

A Tolerance Adjustment Process for Dimensional Validation of Stamping Parts and Welded Assemblies

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ABSTRACT

Product design dimensional specifications provide estimates of what the next process will require to ultimately produce desired finished vehicle specifications. During stamping and body assembly manufacturing validation activities, manufacturers typically reassess these original specifications and make adjustments as needed for monitoring product quality during regular production. These tolerance adjustment practices vary considerably among manufacturers, and often even within an organization. In some cases, different teams working in the same launch program may use different approaches. This paper describes the application of a methodology that was developed and has been adopted by a North American OEM as a standard practice for dimensional evaluation and revision of sheet metal components. The methodology was validated during a recent vehicle program launch by calculating tolerance recommendations for several stamping parts. The results showed that the methodology was able to predict over 90% of the actual variation levels and subsequent process monitoring demands observed later in production.

INTRODUCTION

The development of part tolerances in the sheet metal process has been traditionally centered on the stack-up model of rigid bodies where assembly variation is a direct result of the component variation. There is increasing evidence from industrial practice and previous research that differences in rigidity between components and joint design in welding are significant factors in explaining total assembly variation.

During the launch and validation of stamping parts, the common practice in industry is to first resolve all functional and formability issues that arise during stamping tryouts. Problems such as splits and wrinkles are resolved prior to focusing on dimensional issues. After functional issues are controlled, the goal is to reach dimensional stability. Tolerances are routinely adjusted as a result of functional evaluations and during the early stages of

production. This adjustment is a proper and natural outcome that historically has been documented in over 50% of individual component dimensions during recent vehicle launches. Although few stamped component parts completely meet their original tolerance objectives, they typically are manufactured into acceptable assemblies.

Currently, most automobile companies do not have formal tolerance adjustment strategies. On some occasions, the adjustments are based on the estimated short-term variation of single runs and, on other occasions, tolerances are adjusted using a pooled estimate of the long-term variation of multiple runs. Both situations present important shortcomings. When single runs are used, the variation is usually underestimated because the intrinsic run-to-run variation of the stamping process is overlooked. The tolerance limits under this approach tend to be too narrow by not allowing some inherent amount of run-to-run variation. In the second case, when multiple runs are used to calculate a pooled long-term variance, the total variation can be overestimated if a large mean shift occurred due to an assignable cause across the runs. Thus the resulting proposed tolerance may be excessively wide. Here, the manufacturer should be focusing on stabilizing the process prior to seeking a tolerance adjustment request. In this paper, a revision and adjustment strategy is proposed. The methodology allows tolerances to be set so that mean shifts inherent to the dynamic stamping process are permitted; yet large shifts produced by assignable causes are identified and eliminated prior to calculating a realistic long term estimate of the part-to-part variation. Under this approach, tolerance adjustments may involve a shift of the mean and/or an expansion of the tolerance width. A shift of the mean simply moves the nominal value of the checkpoint to a different value while maintaining the same tolerance width. An expansion of the tolerance width can be done on only one side (unilateral) or on both sides (bilateral) to accommodate a larger part-to-part variation. The methodology was validated during a recent vehicle program launch by calculating tolerance recommendations for several stamping parts. The results showed that the methodology was able to

predict over 90% of the actual variation levels observed later in production.

The study of tolerances continues to represent an important area of research due to the exponential growth of complex assemblies in manufacturing industries. Tolerance analysis or stack-up analysis is the study of the aggregation of individual components on an assembly. Several methods have been proposed in the past, including: linear tolerance stacking, statistical tolerancing, and Monte Carlo simulation. Statistical tolerancing assumes that the tolerances of components follow some specific kind of distribution. The main idea is to determine how to stack the distributions of the components. Shewhart [1] first proposed the idea of statistical tolerancing in the 1930s. Several researchers have since proposed different approaches. A special case of statistical tolerancing is based on assuming that the deviations from nominal are statistically independent and when stacking-up they combine in a root-mean square basis. Other researchers, including Greenwood and Chase [2], applied Root Sum of Squares to nonlinear assembly equations. The results showed significant errors in the assembly acceptance. In real practice, the assumption that the variation of each component is symmetrically distributed about the mean is usually not valid. Mean shifts and drifts are very common in assembly processes. Monte Carlo simulation is used to create a statistical distribution of an assembly by randomly selecting many values from the known distribution of the component parts. Several studies have used this methodology to solve difficult tolerance problems with complex systems. Thus assembly analyses involving complex tolerance parts almost always default to Monte Carlo Simulation or to other methods such as systematic tolerance synthesis [3]. The biggest drawback of the Monte Carlo method is that it requires a large number of samples to be reasonably accurate.

In subsequent research to improve tolerance modeling, Menq et al. [4] have used hypothesis testing on the variance of the residuals that result from a least squares fit. A large variance was an indication of an unacceptable part. The sample size formula is derived to achieve a certain level of type I and type II errors for the test. The results showed that the appropriate sample size depends on both the tolerance specification and the variability of the manufacturing process. The main limitation of this approach is that the result depends on having normally distributed deviations, which may not apply to all instances such as in the presence of systematic errors.

