

Tube Hydroforming: Dimensional Capability Analysis of a High Volume Automotive Structural Component Production Process

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ABSTRACT

The rapidly developing hydroforming industry has become almost a mainstream technology for the manufacture of automotive structural components. Technical information and claims are often incomplete, unspecific and unsupported by production experience and data. This paper contains data accumulated from a hydroforming process that has been in high volume production for 8 years. An objective presentation, explanation and discussion of this information gives a unique view of what is being done at present. It should act as an authoritative reference point against which dimensional capability claims can be judged.

INTRODUCTION

In the past two years tubular hydroforming has rapidly developed from a niche technology known to few in the automotive industry to one that is attracting the attention of a far wider audience, both inside and outside this industry. It has become a viable alternative, and at times a preference to stampings that were previously assembled into tubelike structural components. Such assemblies had a number of drawbacks, but no practical and economical way was available to make them from tubing. This new method improves the accuracy and stability of the stamping and assembly method. What can be reasonably expected is not well understood because automotive structural hydroformed part production history is rare. Experienced companies have not publicized their detailed data.

The rapid and widespread assimilation of this new technology has led to much wider application and a relative vacuum of proven and authoritative knowledge. Some confusion has resulted from the apparently bewildering array of information that often contradictory. Claims have been made without proof or long term production experience. This has led, in some cases, to acceptance of misinformation concerning dimensional capability, how to design parts and the most efficient

way to apply the technology. In short, a 'common sense' about hydroforming has not developed.

In light of this situation, a detailed and factual discussion using examples of automotive structural hydroformed production parts should act as a good reference. A hydroforming process was intentionally devised to make such parts in the most economical manner possible. It started development in 1984 and commenced high volume production (300,000 parts/year) in 1990. Total volume has increased to 3.5 million parts/year while achieving high quality and dimensional capability levels.

A wealth of dimensional data has been generated during this time, some of which will be presented in this paper to provide a factual standard against which claims can be judged. A number of features will be identified and data will be presented and discussed to put it in the proper context. This is intended to provide a framework of different features and a full description of tolerance, capability levels and tolerances that are achievable at normal long term capability values. This should educate the interested party by promoting methodical and objective assessment of process ability, thereby reducing misinformation and proprietary rhetoric. Elevating the understanding of what is reasonable to expect without adding cost is of ultimate importance.

STATISTICAL BACKGROUND

In the developing tube hydroforming industry some claims treat the range of observed readings from a part population as being equivalent to statistically calculated process capability. This is untrue since the former is usually much less than the latter. Inspection normally does not find samples at the outer limits of the distribution curve.

To clarify misconceptions like this and ensure more complete understanding of what the presented information means, it is necessary to explain some of the terminology used in this paper, even though it maybe

redundant to some.

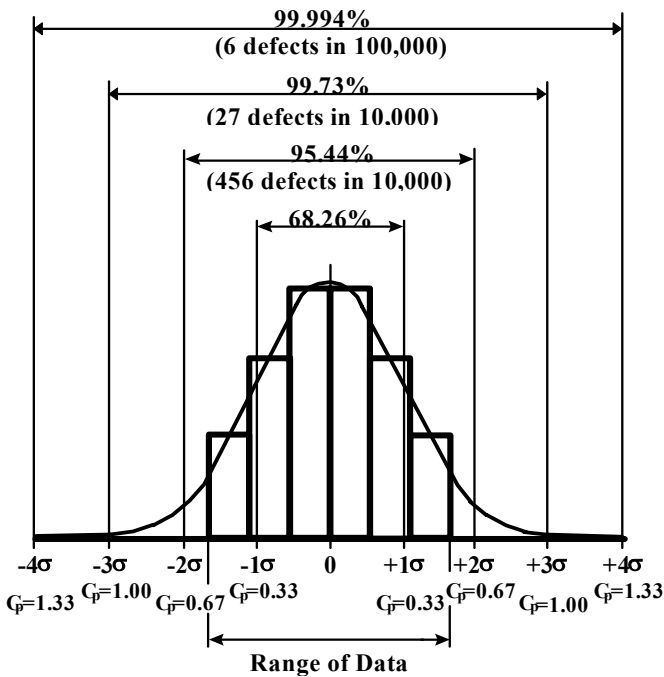


Figure 1

The normal distribution shown above is typical of those found in statistics textbooks. It shows the grouping of actual measurements taken in the histogram bars and the normal distribution curve approximated from them. The vertical lines show zones of capability, the proportion of the population encompassed by each zone, and the predicted rate of part defects.

A key point to understand is the difference between the total range of the measurements and the statistically calculated variance at a given capability level (i.e. $C_p = 1.33$). This latter number expresses the feature size range or tolerance needed to encompass the proportion of measurements (i.e. 99.994% at $C_p = 1.33$) that are required to be capable. The range of data taken from a group of parts, no matter how large, has to be significantly smaller (normally less than half) than the tolerance to be capable to that tolerance. Any inference that the actual range of measurements is the tolerance that can be achieved is statistically incorrect for the capability levels expected in today's auto industry (i.e. $C_p = 1.33$). Examples to show this form the body of this document.

