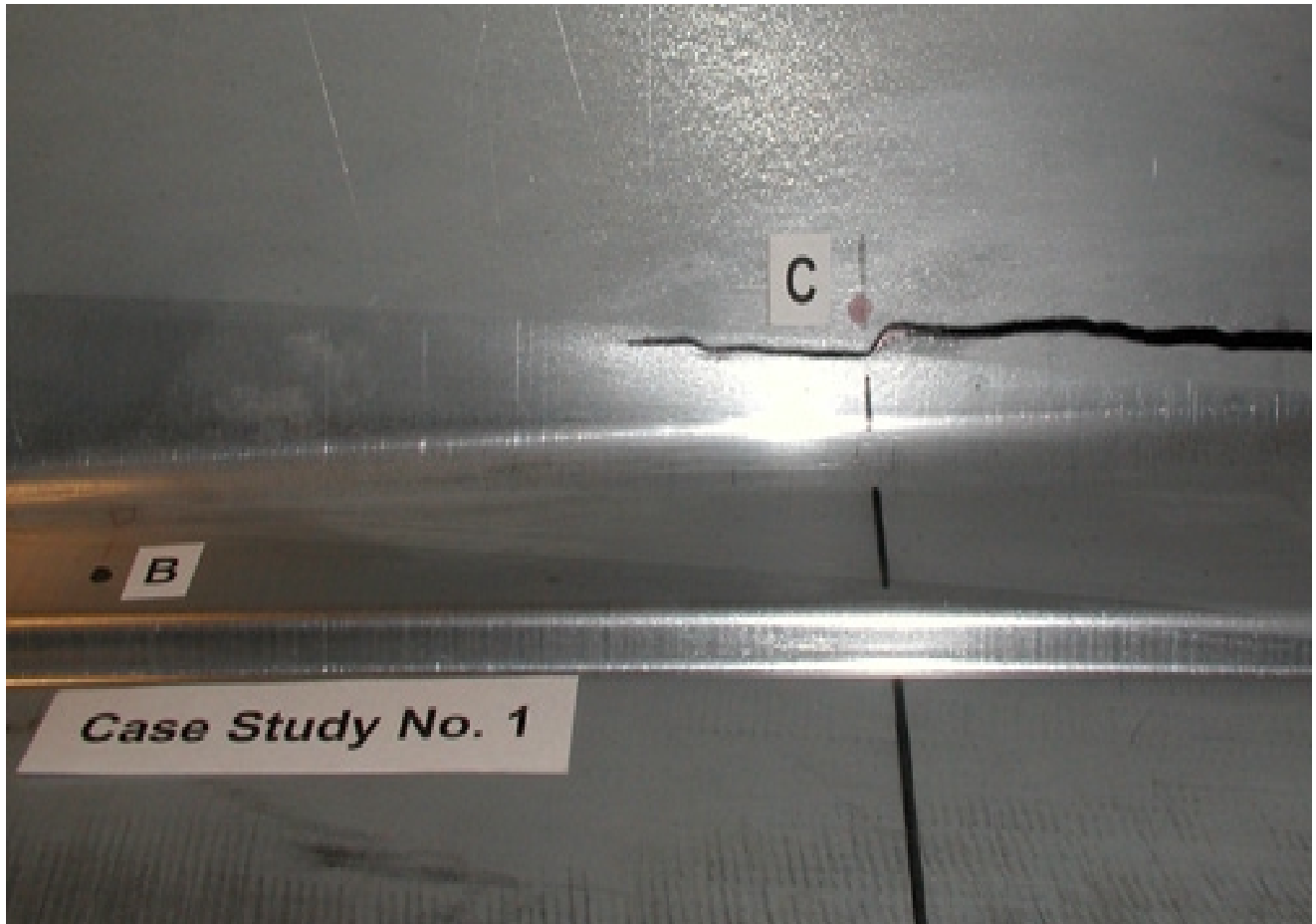


Fig. 8 – Photograph of hood outer with metal pulled through drawbeads at location B and torn metal not pulled through beads at location C.

Location B:

The deformation at location B was measured with an ultrasonic thickness gage and converted to a major strain for analysis.

Forming limit major strain = 34.5%
As-measured major strain = 46.7%
Safety margin = -12.2% (Red zone)

Red zone thinning strain = -25.7%
As-measured thinning strain = -31.8%
Safety margin = red zone

BCF = -22.8%
Corrected major strain = 23.9%
Corrected safety margin = +10.6%
Corrected safety margin is green zone

Yellow zone thinning strain = -19.7%
Corrected thinning strain = -19.3%
Corrected safety margin is green zone

The measured thinning strain for location B exceeds the -25.7% limit associated with the plane strain limit set by the FLC_0 but does not generate breakage.

Location C:

The deformation at location C was measured with an ultrasonic thickness gage and converted to a major strain for analysis.

Forming limit major strain = 34.5%
As-measured major strain = 34.9%
Safety margin = -0.4% (Red zone)

Red zone thinning strain = -25.7%
As-measured thinning strain = -25.8%
Safety margin = red zone

The BCF is not applicable at location C because the analysis point did not go through draw beads or over a tight radius. The stamping failed at location C as predicted by traditional FLC analysis.

This case study shows:

- 1) The largest measured strain (major or thickness) is not always the one that fails.
- 2) Sheet steel that has undergone severe bending and unbending through drawbeads needs to have a correction factor applied to the original measurements before a correct safety margin can be computed.
- 3) The Bead Correction Factor can be sufficiently large to drop a data point from the red zone down to the green zone.
- 4) Sheet steel that has not been subjected to bending and unbending through drawbeads failed at strain states predicted by the traditional FLC analysis.
- 5) If the binder pressure had not been increased, location C would not have failed and most attention could have been placed on the high reading at location B.

4.2 – Case Study #2 – Large Fender at Press Show

A large fender was being prepared for a press show. All incremental hits, gridded samples, and other requirements were met. The panel was ready. When the press show started the next day, the panel tore wide open in sheet steel that had been pulled through the drawbeads (Fig. 9).

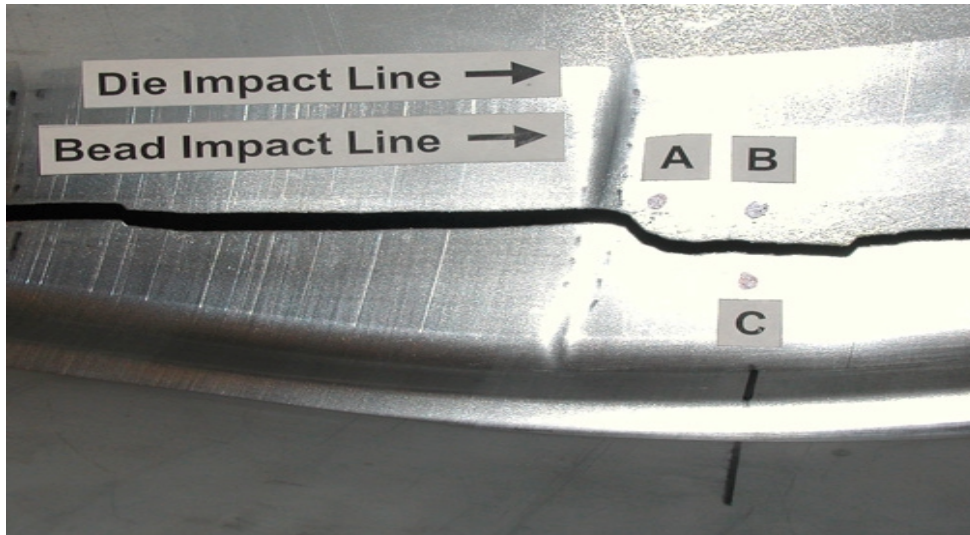


Fig. 9 – Photograph of fender with a tear occurring in metal pulled through the drawbead.

The deformation at location B was measured with an ultrasonic thickness gage and converted to a major strain for analysis.