TOLERANCE REVISION AND ADJUSTMENT

Tolerance adjustments can involve a shift of the mean and/or an expansion of the tolerance width. A shift of the mean simply moves the nominal value of the check point to a different value while maintaining the same tolerance width. An expansion of the tolerance width can be done only on one side (unilateral) or on both sides (bilateral) to

accommodate a larger part-to-part variation. The methodology is based on the following conditions:

1. Process exhibits stability and follows a reasonably normal distribution
2. Next process customer may accept either or both:
 - Component process with mean off target, and/or
 - Slightly larger variation than original design (i.e., next process may be more robust to component variation than originally believed)

METHODOLOGY

The approach for tolerance revision and adjustment has the following main characteristics:

- Utilizes data from multiple stamping runs (setups)
- Incorporates tests for process stability
- Has the functionality to check for outliers
- Provides a common process for gathering analysis data
- Provides a common reporting system

Figure 1 below illustrates the tolerance revision and adjustment process.

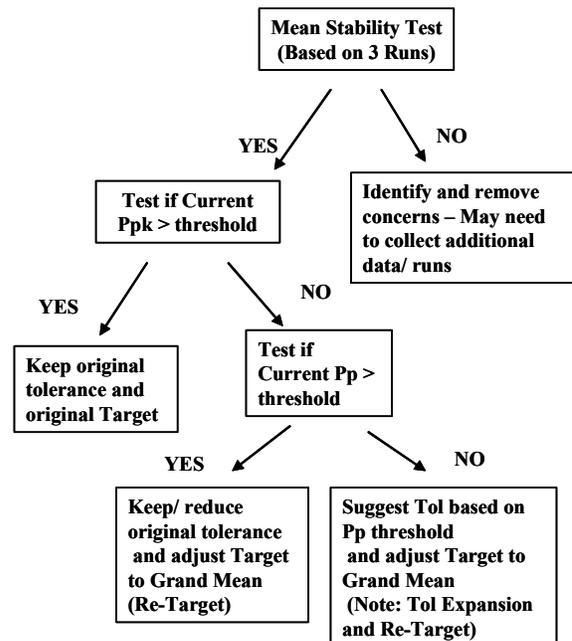


Figure 1. Tolerance Revision and Adjustment Process

The proposed process starts off with a mean stability test. The process requires three stamping runs (batches). Although the authors would prefer

additional runs, demands to approve parts for regular production within increasingly shorter intervals has resulted in a need to limit the number of die setup runs allowed for this methodology.

The objective of the mean stability test is to verify that the runs used to estimate the variation of the process are coming from a stable process. Evidence from previous research [5] has shown that measuring process stability in the stamping process is difficult due to the following process characteristics:

- Inherent variation (within run variation) – the variation in consecutive parts for a stamping process is usually quite small (sigma: 0.05 ~ 0.2)
- Run-run variation (between run variation) – most stamping variation concerns occur between stamping runs due to differences between die setups
- Mean bias – rarely are all the stamping mean dimensions at their original nominal

Due to these characteristics, using a traditional approach such as ANOVA would lead to “statistical significance” between runs even if the difference between runs is non-significant in “practical terms”. Figure 2 illustrates this situation in the stamping process. In the above examples in this figure, the small mean shifts may not present a problem to the assembly process whereas the bottom figure likely will cause a problem.

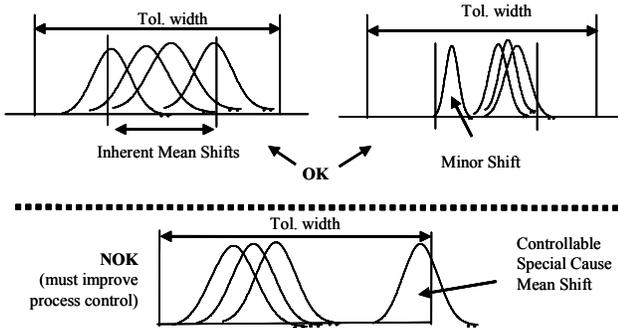


Figure 2. Mean Stability Test

The mean stability test in this proposed methodology is intended to:

- Reject large special cause (controllable) mean shifts
- Accept minor shifts (if within-run variation is small relative to original tolerance width)
- Accept some inherent mean shifts as setup is an inherent feature of a stamping process

Safe process average (SPA) is presented [7] as an alternative for establishing stability for processes that

exhibit small linear shifts. The safe process average is defined as either the largest or smallest average at which it is still safe to operate the process while maintaining a Ppk goal. The mean stability test is then defined as follows:

$$\text{Fail Mean Stability Test if : Mean Range} > \text{Max} \left(T \hat{\sigma}_{pp}, \text{SPA} \right)$$

where:

$$\text{Mean Range} = \max(\bar{X}_i) - \min(\bar{X}_i)$$

$$i = 1..r \text{ runs}$$

$$T = \text{tolerance level}$$

$$\hat{\sigma}_{pp} = \text{part - part sigma estimate}$$

$$\text{SPA} : \text{Safe Process Average}$$

$$\text{SPA} = (\text{USL} - P_{pk, \text{goal}} \hat{\sigma}_{pp}) - (\text{LSL} + P_{pk, \text{goal}} \hat{\sigma}_{pp})$$