This paper focuses on discussing C_p rather than C_{pk} since the former is a pure measure of variation, where C_{pk} expresses variation combined with the data's mean value relative to nominal or CAD model position. Variation is the core subject of this paper and to maintain clarity it seems logical to not complicate the analysis with centering. Where the mean value of the data differs too much from nominal, adjustment can be made. Where the mean differs from the target or CAD position, it is satisfactory to the customer to leave the

feature unchanged, given previously demonstrated repeatability. Assurance is best demonstrated by long term data on a similar feature already in production. All data charts show the C_{pk} for the reader's information.

Any indication of feature position repeatability must include the tolerance and capability level. When either is discussed or specified without the other it is only half of the needed information and essentially meaningless.

To illustrate this point, data from the surface location in an unbent section (Table 2) of the Engine Cradle Capability Analysis on page 3 will be used. Tolerance is ± 1.0 mm, range 0.35 mm and $C_p = 4.28$.

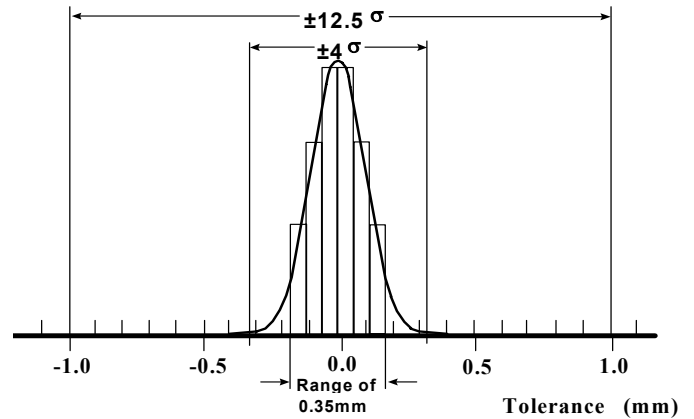


Figure 2

As can be seen, $C_p = 4.28$ is approximately equal to ± 12.5 sigma, which is far beyond what would ever be needed. When the $C_p = 1.33$ or ± 4 sigma the tolerance falls proportionately to ± 0.31 mm. If a tolerance is given without indication of the capability level it is not known what proportion of the total population is encompassed. Similarly if capability level is given with no mention of tolerance, it is unknown how large the tolerance needs to be for this level of capability.

The capability level of $C_p = 1.33$ was chosen for long term data since it is the most demanding, common requirement for automotive part production. A higher capability level increases the needed tolerance and lower capability reduces the tolerance that can be met.

For most of the features presented, the data provided is long term, because it is obviously preferable.

FACTORS AFFECTING THE ANALYSES

Several factors affect hydroforming repeatability. The main ones are consistency of the bent and/or preformed tubular blank that is placed in the die, accuracy of placement in the die, changes in material characteristics within specification limits, and normal variation in process conditions. Measurement methodology and

consistency can easily cause the illusion of not being capable when in fact the process is stable.

EXPLANATION OF TERMS

Sample size and period are the quantity of parts collected and the time over which they were randomly selected and measured.

Tolerance is the total range of variability acceptable to the customer.

Range is the maximum minus minimum readings for the feature being examined and standard deviation or sigma (σ) is calculated from the measurement data.

C_p and C_{pk} are calculated using the tolerance and standard deviation.

The final figure in each table It is the tolerance that can be achieved. It is calculated by setting the long term process capability level at $C_p = 1.33$ which is the highest in common use. Where short term data is presented, 5 sigma or $C_p = 1.67$ is used, which is also common. It is the tolerance that can be achieved.

The histograms following each chart show the distribution pattern of the data.

PRODUCTION PART SELECTION

Three automotive structural components were selected from seven candidates. They were selected for the interesting features they possessed and data availability.

The 1st two parts have a relatively large number of bends (8 and 11 respectively), substantial cross section reshaping that changes considerably along the part length and very complex surfaces. The 3rd example was included to exemplify a part with fewer (4) and smaller angle bends, substantial cross section reshaping that does not change substantially over the part length. In short it is a less demanding part.

ENGINE CRADLE CAPABILITY ANALYSIS

The part in Figure 3 is assembled with a number of brackets for service in the vehicle. It uses 63.5 mm diameter, 2 mm minimum wall thickness, 310 MPa min. yield strength HSLA steel tube. Production cycle time is less than 22 seconds and about 250,000 parts/year are made in a single cavity die in one press in North America and 400,000 parts/year in Europe with a similar setup. Manufacturing scrap from bending, hydroforming with hole punching in the die and shearing is 0.5%.

All data is taken prior to assembly or welding operations.



Figure 3

CROSS SECTION WIDTH

| | |
|---------------------------|---------------|
| Sample Period | 6 Months |
| Sample Size | 30 pcs. |
| Tolerance | ± 1.0 mm |
| Range | 0.09 mm |
| Std. Dev. | 0.024 |
| C_p | 13.60 |
| C_{pk} | 12.35 |
| At $C_p = 1.33$ Tol. = | ± 0.10 mm |

Table 1

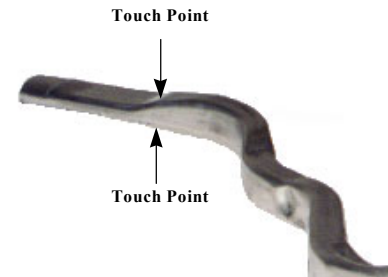


Figure 4

This data (Table 1) shows the impressive precision of hydroforming. It must be realized that it only presents part of the normally required information. The size of a cross section is not normally as important as where those surfaces are located in space relative to a CAD or nominal position. Its main applicability is where surface location opposite a datum is critical or a bracket fits around the tube and is located relative to it.