Forming limit major strain = 34.9%
As-measured major strain = 57.5%
Safety margin = -22.6% (Red zone)

Red zone thinning strain = -25.8%
As-measured thinning strain = -36.5%
Safety margin = red zone

BCF = -18.9%
Corrected major strain = 38.6%
Corrected safety margin = -3.7%
Corrected safety margin is red zone

Red zone thinning strain = -25.8%
Corrected thinning strain = -27.9%
Corrected safety margin is red zone

Observations:

1. The analysis points were outside the actual tear location. This suggests higher level of thinning and a more negative safety margin was present at the initiation of the tear.
2. Whatever caused the very high strain had created a strain level so high that even the BCF could not remove the strain level from the red zone.
3. Even with the correction factor, the safety margin still was -3.7% and in the red zone. The resultant tear indicates that the BCF is a reasonable compensation factor and will correctly predict failures in steel pulled through drawbeads.

4.3 – Case Study #3 – Small Fender at Tool Tryout

A small fender was being examined for possible modification and rework because a forming severity in the addendum area was plotting in the red zone (Fig. 10).

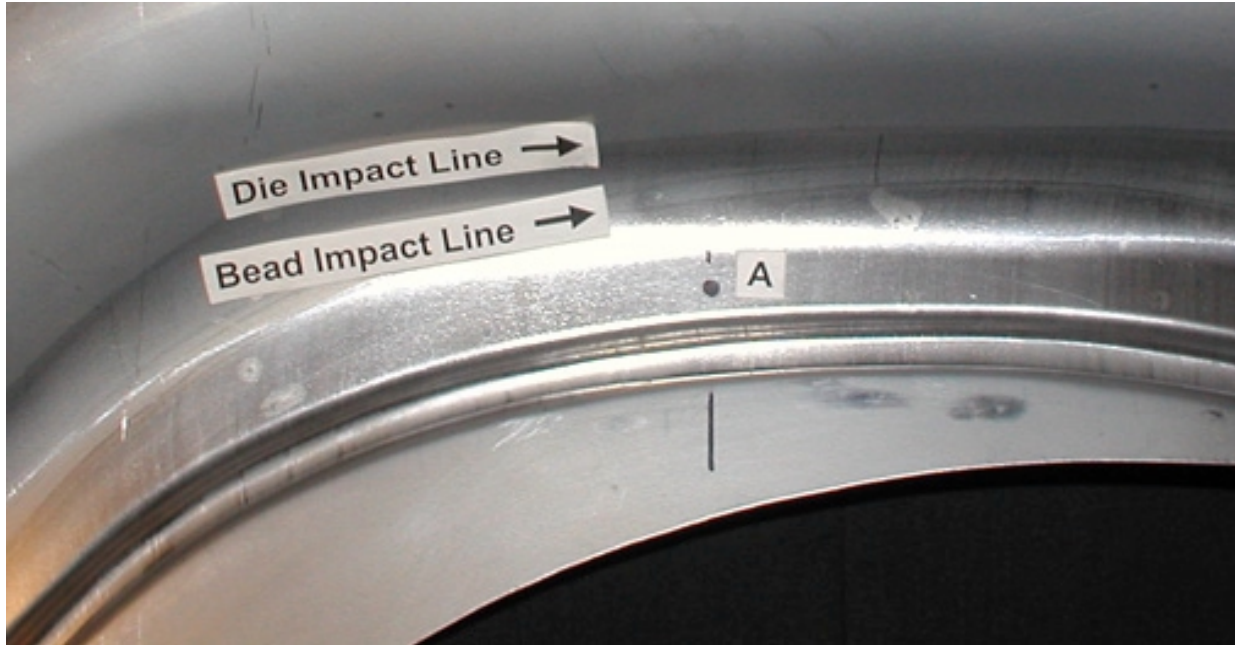


Fig. 10 – Photograph of small fender with metal at location A pulled through a drawbead.

Forming limit major strain = 31.9%
As-measured major strain = 45.2%
Safety margin = -13.3% (Red zone)

Red zone thinning strain = -24.2%
As-measured thinning strain = -31.1%
Safety margin = red zone

BCF = -20.5%
Corrected major strain = 24.7%
Corrected safety margin = +7.2%
Corrected safety margin is yellow zone

Yellow zone thinning strain = -18.0%
Corrected thinning strain = -19.8%
Corrected safety margin is yellow zone

Observations:

1. Even though no splits were being observed, the customer was uneasy about the safety margin being high in the red zone. However, the steel obviously had been pulled through the drawbeads, leading the customer to disregard the values based on past experiences.
2. While a green zone reading had not been achieved, the customer tentatively accepted the corrected yellow zone safety margin with the intent to again evaluate the area after final pre-production tryout was completed. The corrected safety margin is better than no severity reading.

4.4 – Case Study #4 – Hood Outer After One-Year Production

A large hood outer had been in production for over a year without any failures (Fig. 11). However, during the initial final die tryout, all four draw-walls had shown high negative safety margins or red zone conditions. Based on prior plant experience with similar hoods, a decision was made to begin production with the panel. The hood was submitted to the A/S-P Team for evaluation under the new BCF procedures.

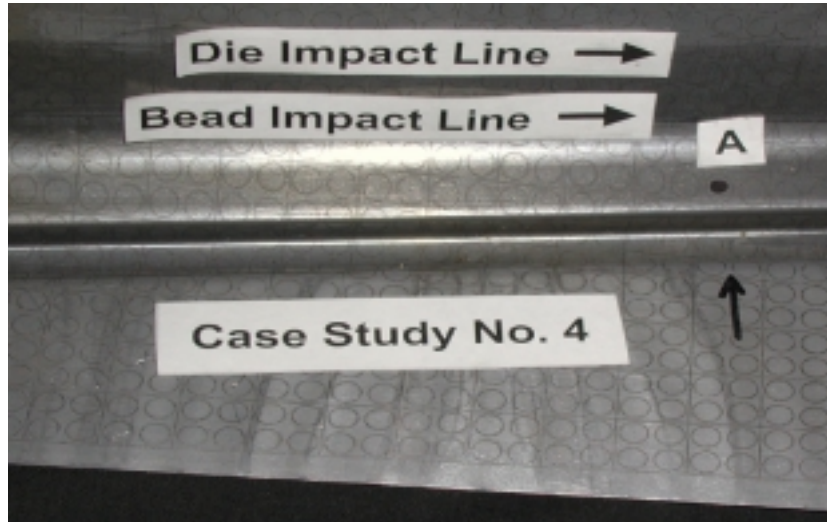


Fig. 11 – Photograph of a production hood with metal at location A pulled through a drawbead.

Forming limit major strain = 36.2%
As-measured major strain = 50.7%
Safety margin = -14.5% (Red zone)

Red zone thinning strain = -26.6%
As-measured thinning strain = -33.6%
Safety margin = red zone

BCF = -21.5%
Corrected major strain = 29.2%
Corrected safety margin = +7.0%
Corrected safety margin is yellow zone

Yellow zone thinning strain = -20.8%
Corrected thinning strain = -22.6%
Corrected safety margin is yellow zone

This case study shows:

1. Production was started even though the worst safety margin of -14.5% was measured on one side of the hood. Similar readings were found on all four sides of the hood and in several locations on each side. This shows the draw bead restraining forces were well balanced around the hood.
2. The reason for the absence of production splits is due to a corrected safety margin of $+7\%$ and a stable production process.
3. While not quite in the green zone, the corrected safety margin of $+7\%$ is more indicative of the forming severity and potential production performance of this hood than the severe as-measured safety margin of -14.5% .

4.5 – Case Study #5 – Bodyside Outer in Early Tool Tryout

The tooling for the bodyside had just been built and was undergoing the required forming severity analysis. High strain values but no failures had yet been observed under tryout conditions (Fig. 12).