The fact that the data is from samples collected over 6 months should give a high degree of confidence.

SURFACE LOCATION-UNBENT SECTION

The distance between the supports is 840 mm and the measurement point is approximately at the midpoint in the up down direction.

| | |
|---------------|--------------|
| Sample Period | 1 Month |
| Sample Size | 30 pcs. |
| Tolerance | ± 1.0 mm |

| | |
|------------------------------------|----------|
| Range | 0.35 mm |
| Std. Dev. | 0.08 |
| C _p | 4.28 |
| C _{pk} | 3.66 |
| At C _p = 1.33 Tol. = | ±0.31 mm |

Table 2

| | | | |
|---|-------|-------|-------|
| C _p | 4.20 | 6.07 | 4.91 |
| C _{pk} | 3.67 | 5.34 | 3.38 |
| At C _p = 1.33 Tol. (mm) = | ±0.32 | ±0.20 | ±0.28 |

Table 3

Slot 4 (7.5 x 11.5 mm, radiused ends)

| | X | Y | Z (Surf.) |
|---|----------|-------|-----------|
| Sample Period | 6 Months | | |
| Sample Size | 35 pcs. | | |
| Tolerance | ±1.0 mm | | |
| Range (mm) | 0.56 | 0.34 | 0.18 |
| Std. Dev. | 0.16 | 0.10 | 0.04 |
| C _p | 2.11 | 3.35 | 7.80 |
| C _{pk} | 1.94 | 3.27 | 6.25 |
| At C _p = 1.33 Tol. (mm) = | ±0.64 | ±0.40 | ±0.16 |

Table 4

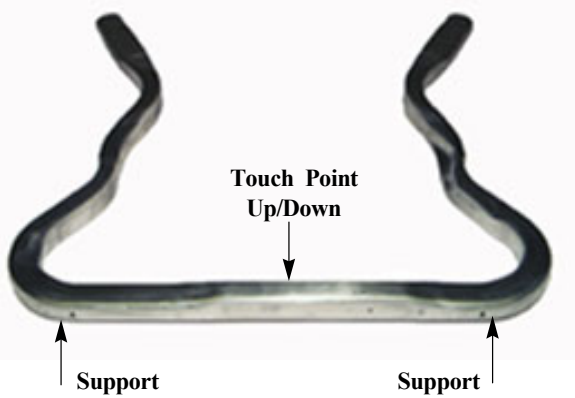


Figure 5

Surface location at any point on the part relative to the CAD model is of far wider interest. This data describes the process capability where the part is clamped at either end of the straight crossbar over the support points and the surface location is checked in the center of the span, as shown in Figure 5. The absence of bends in this section allows a look at a situation where the only reason for variation is the hydroforming operation with its normal process parameter variation.

The surface is easily capable to the prescribed tolerance and can achieve ±0.31 mm when only considering C_p. Since data for a feature is rarely perfectly centered on the nominal, the tolerance that could be achieved at C_{pk}=1.33 would have to be higher to account for this. Samples collected over 1 month would encompass a large degree of the variability of the process.

Later analyses will include other potential sources of variation and should be compared with the data from this chart to get a view of the influence of each of the separate factors.

HOLE AND SLOT POSITION

Hole 11 (5.2 mm diameter)

| | X | Y | Z (Surf.) |
|---------------|----------|------|-----------|
| Sample Period | 6 Months | | |
| Sample Size | 35 pcs. | | |
| Tolerance | ±1.0 mm | | |
| Range (mm) | 0.28 | 0.18 | 0.21 |
| Std. Dev. | 0.08 | 0.05 | 0.07 |

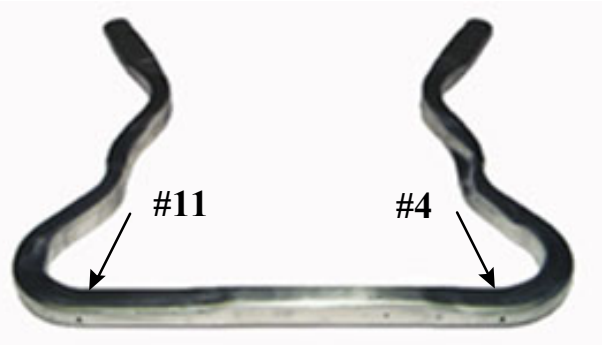


Figure 6

The sample period is 6 months. The datums are very close which makes the stability of these holes high relative to holes that are farther from a datum. The lower tolerances shown could be achieved in a similar situation, but cannot necessarily elsewhere.

INSTRUMENT PANEL BEAM CAPABILITY ANALYSIS

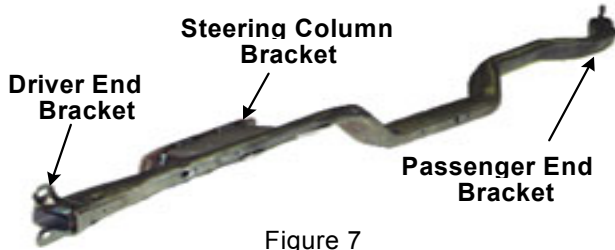


Figure 7

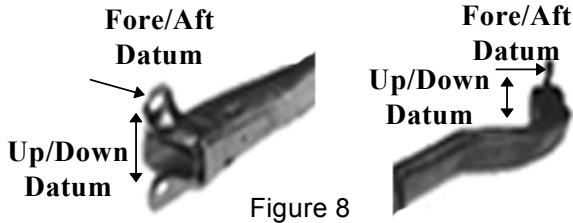


Figure 8

The part has three brackets welded as shown in Figure 7 & 8 and provides most of the structural strength for the instrument panel, supports the steering column and is part of the body in white structure. The part uses 50.8 mm diameter, 2 mm minimum wall thickness, SAE1008/1010 mild steel tube. It has a cycle time of less than 17 seconds and has achieved a volume of 780,000 parts per year on 2 shifts with a partial third. This third iteration of a part that has been in production for 8 years runs in one press in a single cavity die with no backup tooling. Manufacturing scrap rates from bending, hydroforming with hole punching in the die and shearing total 0.5%. Welding causes another 0.5%.

Of the 4 analyses the 1st, 3rd and 4th analyses examine the assembled final part (irrelevant for the 1st analysis). The 2nd analysis measures the tube after hydroforming and before welding. For the 3rd and 4th analyses this is important because the up/down and fore/aft datums are transferred to the welded brackets at the tube ends (Figure 8). The achievable repeatability is adversely affected by this change and related weld distortion. It is therefore not a pure indication of hydroforming dimensional capability.

CROSS SECTION WIDTH

Long Term

| | |
|------------------------------------|----------|
| Sample Period | 6 Months |
| Sample Size | 30 pcs. |
| Tolerance | ±1.5mm |
| Range | 0.21 mm |
| Std. Dev. | 0.04 |
| C _p | 12.99 |
| C _{pk} | 12.21 |
| At C _p = 1.33 Tol. = | ±0.23 mm |

Table 5

Short Term

| | |
|---------------|---------|
| Sample Period | 1 Day |
| Sample Size | 30 pcs. |

| | |
|------------------------------------|----------|
| Tolerance | ±1.5mm |
| Range | 0.06 mm |
| Std. Dev. | 0.013 |
| C _p | 29.92 |
| C _{pk} | 28.95 |
| At C _p = 1.67 Tol. = | ±0.10 mm |

Table 6

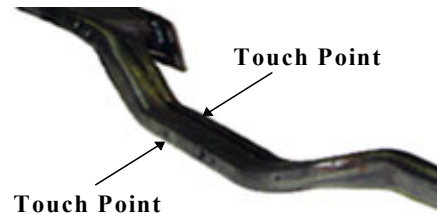


Figure 9

The very high C_p and C_{pk} numbers and low short and long term tolerance reiterates cross section stability.

The section is measured roughly perpendicular to press travel direction which explains much of the difference between these and the engine cradle results. This lesser stability may be attributed to slight sideways movement between the die halves compared to the greater stability of closing the die halves against solid stops. This result is more than double the comparable engine cradle number, but is still very small, especially considering the sample period. It may be partly due to other causes.

SURFACE LOCATION-CENTER SECTION, 11 BENDS (BEFORE WELDING)

Center- Up/Down

| | |
|------------------------------------|----------|
| Sample Period | 3 Months |
| Sample Size | 1000pcs. |
| Tolerance | ±1.5 mm |
| Range | 1.10mm |
| Std. Dev. | 0.17 |
| C _p | 2.94 |
| C _{pk} | 2.47 |
| At C _p = 1.33 Tol. = | ± 0.68mm |

Table 7

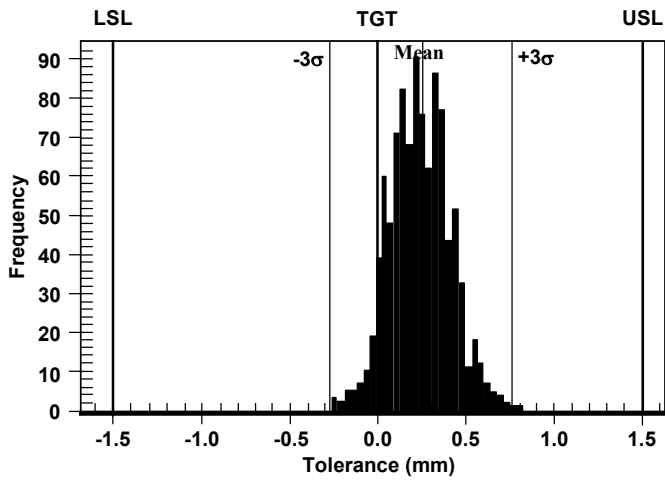


Figure 10

Center- Fore/Aft

| | |
|--------------------------|----------|
| Sample Period | 3 Months |
| Sample Size | 1000pcs. |
| Tolerance | ±1.5 mm |
| Range | 0.95mm |
| Std. Dev. | 0.14 |
| C _p | 3.57 |
| C _{pk} | 3.07 |
| At C _p = 1.33 | |
| Tol. = | ± 0.56mm |