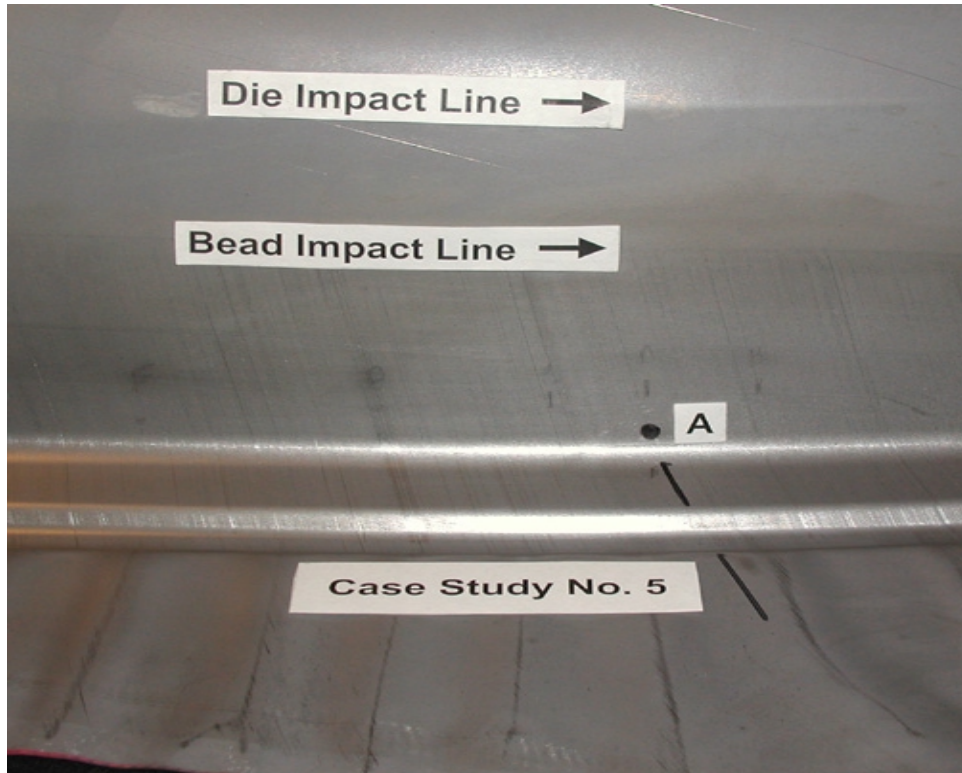


Fig. 12 – Photograph of bodyside with metal at location A pulled through a drawbead.

Forming limit major strain = 35.5%
As-measured major strain = 47.1%
Safety margin = -11.6% (Red zone)

BCF = -18.4%
Corrected major strain = 28.7%
Corrected safety margin = +6.8%
Corrected safety margin is yellow zone

Red zone thinning strain = -26.2%
As-measured thinning strain = -32.0%
Safety margin = red zone

Yellow zone thinning strain = -20.3%
Corrected thinning strain = -22.3%
Corrected safety margin is yellow zone

Observations:

1. After applying the BCF, the concerns about the severity of the panel were reduced. The decision was made to proceed with normal tryout procedures without making modifications to area A. This area would again be evaluated further in the tool tryout cycle.

2. Of the five case studies analyzed for this project, the lowest BCF (-18.4%) was obtained on this stamping. This BCF was generated by a thinning strain of -26.5% created as the metal bent and unbent through the beads.

5.0 – Implementation Issues

5.1 – Role in Press Shop

The goal of the research program was to eliminate false severity values for sheet steel that underwent bend and unbend deformation through drawbeads and/or sliding over tight die and punch radii. The research showed that the severity readings were artificially high for these modes of deformation. This would prompt tool modifications to reduce the severity of drawbead deformation, increase die radii, or even increase punch radii. By correctly assessing the forming severity, unnecessary die modifications could be eliminated in die tryout with the corresponding reduction in die tryout time and cost.

Even more important, and not always obvious, is the affect on panel quality. Reducing the severity of drawbead deformation can create less stress applied to the product sheet metal. Often the result is less deformation and less “tightness” in the body of the panels. Dent resistance is decreased. Bake hardenable steel may not reach minimum strain needed to trigger the hardening effect.

The research program covered a wide range of steels, including four AKDQ (aluminum-killed, draw quality), two BH210 (bake hardenable), two HSLA (high-strength, low-alloy), and one DP600 (dualphase). Of the nine lots of steel evaluated, three were bare cold-rolled, four electrogalvanized, and two hot-dipped galvanized. On the underlying mechanisms for the measured enhanced FLC effect, the concept should apply to other steel grades with similar microstructures and cyclic stress-strain behavior at high strain amplitudes (5). However, the Research Report indicated caution in applying this work to TRIP or complex phase steels. In addition, commercial dualphase steels exhibit a range of microstructures. Therefore, some dualphase steels may not reproduce the results obtained in the research program.

Bead configurations included round bead, double round beads, square beads, and double square beads. Bead width ranged from 4 to 10.8 mm (0.16 to 0.43 in.). Bead penetration and back tensions were changed to increase the number of test conditions for given beads.

The two levels of sheet thickness were 0.7mm (0.028 in.) and 1.2 mm (0.048 in.). With regard to sheet thickness, it seems reasonable that the applicable thickness range can be extended beyond the 0.7 to 1.2 mm (0.028 to 0.048 inch) range evaluated experimentally (5). On a speculative base, the Research Report suggests that extending the press shop application to a thickness range of 0.55 to 1.65 mm (0.021 to 0.065 inches) would seem reasonable.

The experimental data acquired in the research program suggest that at large net thinning strains there are indications of non-linearity. Therefore, for true thinning strains greater than negative 0.3 (engineering thinning strains greater than negative 26%) the BCF values are to be considered conservative. The Research Report also recommends not using the BCF procedure for true thinning strains greater than negative 0.4 (engineering thinning strains greater than negative 33%).

The research program also indicated that the same analysis could be used for metal flow off a post or punch. However, as the R/t (bending radius to sheet thickness) increases, the effect of the BCF diminishes rapidly. Therefore, the corrections are targeted for R/t ratios less than five. The bend radius is the post entry radius. In using equation 5, thickness would be measured for material that flowed off the post. However, a conservative approach for calculating net thinning strain would be to use the thickness of the material prior to its moving over the entry radius on the post, which would be the deformed thickness instead of the as-received thickness.

5.2 – Required Steel Characteristics

Two steel characteristics are required for the circle grid / FLC analysis. These are the initial sheet metal thickness and the terminal n value. Both are used to compute the FLC_0 value that fixes the height of the FLC. The accuracy of the FLC_0 computation depends on accurate values of metal thickness and terminal n for the blank on which the grid analysis is being performed.

Ideally the metal thickness should be measured from the flat blank being gridded and at the critical location. Ordered thickness or measurements from the head or tail of the coil are often quite different than the actual value for a blank taken from the body of the coil. Attempting to acquire the initial blank thickness from the deformed stamping may or may not be successful, depending on the amount of deformation throughout the stamping.

Even greater importance is placed on obtaining an accurate terminal n value for the blank being gridded. The equation for FLC_0 is:

$$FLC_0 = (23.3 + 360 t) n/0.21 \text{ for thickness in inches}$$

$$FLC_0 = (23.3 + 14.2 t) n/0.21 \text{ for thickness in mm.}$$

It is evident from the above equations that the n value is a major factor in determining FLC_0 , the allowable major strain, and the safety margin for both the as-measured major strain and the bead corrected major strain. A plot of instantaneous n value as a function of tensile strain is the best method to determine the n value plateau at high levels of strain. A more practical tensile test method for approximating the terminal n value is to determine the n value between 10 percent stretch and 20 percent stretch or between 10 percent stretch and the ultimate tensile strength (uniform elongation).

5.3 – Role in Computer Simulation

The use of enhanced FLCs is more complex when applied to FEA computations. The Research Report (5) indicated that equations 1 and 2 (duplicated below) were applicable for use with FEA modeling.

$$\text{Equation 1) } \quad \Delta FLC_0 = (41.7 + 104 \text{ BTR}) \text{BSF}^{1.54}$$

$$\text{Equation 2) } \quad \epsilon_t = (0.624 + 1.20 \text{ BTR}) \text{BSF}^{1.27}$$

where BTR is the Back Tension Ratio, BSF is the Bending Strain Factor, and ϵ_t is the thinning strain through the drawbead or drawbead and die radius combination.

Concerns with application of the above equations are:

1. The BTR or Back Tension Ratio is difficult to determine prior to actual tool building.
2. The BTR is affected by the stop block (kiss block) clearances and resultant sheet wrinkling when the shape of the blank edge becomes uneven because of insufficient metal control.
3. The BTR is affected by the spotting of the blankholder when stop blocks are not used. This spotting pattern not only can change the BTR from point to point around the perimeter, but also can cause major changes as the forming process progresses.
4. For dies without stop blocks, changes in the coefficient of friction and thickness profile of the blank can strongly affect the BTR.
5. To calculate the BSF the actual bending radii of the sheet metal traveling through the drawbead is required. As the IRDI study showed and is depicted in both the Research Report (5) and the video segments stored on IRDI data CD # 2, the shape of the sheet metal can deviate greatly from the traditional analysis of flow from radius tangent to radius tangent.
6. In production dies, drawbead radii may not be uniform in size, shape, or penetration, especially after completion of die tryout.
7. In the production environment, bending of the die, upper platen, lower bolster, and other components can further generate unpredictable changes in the bead deformation. An additional effect is the placement of cushion pressure pins.