Table 8

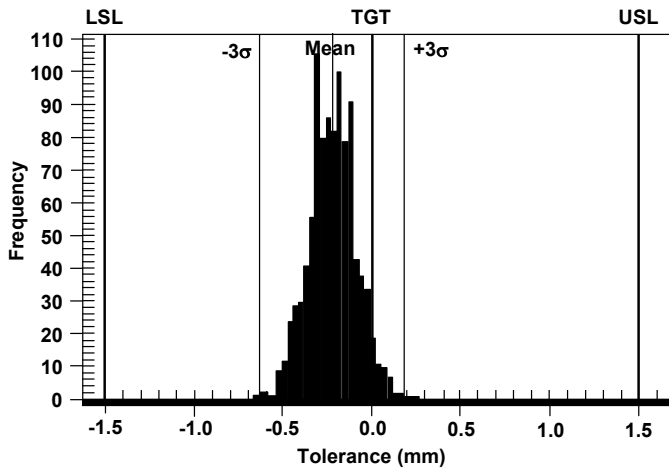


Figure 11

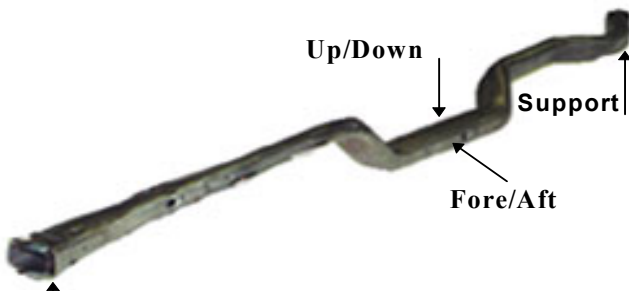


Figure 12

the tube 1415 mm and the touch point is 40 mm from the midpoint.

Measurements before are taken as shown in Figure 12 the brackets are welded on, and only show the effect of bending and hydroforming.

SURFACE LOCATION-CENTER SECTION, 11 BENDS (AFTER WELDING)

The distance between supports on the brackets is 1500 mm and the measurement points is near the midpoint.

Center- Up/Down

| | |
|--------------------------|----------|
| Sample Period | 4 Months |
| Sample Size | 1200pcs. |
| Tolerance | ±1.5 mm |
| Range | 1.32mm |
| Std. Dev. | 0.18 |
| C _p | 2.77 |
| C _{pk} | 2.44 |
| At C _p = 1.33 | |
| Tol. = | ± 0.71mm |

Table 9

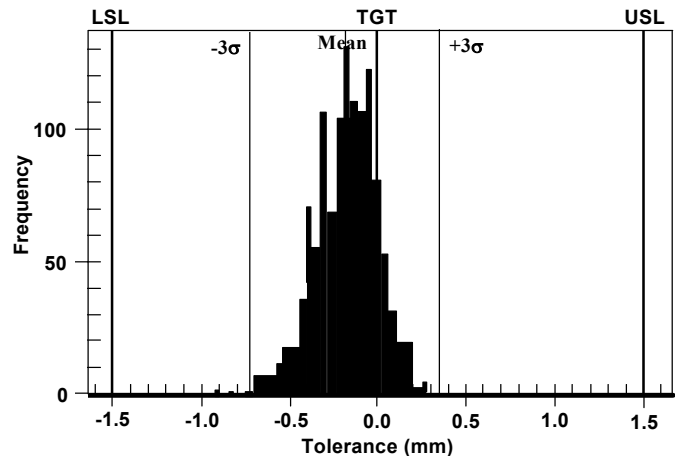


Figure 13

Center- Fore/Aft

| | |
|--------------------------|----------|
| Sample Period | 4 Months |
| Sample Size | 1200pcs. |
| Tolerance | ±1.5 mm |
| Range | 1.37mm |
| Std. Dev. | 0.17 |
| C _p | 2.94 |
| C _{pk} | 1.87 |
| At C _p = 1.33 | |
| Tol. = | ± 0.68mm |

Table 10

The distance between the supports is near the ends of

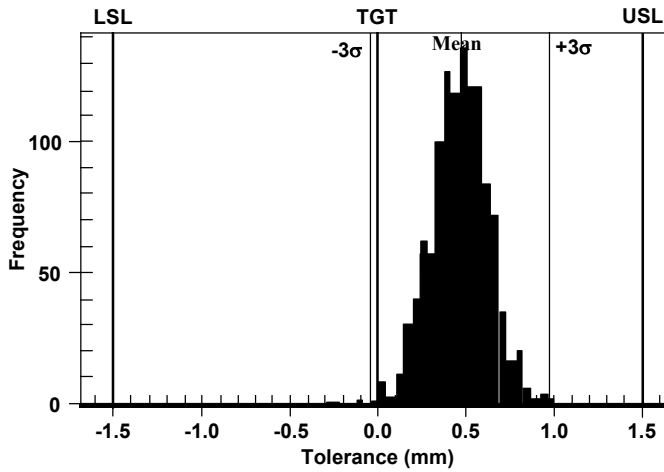


Figure 14

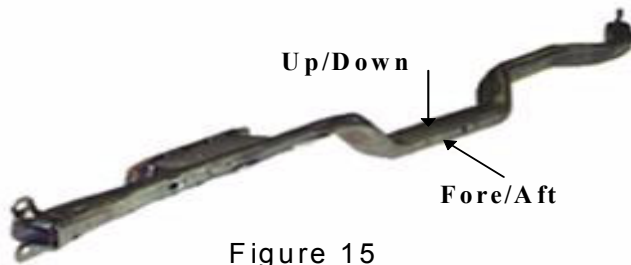


Figure 15

The numbers show the effect of bending, hydroforming and welding. In addition to the datum change, welding the steering column bracket causes distortion. The difference between these results and the previous section are from these changes. The larger than normal tolerance of ± 1.5 mm was made to accommodate the expected higher variability.

HOLE AND SLOT POSITION

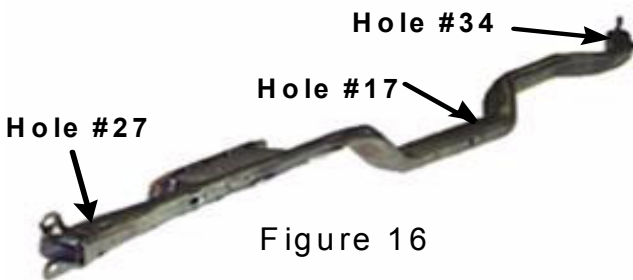


Figure 16

Hole #34 (5.68 mm) Near Datum
Long Term

| | X (Surf.) | Y | Z |
|--------------------------------|------------|------------|------------|
| Sample Period | 6 Months | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ± 1.5 | ± 1.0 | ± 1.5 |
| Range (mm) | 1.15 | 0.04 | 0.74 |
| Std. Dev. | 0.24 | 0.11 | 0.19 |
| C_p | 2.10 | 2.91 | 2.58 |
| C_{pk} | 1.82 | 2.54 | 2.27 |
| At $C_p = 1.33$ Tol. (mm) = | ± 0.96 | ± 0.44 | ± 0.76 |

Table 11
Short Term

| | X (Surf.) | Y | Z |
|--------------------------------|------------|------------|------------|
| Sample Period | 1 Day | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ± 1.5 | ± 1.0 | ± 1.5 |
| Range (mm) | 0.16 | 0.19 | 0.59 |
| Std. Dev. | 0.05 | 0.04 | 0.15 |
| C_p | 8.34 | 6.32 | 2.74 |
| C_{pk} | 8.04 | 4.50 | 1.82 |
| At $C_p = 1.67$ Tol. (mm) = | ± 0.25 | ± 0.20 | ± 0.75 |

Table 12

Hole #27 (5.68 mm) Near Datum
Long Term

| | X (Surf.) | Y | Z |
|--------------------------------|------------|------------|------------|
| Sample Period | 6 Months | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ± 1.5 | ± 1.0 | ± 1.5 |
| Range (mm) | 0.71 | 0.26 | 0.36 |
| Std. Dev. | 0.19 | 0.07 | 0.10 |
| C_p | 2.61 | 4.66 | 5.13 |
| C_{pk} | 2.53 | 4.29 | 4.86 |
| At $C_p = 1.33$ Tol. (mm) = | ± 0.76 | ± 0.28 | ± 0.40 |

Table 13

Short Term

| | X (Surf.) | Y | Z |
|--------------------------------|------------|------------|------------|
| Sample Period | 1 Day | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ± 1.5 | ± 1.0 | ± 1.5 |
| Range (mm) | 0.35 | 0.21 | 0.37 |
| Std. Dev. | 0.08 | 0.05 | 0.10 |
| C_p | 4.98 | 5.41 | 4.14 |
| C_{pk} | 4.50 | 5.26 | 3.95 |
| At $C_p = 1.67$ Tol. (mm) = | ± 0.40 | ± 0.25 | ± 0.50 |

Table 14

Hole #17 (5.68 mm) At Tube Center
Long Term

| | X (Surf.) | Y | Z |
|--------------------------------|------------|------------|------------|
| Sample Period | 6 Months | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ± 1.5 | ± 1.0 | ± 1.5 |
| Range | 0.84 | 0.18 | 0.96 |
| Std. Dev. | 0.26 | 0.05 | 0.25 |
| C_p | 1.90 | 6.25 | 2.02 |
| C_{pk} | 1.56 | 4.42 | 1.93 |
| At $C_p = 1.33$ Tol. (mm) = | ± 1.04 | ± 0.20 | ± 1.00 |

Table 15

Short Term

| | X (Surf.) | Y | Z |
|--|-----------|---|---|
|--|-----------|---|---|

| | | | |
|------------------------------------|---------|-------|-------|
| Sample Period | 1 Day | | |
| Sample Size | 30 pcs. | | |
| Tolerance (mm) | ±1.5 | ±1.0 | ±1.5 |
| Range | 0.58 | 0.06 | 0.37 |
| Std. Dev. | 0.14 | 0.02 | 0.09 |
| C _p | 2.92 | 13.68 | 4.70 |
| C _{pk} | 1.62 | 10.33 | 2.83 |
| At C _p = 1.67 Tol. = | ±0.70 | ±0.10 | ±0.44 |

Table 16

Holes 34 and 27 are located close to the end brackets to isolate the accuracy of hole punching from the effects of welding and hydroforming.