In addition, most FEA formability analyses treat drawbeads as a line of force. As a result, thinning strain is underestimated and the use of the BCF would result in an additional overestimate of formability. Therefore, additional research and changes to FEA procedures are required before this correction factor becomes part of routine FEA formability analyses.

However, these concerns do not limit press shop application of the BCF. While the contribution of each individual variable cannot be identified, their total effect is included by measuring the actual increment of sheet thinning due to the metal passing through the drawbeads and/or die radii.

6.0 – Applications for assessment of drawbead thinning

6.1 – Die Source and Plant Die Tryout

1. Applying the Bead Correction Factor (BCF) can reduce the severity of metal flowing through the drawbead from the red zone down to yellow or even the mandatory green zone. This can minimize added work, time, and cost to bring the stamping into the mandatory green zone specifications
2. By downgrading the forming severity of the metal that has flowed through drawbeads, additional drawbead restriction can be generated to increase stretch in the body of the stamping – particularly in low sweep panels with low amounts of stretch.
3. Drawbeads of constant geometry and penetration around the perimeter are intended to generate constant restraining forces. The constancy of the restraining forces can be evaluated by measuring the increase in thinning strain of metal flowing through the beads.
4. Reduced panel severity can help when implementing engineering changes.
5. The BCF can be applied to flow of metal over punch radii, especially for punches with r/t (radius/sheet thickness) ratio less than 5.

6.2 – Production Monitoring

1. Previously most of the stamping could use traditional forming severity as a process-monitoring index. Now the metal flowing through the drawbeads also can be monitored for forming severity.
2. As dimensional consistency of stampings becomes more important, the variation in restraining forces generated by the drawbead, blank position, kiss blocks, and other parameters controlling metal flow into the die opening become more important. Tracking the severity of deformation of metal flowing through the drawbeads is another measure of process consistency.

6.3 – Troubleshooting Opportunities

1. The severity of the metal that has been pulled through the drawbeads can be tracked for changes that cause other stamping problems. The tracking can be limited to only trouble occurrences or a routine SPC type of process monitoring.
2. Ultrasonically measuring the thickness strain accumulated by the metal passing through the beads can detect a change in other process parameters. Any change means the drawbead restraining force has changed. Some of possible causes are drawbead wear, drawbead modification, stop (kiss) block wear, change in shims on the stop blocks, etc.
3. A reduction in strain levels in the face of the stamping often can be traced to a reduction in restraining forces generated by the drawbeads.

7.0 – List of references

1. Keeler, S. P., "Circular Grid System – A Valuable Aid for Evaluating Sheet Metal Formability," SAE Paper No. 680092 (January 1968).
2. Goodwin, G. M., "Application of Strain Analysis to Sheet Metal Forming Problems in the Press Shop," SAE Paper No. 680093 (January 1968).
3. Hecker, S.S., "A Simple Forming Limit Curve Technique and Results on Aluminum Alloys," in *Sheet Metal Forming and Formability*, Proceedings of the 7th Biennial Congress of the IDDRG, Amsterdam, (October 1972), pp 5.1 – 5.8.
4. Keeler, S. P. and Brazier, W. G., "Relationship Between Laboratory Material Properties and Press Shop Formability," Proceedings of Microalloy 75, New York, NY, (1977), pp.517-530.
5. Levy, B.S. and Green, D. E., "Enhanced Forming Limit Diagram – Project Team Research Report," Auto/Steel Partnership, Southfield, MI, (2002), Available at <www.a-sp.org>.
6. Stoughton, T.B. "A general forming limit criterion for sheet metal forming," Int. Journal of Mechanical Sciences, Vol. 42, 2000, pp. 1-27.
7. Auto/Steel Partnership, "The Bead Correction Factor," A Training Manual for the Press Shop, Auto/Steel Partnership, Southfield, MI, (2002), Available at <www.a-sp.org>.

8.0 – Appendices

The following appendices are provided for additional information on some of basic techniques utilized in Circle Grid Analysis and Forming Limit Curves. In addition, the Computational Work Sheets for the Bead Correction Factor case studies are included.

8.1 – Strain Measurement Techniques

Numerous methods have been used to measure deformation in a formed stamping. The scribe square method was the forerunner of the current circle grid method. Both methods are described and compared. Today ultrasonic thickness measurements provide quick access to additional strain information.

8.1.1 – Scribed Square Grids

One of the first attempts to measure deformation was the scribed square system. Here the sheet surface was inked and then marked with points spaced every inch along the rolling and transverse directions. Lines connecting the points were scribed into the surface of the sheet metal to generate a series of one-inch squares. Various measurements of the deformed square were made. The most common measurement was the increase in surface area.

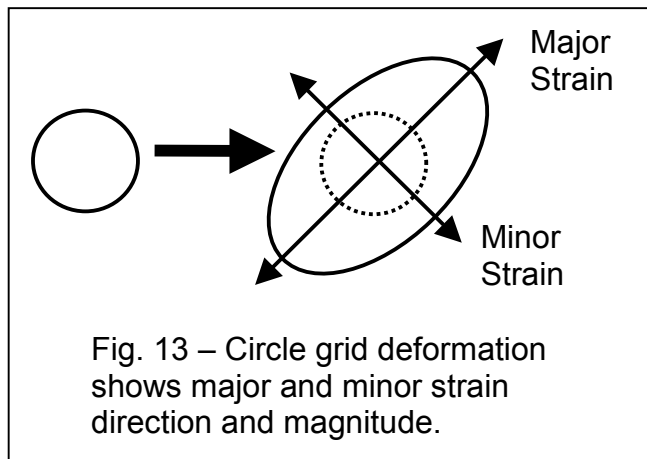
Several problems were encountered when using the scribed square system. The one-inch gage length averaged all deformation changes within the scribed lines. The squares were too large to define the severe strain gradients found in most stampings. Many times one or more scribe lines were much deeper than the other lines, leading to premature failure along one of the lines. The actual production failure mode was no longer operative and could not be measured.

Even worse, the squares rarely could be oriented with the direction of strain because of the changing direction of strain at different locations in the stamping. This resulted in deformed squares that were hard to understand and harder to compute for the two principal strain values and directions.

Today various 3-D camera systems can easily define the line intersections or nodes in space and compute the two principal strain values and directions through different algorithms.

8.1.2 – Circle Grids

The problems with the scribed squares are solved with the introduction of the circle grid system. Here the square grids are replaced by small diameter circles imprinted on or into the surface of the sheet metal. The circles are non-directional and are properly oriented for any direction of strain in the part. The size of the circles is small with a common diameter of 0.1 inch (2.5 mm), which allows for detection of sharp strain gradients. Techniques to electrochemically etch the circles into the surface of the sheet metal are used to avoid the deep surface scribing common to the square grids.



The circles deform into ellipses (Fig. 13). The longest axis of the ellipse is the major strain and is always positive. The axis perpendicular to the longest axis is the minor strain, which can be positive, zero, or negative.

8.1.3 – Grid Application

The circle grids can be applied to the sheet metal by many techniques. The most common technique used today is electrochemical etching. An electrical

stencil is made that performs in the same manner as a paint stencil. A random fiber mat is covered with a non-conductive film. A negative of the circle pattern is placed over the film and exposed. When developed, the film is removed from the areas where the circles are to be etched. This creates an electrical stencil.

A pad soaked in electrolyte is placed on top of the stencil and an electrode applies current from the electrode, through the stencil, and into the sheet metal only where the circle pattern allows the current to flow. The current and electrolyte cause the circle pattern to be etched into the surface of the blank. This allows the grid to withstand very severe deformation of the sheet surface without being removed.