Hole 17 is located at the center of the part where the above two effects have the most influence. The short term and long term capability of holes 34 and 27 are better than hole 17, but the difference is relatively small. The difference between long and short term capability for all holes is substantial, as expected.

The maintainable tolerance in the Y direction is generally dramatically better than in the X, and Z directions as has been our previous experience.

RADIATOR ENCLOSURE TOP BAR ANALYSIS

This part has 1 bracket welded to the front surface at the center. It uses 76.2 mm diameter, 1.3 mm minimum wall thickness, SAE 1010/1008 galvaneal steel tube. The cycle time is under 18 seconds and is produced at a rate of approximately 400,000 part/year. Manufacturing scrap rates from bending, hydroforming with hole punching in the die and shearing normally total 0.2%. Welding the bracket to the tube normally causes scrap of 0.4%.

All data is measured prior to welding.

SURFACE LOCATION-CENTER SECTION, 4 BENDS

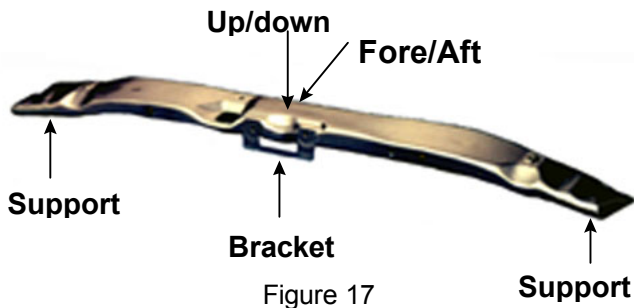


Figure 17

Center- Up/Down

| | |
|---------------|------------|
| Sample Period | 2.5 Months |
|---------------|------------|

| | |
|------------------------------------|----------|
| Sample Size | 184 pcs. |
| Tolerance | ±1.5 mm |
| Range | 0.17mm |
| Std. Dev. | 0.04 |
| C _p | 13.35 |
| C _{pk} | 11.12 |
| At C _p = 1.33 Tol. = | ± 0.16mm |

Table 17

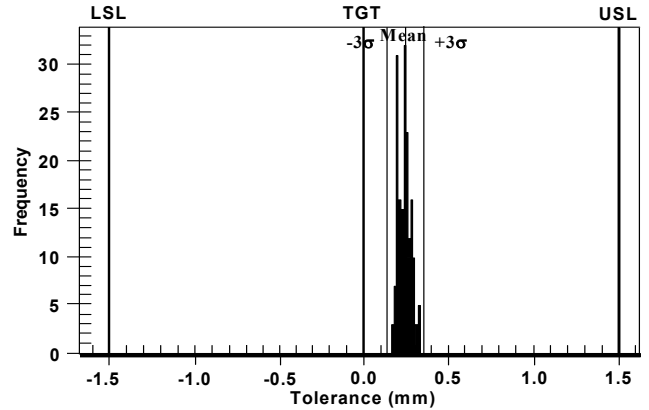


Figure 18

Center- Fore/Aft

| | |
|------------------------------------|------------|
| Sample Period | 2.5 Months |
| Sample Size | 185 pcs. |
| Tolerance | ±1.5 mm |
| Range | 0.40mm |
| Std. Dev. | 0.04 |
| C _p | 11.45 |
| C _{pk} | 9.98 |
| At C _p = 1.33 Tol. = | ± 0.16mm |

Table 18

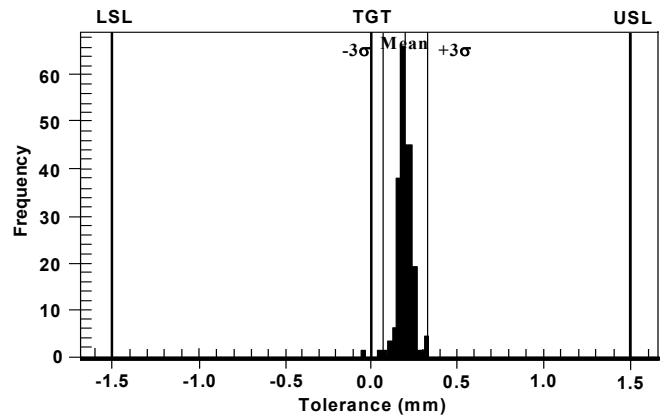


Figure 19

The high C_p is partly from the higher than normal tolerance of 1.5 mm. The sample period is shorter than some of the other data, but 80,000 pieces were produced during this time.

The up/down measurement is conditional because it is very near a datum support. The fore/aft data is unrestricted, but it can be seen that there is only a small reduction in capability. The latter is made more remarkable because the span is 1260mm. The 4 bends of 7° apparently have little detrimental effect.