For non-conductive blanks, such as prepainted sheet steel, a photographic process similar to the one used to make printed circuit boards is used. The surface of the blank is coated with a photosensitive liquid and allowed to dry. A negative of the grid pattern is placed on the photosensitive surface and exposed to ultraviolet light. This sets the areas of the film that are not to be removed. When developed, the film remaining on the blank is the grid pattern. The remaining film is then dyed a dark color to be visible. A common name for the process is photo resist.

The problem with all grid-imprinting processes, except electrochemical etching, is the grid resides on top of the blank. This makes it vulnerable to removal by the tools during the forming process.

8.1.4 – Grid Measurements

The most common method to measure the circle grids is a flexible, sheet plastic tape with diverging lines. These lines are calibrated at intervals with percent engineering strain. Of course, the correct tape calibration must be matched to the correct initial circle diameter. The tape is lightweight, inexpensive, and conforms to various radii and curvatures for more accurate measurements.

Small stampings or small sections of stampings can be placed under a microscope containing a calibrated reticule. The dimensions of the ellipse are determined visually and converted into strain values.

Electronic cameras can be used to measure circle grids. In this case the circles are printed on the blank as solid dots. After deformation, the solid ellipse is scanned to define the edges of the ellipse. A best-fit mathematical ellipse is then created to match the edges. The major and minor strains are calculated from the dimensions of the ellipse.

8.1.5 – Sheet Thickness Measurements

Direct measurement of thickness strains is often desired. Ultrasonic thickness gages are excellent for this purpose. Comparing the thickness of the deformed metal in the stamping with the original thickness of the as-received sheet allows computation of thickness strain anywhere on the part. If a second strain is known at that same location (a major or minor strain), the constancy of volume computation (section 8.4) allows determination of the missing strain. Measurement of all three strains (major, minor, and thickness) can be used to check the validity of the strain measurements.

A major advantage of using the ultrasonic thickness gage for strain measurement is ease of repetitive measurements over time for the same location on identical stampings. The blanks do not have to be gridded in advance and all stampings can be returned to production. There are no stampings with grids that must be scrapped. These ultrasonic measurements are excellent for process monitoring, die tryout, and other tracking functions.

A second option for thickness strain measurements is to cut the sheet metal at desired locations and use micrometers or other devices to physically measure the sheet thickness.

8.2 – Construction of FLCs

The foundation of strain severity measurement and tracking in sheet metal stampings today is the Forming Limit Curve (FLC).

8.2.1 – Definition of the FLC

The forming limit curve defines the strain state at which conditions are met for the onset of a local neck in a sheet of metal (Fig. 3). This local neck is not the diffuse or width neck generated during a tensile test, but is a thickness neck that is the precursor to fracture.

8.2.2 – Construction of the FLC

The major and minor strains measured from the ellipse directly over the incipient neck are plotted in strain space. Sometimes the start of the neck cannot be obtained. In this case major and minor strain combinations for non-necked specimens are plotted as closed circles and those with a well-defined local neck are plotted as open circles (Fig. 14). The FLC is drawn below the open circles. Once the local neck begins, deformation stops in the remainder of the specimen and concentrates in the local neck. Soon a through thickness failure occurs. By varying the minor strain value, a wide range of strain states can be created experimentally for defining the formation of a local neck and plotted in the strain space.

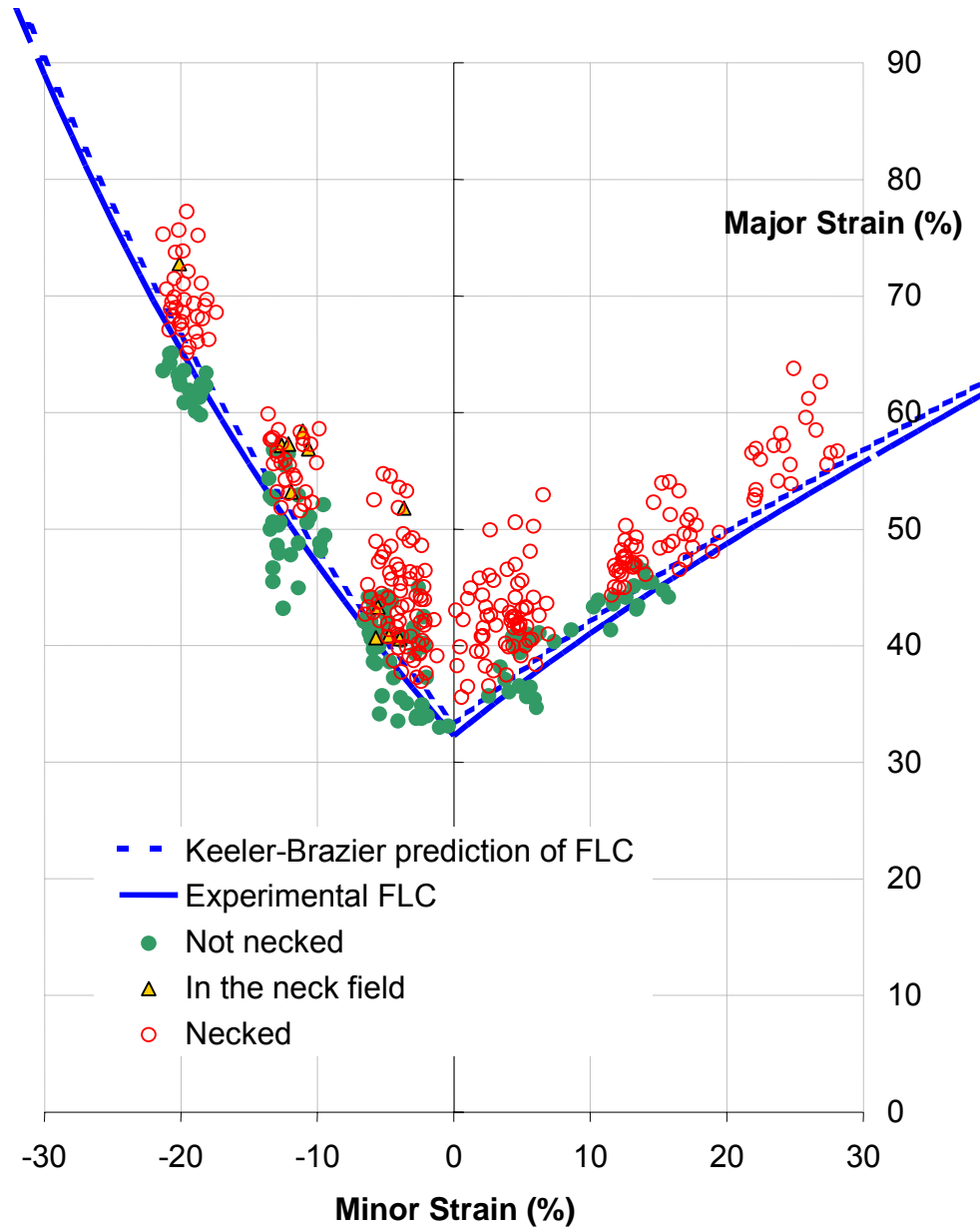


Fig. 14 – A typical FLC created by IRDI for the A/S-P FLC project (5)

8.2.3 – FLC Test Specimens

Two different specimen configurations typically are used to vary the minor strain state.

The first configuration utilizes seven-inch long strips of metal locked at the binder and stretched over a four-inch (100 mm) diameter hemispherical punch. By varying the widths of the strips from one inch (25 mm) to seven inches (175 mm), a large number of strain states can be generated to define the entire strain space. Historically this configuration has been used for most of the FLCs developed to date.

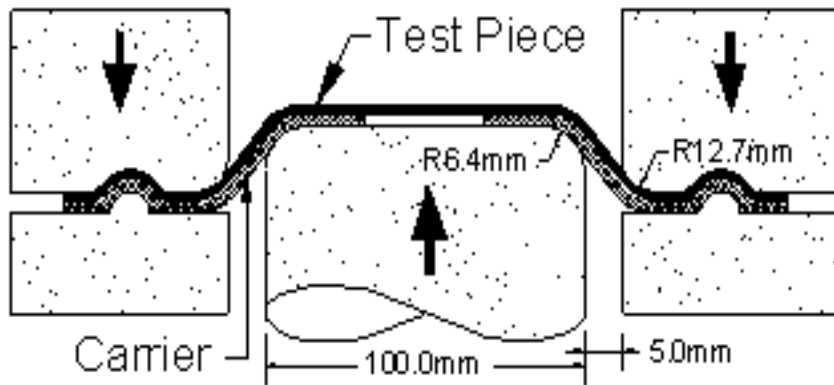


Fig. 15 – Schematic of the Marciniak Double Blank Test showing the test piece and the carrier blank with the center hole (5)

The second configuration is a flat test blank placed on top of a carrier blank containing a central hole (Fig. 15). These two blanks are locked at the parameter and deformed with a flat punch. This is known as the Marciniak Double Blank test and was used for the research conducted during the A/S-P research program on forming limits of metal subjected to bend and unbend strains through draw beads and die radii.