The tolerance at $C_p = 1.33$ is ± 0.16 mm. This is lower than the surface location in an unbent section for the engine cradle (Table 2). It is even lower than the cross section measurement for the instrument panel beam (Table 5 & 6). Possible explanations for this improved result are that the tube has larger diameter, thinner wall and the material is lower strength SAE 1008/1010 galvaneal.

HOLE SIZE CAPABILITY ANALYSIS

| | | |
|--------------------------------|-------------|------------|
| Hole Dia. (mm) | 5.69 | 25.4 |
| Sample Period | 1 Day | |
| Sample Size | 30 pcs. | |
| Tolerance (mm) | ± 0.065 | ± 0.50 |
| Range (mm) | 0.01 | 0.04 |
| Std. Dev. | 0.0025 | 0.012 |
| C_p | 6.83 | 11.15 |
| C_{pk} | 6.38 | 9.04 |
| At $C_p = 1.67$ Tol. (mm) = | ± 0.01 | ± 0.06 |

Table 19



Figure 20

Hole sizes could not be measured on a CMM since accuracy is insufficient for the small part to part variation. This makes hole sizing capability appear worse than it actually is. Plug gauges were used to measure this characteristic and only short term data is available.

The capability level is very high for both holes. What short term does not include is the maintenance minimization practice of letting the punches wear until they approach the low side of the hole size tolerance before they are changed. Lower tolerances can be achieved, but punches would not be able to wear as much between changes. This would require more frequent changes and maintenance cost. The tolerance at a $C_p = 1.33$ is proportional to hole size.

The higher C_p and C_{pk} figures for the larger hole are because the tolerance is much larger.

OBSERVATIONS AND DISCUSSION

It is important to reiterate that the capability index discussed is C_p because it quantifies and focuses on variation. It does not consider how close the data mean is to nominal measurement. As a result applying this information must include some forgiveness for the probability that the mean will not equal nominal.

Hydroforming is less affected by weld distortion than the stamped and welded assemblies that they replace because weld assembly is not needed. Another reason is the lower residual stresses are found in some hydroformed parts since they are not formed by stretching, as stampings are.

The examples have been associated with different causes of variation to allow comparison for determining how much variation may be attributed to each cause.

Cross section dimensions (not surface location relative to the CAD model), are produced so repeatably that 4 sigma capable tolerances in the range of ± 0.10 - ± 0.23 mm can be achieved where required (Tables 1, 5 & 6).

Surface location on the engine cradle crossbar with no bends or welding represents the next step of higher variability. This is comparable to the engine cradle cross section at ± 0.10 mm (Table 1). Four sigma capability tolerance is higher at ± 0.31 mm (Table 2) and is due to hydroforming. There is 840 mm between supports.

Next is surface location in the center of the instrument panel beam that has 11 bends of 40° or less. Two main factors causing higher tolerances of ± 0.68 mm (U/D) and ± 0.56 mm (F/A) at $C_p = 1.33$ (Tables 7 & 8) are bending and the larger distance between supports of 1415 mm.

Welding three brackets to the instrument panel beam and changing the up/down and fore/aft datums to the two end brackets causes a lower than expected tolerance increase. It is ± 0.71 mm (U/D) and ± 0.68 mm (F/A) over a span of 1500 mm.

For the instrument panel beam the capability of hole 17 is not as good as holes 27 & 34. The most stable hole position coordinate is parallel to the tube centerline and the least stable may be the coordinate describing the surface position. One explanation is that hole position (where the punch pierces the surface) may be more stable than surface location (compared to the nominal).

Surface location of the radiator enclosure top bar center section is remarkably repeatable. The histogram (Figure 20) shows very tight data distribution. Table 18 shows a tolerance of ± 0.16 mm at $C_p = 1.33$ which is half the number for the unbent section (Table 2) and is better than one of the cross sections (Table 5 & 6).

Hole size accuracy is very high, but short term data

shows only part of the variation. To minimize downtime and maintenance cost, the punches are made to the high side of the tolerance and allowed to wear to the low side, which increases long term capability. These numbers indicate that much lower tolerances could be maintained if required, but would increase maintenance cost.

CONCLUSIONS

All the data presented is from production hydroformed parts and as such is an authoritative guide to what is achievable in similar situations. A key to understanding and using this data is ensuring that any other example being compared to it is truly equivalent.

Expressing the tolerance at which a particular capability level ($C_p = 1.33$) is achieved seems to translate the statistical calculations to a number that is easier to relate to for most technical people.

Hole sizes are the most dimensionally stable feature on a hydroformed part.

Tight tolerances on cross sections are not usually customer requirements, but very high stability assures that will rarely be a problem.

Surface location is the most accurate on relatively straight parts. It tends to degrade as bends get more numerous and severe, welding is introduced and datums change during assembly. These conclusions are not surprising, but quantifying the differences is very informative.

A hole in the center of a part span is more variable than near a datum. As a result there is some opportunity to promise lower tolerances near part datums.

Hole location generally is particularly good along the tube centerline. Both this and the coordinate that is perpendicular to the centerline tends to be more capable than the surface location.

For the achievable surface complexity that is demonstrated, assembly the tolerances that can be achieved are superior to the stamp and weld assembly method that they are replacing.