8.2.4 – A/S-P Research Procedures for FLC Determination

Details of the IRDI procedure used for the A/S-P Program are reproduced below from the Research Report by B. Levy and D. Green (5).

FLCs were determined using the Marciniak Double Blank method in a hydraulic press at a constant punch velocity. The schematic of the Marciniak Double Blank test is shown in Figure 15. The die set includes a binder and a 100 mm diameter flat bottom punch with a 6.4 mm punch profile radius. The working surface of the punch is hardened and non-directionally polished with a 1200 grit-polishing compound. Clearance between the binder and the punch is 5.0 mm per side. The binder has a lock bead and a 12.7 mm die entry radius.

The Marciniak Double Blank method uses a carrier blank that is placed under the test piece. The carrier blank has a centrally located hole. The test piece is placed on top of the carrier blank and the two pieces are securely clamped in the die. As stretching proceeds, the hole in the carrier blank increases in diameter allowing it to more easily slide over the punch profile radius. The friction between the carrier blank and the test piece pulls the test piece over the punch radius with the deformation centered over the hole in the carrier blank. The extent of deformation is controlled by punch travel, and the blank width determines minor strain. Blank length is approximately 200 mm and blank widths ranging from 100 to 130 mm were used for evaluating the left side of the FLC. Two or three sample widths were used in determining the left side of the FLC. In determining the right side of the FLC, blank widths of up to 200 mm were used.

All test samples were electrochemically etched prior to forming the channel draw pieces with a grid of 2.54 mm diameter circles. Undeformed grids are periodically measured 3 times by an operator. Using this quality control process, it was found that the as-applied circle diameter is 2.54 ± 0.076 mm.

Holes in the carrier blanks were machined to minimize edge damage and avoid splitting before the end of a test. Carrier blank hole diameters are 50.8 mm for test pieces with widths between 100 and 130 mm. For larger widths, the carrier blank hole diameter is 34 mm.

In running tests, lubrication is applied to the surface of the carrier blank in contact with the punch. The carrier blank, test piece combination is aligned and clamped in the die with sufficient binder force so that it is locked on the binder.

Tests were terminated at a punch height that corresponded to the onset of local necking. Punch height is controllable to a resolution of 0.03 mm. To provide sufficient samples for evaluation, 7 or 8 test pieces were produced at each blank width.

The Marciniak Double Blank tests were carried out for each of the as-received materials and also for the material taken from the sidewalls of channel sections prestrained under various conditions. In evaluating test pieces, a light oil film was applied to the surface to enhance the appearance of surface features. Identification of local necks was done visually. The first observable stage in neck development is surface roughening. Such roughening is not necking. As deformation continues, a regular pattern of very shallow, narrow, long depressions form in the central region of samples. These depressions are a field of incipient necks. Samples with this condition were evaluated to determine critical local necks. These critical local necks are the failure criteria in this study. Test pieces deformed beyond this point were not used to determine FLCs.

After samples were removed from the press, deformed electro-etched circles were determined to be safe or necked and identified inside the circle with a light pencil mark. In most cases, circles lie across a critical local neck. However, in some cases, particularly for narrow samples, deformed circles do not lie across a critical local neck, but were within a field of necks. Such deformed circles were classified separately.

Strain measurement on identified deformed circles was done by placing a test piece on an X-Y translating table with adjustable Mitutoyo Digital Verniers that have an accuracy of ± 0.001 mm. A Leica MZ8 optical microscope is focused on the X-Y translating table. A digital camera with its horizontal and vertical axes parallel to the axes of the X-Y table is used to produce an image. This image is displayed on a 1270 mm television monitor that produces a magnification of about 140X.

Deformed circles are measured using perpendicular cross hairs that intersect at the center of the television monitor. Each axis of the deformed circle (ellipse) is measured sequentially by visually aligning the cross hairs on the monitor with the center of the grid line on one side of the ellipse and then displacing the X-Y translating table with the verniers until the cross hairs are aligned with the center of the grid line on the other side of the ellipse.

For each sample width (strain path), 33 to 67 deformed circles were measured which provides sufficient data to produce statistically valid FLCs. In plotting FLCs, the left side is assumed to be a line of constant thickness. A typical FLC is shown in Fig. 14. Since all necked data points must lie above the FLC, accuracy in determining individual data points is important to accurately determining FLCs. This is particularly important when sample sizes are large because the more data points, the more likely it is to obtain a low value of minor and/or major strain. Thus, the repeatability and reproducibility of the strain measurement system has an effect on the accuracy of FLC results.

8.2.5 – Computing FLC₀

Construction of FLCs for as-received steels used in the press shops can be simplified by using a standard shape FLC (Figs. 2 and 14) and an FLC₀ determined by the formulas:

$$FLC_0 = (23.3 + 360 t) n/0.21 \text{ for thickness in inches}$$

$$FLC_0 = (23.3 + 14.2 t) n/0.21 \text{ for thickness in mm.}$$

To use the equation, the work hardening exponent (n value) and the sheet thickness of the steel being used are required. The resulting FLC₀ value is then used to set the height of the standard shaped FLC.

8.3 – Determination of Forming Severity

A key to practical use of FLCs in the press shop is an easy method to define forming severity or determine how close the stamping is to the edge of the cliff. One could record the major/minor strain combination of the stamping and the major/minor strain combination of the nearest point on the FLC as one measure of forming severity. However, a single number for forming severity is more desirable for recording, control chart plotting, trend analysis, and other process tracking procedures.

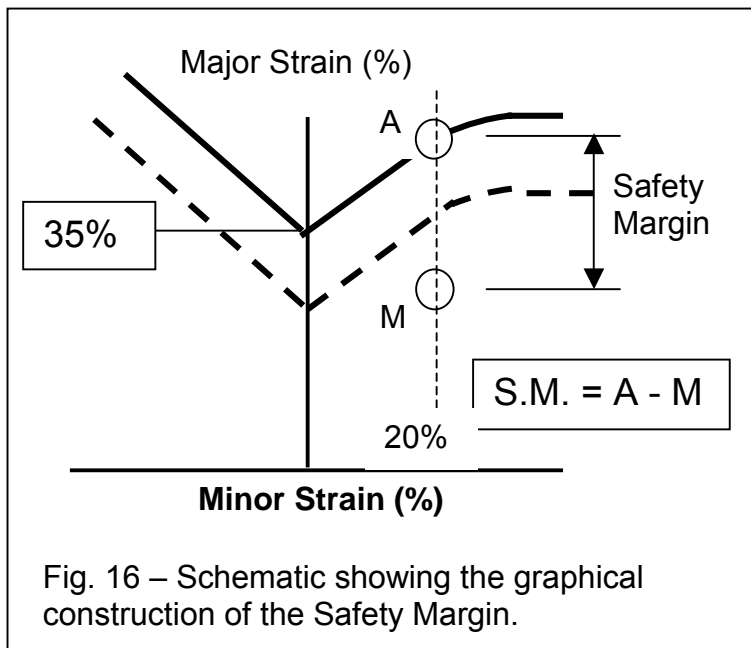


Fig. 16 – Schematic showing the graphical construction of the Safety Margin.

One common method of assigning forming severity is subtracting the measured major strain in the stamping from the allowable major strain. This is shown graphically in Fig. 16. The following procedure is used:

1. Construct the FLC for the steel being used. Assume in Fig. 16 that an FLC₀ value of 35 percent was determined from the work hardening exponent (n) and the sheet thickness according to section 8.2.5 and the height of the FLC is set accordingly.

2. Obtain the major and minor strain values for the data point being evaluated.
3. Extend a vertical line from the measured minor strain value (20 percent for this example) to the upper line (red zone) of the FLC from step 1. The intersection of the vertical line and the upper line is the Allowable Major Strain (A).
4. Plot the measured data point (major- minor strain combination) on the chart. This data point is the Measured Major Strain (M).
5. Subtract the Measured Major Strain from the Allowable Major Strain. The resultant is the Safety Margin or S.M. = A – M.

8.4 – Constancy of Volume Calculations

Sheet metal follows the constancy of volume rule. An extension of this rule means that knowing two of the principal strains (major, minor, thickness) allows computation of the third principal strain. Another application of the constancy of volume rule is checking whether the physical measurements of the three principal strains are consistent with each other.

8.4.1 - Analysis in Engineering Strains:

$$\text{Engineering strain } \epsilon_1 = [(\ell_f - \ell_0) / \ell_0] \times 100$$

$$\text{Constancy of volume equation: } (\epsilon_1 + 1) (\epsilon_2 + 1) (\epsilon_3 + 1) = 1$$

where strains 1,2, 3 can be major, minor, thickness

8.4.2 - Analysis in True Strains:

$$\text{True strain } \epsilon_1 = \ln(1 + \epsilon_1) = \ln(\ell_f / \ell_0)$$

$$\text{Constancy of volume equation: } (\epsilon_1 + \epsilon_2 + \epsilon_3) = 0$$

where strains 1,2, 3 can be major, minor, thickness

The constancy of volume computation in true strains is very much easier than the computation in engineering strains. Therefore, less benefit is derived from a constancy of volume nomograph in true strains.

8.5 – Computational Work Sheets for Case Studies

The following pages show the computations necessary to determine the Bead Correction Factor (BCF) and the corrected forming severity for each of the case studies discussed in the body of this report.

8.5.1.1 - Case Study No. 1 – Hood Outer – Area B

Record Raw Data:

As-received steel: $n = 0.212$ $t_0 = 0.0302$ in.

Panel thickness at study location = 0.0206 in.

Bead thinning: t (enter) = 0.0301 in. and t (exit) = 0.0206 in.

Step 1: Compute FLC_0 for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0302 \text{ in.})] 0.212 / 0.21 = 34.5\%$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0206 in.

True thickness strain: $\epsilon_t = \ln(t_{\text{meas}} / t_0) = \ln(0.0206 / 0.0302) = -0.383$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.383$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $(e^{0.383} - 1) 100 = 46.7\%$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 34.5%

Subtract as-measured major strain (step 2) = (-) 46.7%

As-measured Safety Margin = -12.2% (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0206 / 0.0301)$

BCF = -22.8%

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +46.7%

Add BCF (step 4) = -22.8%

Corrected major strain = +23.9%

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 34.5%

Subtract corrected major strain (step 5) = (-) 23.9%

Corrected Safety Margin = +10.6% (Green Zone)

8.5.1.1 -Case Study No. 1 – Hood Outer – Area B – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$FLC_0 = (23.3 + 360 t) n/0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0302 \text{ in.})] 0.212/0.21 = 34.5\%$

$FLC_0 = 34.5\%$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 34.5 %

True major strain = $\ln(1 + 34.5/100) = 0.296$

True thickness strain = -True major strain = -0.296

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.296} - 1) 100 = -25.7\%$

Compute thinning strain for yellow zone

Engineering major strain = 34.5 % -10% = 24.5 %

True major strain = $\ln(1 + 24.5/100) = 0.219$

True thickness strain = -True major strain = -0.219

Yellow engineering. thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.219} - 1) 100 = -19.7\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0206/0.0302) - 1] 100 = -31.8\%$

Red zone start line (step 7) = -25.7%

As-measured thickness strain is above red zone line (Red Zone)

Step 9 Determine severity of corrected thickness strain

Corrected major strain (step 5) = +23.9%

True major strain = $\ln(1 + 23.9/100) = 0.214$

True thickness strain = -True major strain = -0.214

Corrected engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.214} - 1) 100 = -19.3\%$

Yellow zone start line (step 7) = -19.7%

Corrected thickness strain is below the yellow zone line (Green Zone)

8.5.1.2 - Case Study No. 1 – Hood Outer – Area C

Record Raw Data:

As-received steel: $n = 0.212$ $t_0 = 0.0302$ in.

Panel thickness at study location = 0.0224 in.

Bead deformation: t (enter) = N.A. and t (exit) = N.A.

Step 1: Compute FLC0 for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0302 \text{ in.})] 0.212 / 0.21 = \mathbf{34.5\%}$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0224 in.

True thickness strain: $\epsilon_t = \ln(0.0224/0.0302) = -0.299$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.299$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $(e^{0.299} - 1) 100 = \mathbf{34.9\%}$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 34.5%

Subtract as-measured major strain (step 2) = (-) 34.9%

As-measured Safety Margin = - 0.4% (Red Zone)

The steel at location C was not pulled through the beads.

Therefore no correction factor (BCF) can be applied.

8.5.1.2 - Case Study No. 1 – Hood Outer – Area C – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$FLC_0 = (23.3 + 360 t) n/0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0302 \text{ in.})] 0.212/0.21 = 34.5\%$

$FLC_0 = 34.5\%$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 34.5 %

True major strain = $\ln(1 + 34.5/100) = 0.296$

True thickness strain = -True major strain = -0.296

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.296} - 1) 100 = -25.7\%$

Compute thinning strain for yellow zone

Engineering major strain = 34.5 % -10% = 24.5 %

True major strain = $\ln(1 + 24.5/100) = 0.219$

True thickness strain = -True major strain = -0.219

Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.219} - 1) 100 = -19.7\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0224/0.0302) - 1] 100 = -25.8\%$

Red zone start line (step 7) = -25.7%

As-measured thickness strain is above red zone line (Red Zone)

The steel at location C was not pulled through the beads.

Therefore no correction factor can be applied

8.5.2 - Case Study No. 2 – Large Fender – Area C

Record Raw Data:

As-received steel: $n = 0.212$ $t_0 = 0.0312$ in.

Panel thickness at study location = 0.0198 in.

Bead deformation: t (enter) = 0.0315 in. and t (exit) = 0.0230 in.

Step 1: Compute FLC0 for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0312 \text{ in.})] 0.212 / 0.21 = 34.9\%$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0198 in.

True thickness strain: $\epsilon_t = \ln(0.0198/0.0312) = -0.454$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.454$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $(e^{0.454} - 1) 100 = 57.5\%$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 34.9%

Subtract as-measured major strain (step 2) = (-) 57.5%

As-measured Safety Margin = -22.6% (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0230/0.0315)$

BCF = -18.9%

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +57.5%

Add BCF (step 4) = -18.9%

Corrected major strain = +38.6%

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 34.9%

Subtract corrected major strain (step 5) = (-) 38.6%

Corrected Safety Margin = -3.7% (Red Zone)

8.5.2 - Case Study No. 2 – Large Fender – Area C – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$$FLC_0 = (23.3 + 360 t) n/0.21 \text{ for thickness in inches}$$
$$FLC_0 = [23.3 + 360 (.0312 \text{ in.})] 0.212/0.21 = 34.9\%$$

$FLC_0 = 34.9\%$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 34.9 %
True major strain = $\ln(1 + 34.9/100) = 0.299$
True thickness strain = -True major strain = -0.299
Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.299} - 1) 100 = -25.8\%$

Compute thinning strain for yellow zone

Engineering major strain = 34.5 % -10% = 24.9 %
True major strain = $\ln(1 + 24.9/100) = 0.222$
True thickness strain = -True major strain = -0.222
Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.222} - 1) 100 = -19.9\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0198/0.0312) - 1] 100 = -36.5\%$

Red zone start line (step 7) = -25.8%

As-measured thickness strain is above red zone line (Red Zone)

Step 9 Determine severity of corrected thickness strain

Corrected major strain (step 5) = +38.6%

True major strain = $\ln(1 + 38.6/100) = 0.326$

True thickness strain = -True major strain = -0.326

Corrected engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.326} - 1) 100 = -27.9\%$

Red zone start line (step 7) = -25.8%

Corrected thickness strain is still above the red zone line (Red Zone)

8.5.3 - Case Study No. 3 – Small Fender – Area A

Record Raw Data:

As-received steel: $n = 0.199$ $t_0 = 0.0289$ in.

Panel thickness at study location = 0.0199 in.

Bead deformation: t (enter) = 0.0280 in. and t (exit) = 0.0199 in.

Step 1: Compute the FLC_0 for steel used

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0289 \text{ in.})] 0.199 / 0.21 = \mathbf{31.9\%}$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0199 in.

True thickness strain: $\epsilon_t = \ln(0.0199/0.0289) = -0.373$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.373$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $e^{0.373} - 1 = \mathbf{45.2\%}$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 31.9%

Subtract as-measured major strain (step 2) = (-) 45.2%

As-measured Safety Margin = $\mathbf{-13.3\%}$ (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0199/0.0280)$

BCF = $\mathbf{-20.5\%}$

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +45.2%

Add BCF (step 4) = -20.5%

Corrected major strain = $\mathbf{+24.7\%}$

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 31.9%

Subtract corrected major strain (step 5) = (-) 24.7%

Corrected Safety Margin = $\mathbf{+7.2\%}$ (Yellow Zone)

8.5.3 - Case Study No. 3 – Small Fender – Area A – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$FLC_0 = (23.3 + 360 t) n/0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0289 \text{ in.})] 0.199/0.21 = 31.9\%$

$FLC_0 = 31.9\%$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 31.9 %

True major strain = $\ln(1 + 31.9/100) = 0.277$

True thickness strain = -True major strain = -0.277

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.277} - 1) 100 = -24.2\%$

Compute thinning strain for yellow zone

Engineering major strain = 31.9 % -10% = 21.9 %

True major strain = $\ln(1 + 21.9/100) = 0.198$

True thickness strain = -True major strain = -0.198

Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.198} - 1) 100 = -18.0\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0199/0.0289) - 1] 100 = -31.1\%$

Red zone start line (step 7) = -24.2%

As-measured thickness strain is above red zone line (Red Zone)

Step 9 Determine severity of corrected thickness strain

Corrected major strain (step 5) = +24.7%

True major strain = $\ln(1 + 24.7/100) = 0.221$

True thickness strain = -True major strain = -0.221

Corrected engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.221} - 1) 100 = -19.8\%$

Yellow zone start line (step 7) = -17.9%

Corrected thickness strain is above the yellow zone line (Yellow Zone)

8.5.4 - Case Study No. 4 – Hood Outer – Area A

Record Raw Data:

As-received steel: $n = 0.218$ $t_0 = 0.0321$ in.

Panel thickness at study location = 0.0213 in.

Bead deformation: t (enter) = 0.0305 in. and t (exit) = 0.0213 in.

Step 1: Compute FLC0 for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0321 \text{ in.})] 0.218 / 0.21 = 36.2\%$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0213 in.

True thickness strain: $\epsilon_t = \ln(0.0213/0.0321) = -0.410$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.410$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As-measured major strain = $(e^{0.410} - 1) 100 = 50.7\%$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 36.2%

Subtract as-measured major strain (step 2) = (-) 50.7%

As-measured Safety Margin = -14.5% (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0213/0.0305)$

BCF = -21.5%

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +50.7%

Add BCF (step 4) = -21.5%

Corrected major strain = +29.2%

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 36.2%

Subtract corrected major strain (step 5) = (-) 29.2%

Corrected Safety Margin = +7.0% (Yellow Zone)

8.5.4 - Case Study No. 4 – Hood Outer – Area A – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$FLC_0 = (23.3 + 360 t) n/0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0321 \text{ in.})] 0.218/0.21 = \mathbf{36.2\%}$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 36.2 %

True major strain = $\ln(1 + 36.2/100) = 0.309$

True thickness strain = -True major strain = -0.309

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.309} - 1) 100 = \mathbf{-26.6\%}$

Compute thinning strain for yellow zone

Engineering major strain = 36.2 % -10% = 26.2 %

True major strain = $\ln(1 + 26.2/100) = 0.233$

True thickness strain = -True major strain = -0.233

Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.233} - 1) 100 = \mathbf{-20.8\%}$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0213/0.0321) - 1] 100 = \mathbf{-33.6\%}$

Red zone start line (step 7) = -26.6%

As-measured thickness strain is above red zone line (Red Zone)

Step 9 Determine severity of corrected thickness strain

Corrected major strain (step 5) = +29.2%

True major strain = $\ln(1 + 29.2/100) = 0.256$

True thickness strain = -True major strain = -0.256

Corrected engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.256} - 1) 100 = \mathbf{-22.6\%}$

Yellow zone start line (step 7) = -20.8%

Corrected thickness strain is above the yellow zone line (Yellow Zone)

8.5.5 - Case Study No. 5 – Body Side – Area A

Record Raw Data:

As-received steel: $n = 0.211$ $t_0 = 0.0334$ in.

Panel thickness at study location = 0.0227 in.

Bead deformation: t (enter) = 0.0340 in. and t (exit) = 0.0250 in.

Step 1: Compute FLC0 for steel used:

$FLC_0 = (23.3 + 360 t) n / 0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0334 \text{ in.})] 0.211 / 0.21 = 35.5\%$

Step 2: Obtain the as-measured major strain at study location by:

a) Major strain measurement on gridded sample

b) Conversion from ultrasonic thickness value for minor strain = 0

Ultrasonic thickness value = 0.0227 in.

True thickness strain: $\epsilon_t = \ln(0.0227/0.0334) = -0.386$

True major strain: $\epsilon_{\text{major}} = -\epsilon_{\text{thickness}} = +0.386$ for $\epsilon_{\text{minor}} = 0$

Engineering major strain: $\epsilon_{\text{major}} = (e^{\text{true major}} - 1) 100$

As measured major strain = $(e^{0.386} - 1) 100 = 47.1\%$

Step 3: Compute as-measured Safety Margin

FLC_0 (step 1) = 35.5%

Subtract as-measured major strain (step 2) = (-) 47.1%

As-measured Safety Margin = -11.6% (Red Zone)

Step 4: Compute Bead Correction Factor (BCF)

$BCF = 60 \ln(t \text{ exit bead} / t \text{ enter bead})$

$BCF = 60 \ln(0.0250/0.0340)$

BCF = -18.4%

Step 5: Compute corrected engineering major strain

As-measured major strain (step 2) = +47.1%

Add BCF (step 4) = -18.4%

Corrected major strain = +28.7%

Step 6: Compute corrected Safety Margin

FLC_0 (step 1) = 35.5%

Subtract corrected major strain (step 5) = (-) 28.7%

Corrected Safety Margin = +6.8% (Yellow Zone)

8.5.5 - Case Study No. 5 – Body Side – Area A – Cont.

Computation For Thinning Strain Severity (Optional)

Step 7: Compute thinning strain severity levels for steel used:

Compute FLC_0

$FLC_0 = (23.3 + 360 t) n/0.21$ for thickness in inches

$FLC_0 = [23.3 + 360 (.0334 \text{ in.})] 0.21/0.21 = 35.5\%$

Compute thinning strain for red zone (assuming minor strain = 0)

Engineering major strain = 35.5 %

True major strain = $\ln(1 + 35.5/100) = 0.304$

True thickness strain = -True major strain = -0.304

Red engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.304} - 1) 100 = -26.2\%$

Compute thinning strain for yellow zone

Engineering major strain = 35.5 % - 10% = 25.5 %

True major strain = $\ln(1 + 25.5/100) = 0.227$

True thickness strain = -True major strain = -0.227

Yellow engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.227} - 1) 100 = -20.3\%$

Step 8: Determine severity of as-measured thickness strain

As-measured thickness strain = $[(0.0227/0.0334) - 1] 100 = -32.0\%$

Red zone start line (step 7) = -26.2%

As-measured thickness strain is above red zone line (Red Zone)

Step 9 Determine severity of corrected thickness strain

Corrected major strain (step 5) = +28.7%

True major strain = $\ln(1 + 28.7/100) = 0.252$

True thickness strain = -True major strain = -0.252

Corrected engineering thickness strain: $\epsilon_{\text{Thick}} = (e^{-0.252} - 1) 100 = -22.3\%$

Yellow zone start line (step 7) = -20.3%

Corrected thickness strain is above the yellow zone line (Yellow Zone)