In the first part of the test, if the part-part variation is small, then the mean range will be allowed to be wider as long as it does not exceed the tolerance level objective; on the other hand, the SPA will allow minor shifts of individual runs as long as they do not jeopardize reaching the Ppk goal. For the purpose of this study, the tolerance level for the process was set at 4 and the Ppk goal was set at greater than 1.33 as per the Production Part Approval Process developed by the Automotive Industry Action Group [7]. The estimation of $\hat{\sigma}_{pp}$ is calculated by pooling the sample standard deviation based on the number of runs (setups) available and their corresponding sample size.

DATA ANALYSIS

Data from a recent automotive launch was used to test and validate the proposed methodology. Table 1 presents 42 stamping panels grouped in 16 categories. The panels were analyzed throughout several months and roughly eight tryout events prior to the start of production. Each part had multiple characteristics or checkpoints, ranging from nine to 45 for a total of 905 measurement checkpoints. After going through functional evaluations to determine their effect on their subsequent assembly operation, 55% of the dimensions examined had some kind of tolerance adjustment (13% expansions and 42% re-targets). These adjustments were made by the OEM following a single run approach.

Table 1. Part Descriptions

Category	# Checkpts	# Expansions	# Re-targeting	Total
Front Wheel Houses	41	9	26	35
Fenders	201	65	138	203
Frame & Reinf BK	65	1	20	21
Roof	38	3	13	16
Body Side Outers	149	23	77	100
Rear Wheel Houses	24	0	3	3
C/Pillars	20	0	1	1
Body Side Inners	20	3	9	12
Lift Gate Outer	52	0	23	23
Plenum Frt	15	2	6	8
Dash	27	3	9	12
Rail F/Compt	26	1	10	11
Floor Panels	86	0	8	8
Sill Cross	38	2	12	14
Hood Outer	29	5	11	16
Hood Inner	74	1	13	14
	905	118	379	497

The focus of the analysis was to determine actual production capability and compare the current approach (with the adjustment recommendations listed in Table 1 above) to the tolerance adjustment methodology proposed in this paper. Based on the input from the production plant after six months of production, 10 of the 42 parts were selected for a detailed analysis. The checkpoints of these 10 parts were evaluated using the historical approach (single run) versus the proposed methodology. The approved engineering changes based on the historical single run approach were compared to the production performance and to the levels of variation and tolerance recommendations estimated using the proposed methodology.

Table 2 presents the results of the comparison between actual production needs and the recommendations made by the two different methodologies. The production needs were estimated using a Ppk goal of 1.33. Further details on the comparison between the methods are attached in the Appendix.

Table 2. Production Needs Comparison

Method	Production Needs	
	Re-target	Expansion
Single Run	47%	60%
Prop. Methodology	96%	93%

The results in Table 2 show that the single run approach, which has traditionally been used by the OEM, predicted 47% of the re-target needs and 60% of the tolerance expansions that were required during regular production. On the other hand, the proposed methodology predicted 96% and 93% of the re-target and tolerance expansion needs observed during production.

CONCLUSION

Tolerance revisions and adjustments are a key step in the validation process of a new vehicle. These revisions and adjustments should be carried out only after a functional evaluation activity has agreed or signed-off on the functionality of parts in the subsequent assembly operations. Therefore the proposed adjustments should reflect the inherent variability of a stable process. In this paper, the application of a tolerance adjustment methodology was presented. This approach was developed for a stamping process and its variability decomposition. Previous tolerance adjustment approaches have used estimates of short term variation, based on single die sets, to recommend tolerance expansions. The proposed multi-run methodology presented here takes into account the inherent part-to-part and run-to-run variation of the process. The main advantages of the methodology are that it tests for large mean shifts that can be attributed to assignable causes,

and it also allows for a safe level of mean shifts. The validation study showed that tolerance predictions from production plant tryout can effectively predict production if multi-run data is used. The limitation of this method is that it is sensitive to the quality of the historical data. If unrepresentative data are used, the variance estimates will not reflect the expected levels of a stable process.

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CONTACT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ANOVA: Analysis of Variance

CMM: Coordinate Measuring Machine

Cpk/Ppk: Performance capability index, takes into account differences between design target and actual process mean. Cpk index is calculated using an estimate of sigma based on process control charts ($R\text{-bar}/d_2$ or $MR\text{-bar}/d_2$), while Ppk is calculated using an estimate of sigma based on the sample standard deviation.

d_2 : Mean of the relative range, parameter to estimate sigma depending on sample size

MR-bar: Average Moving Range

OEM: Original Equipment Manufacturer

R-bar: Average Range

SPA: Safe Process Average

APPENDIX

The single run method also showed significantly higher levels of over-predictions for tolerance expansions (false alarms). As seen in Figure 3, there were 15% false alarms in the recommended revisions of tolerance width. The under-predictions were at 40%.

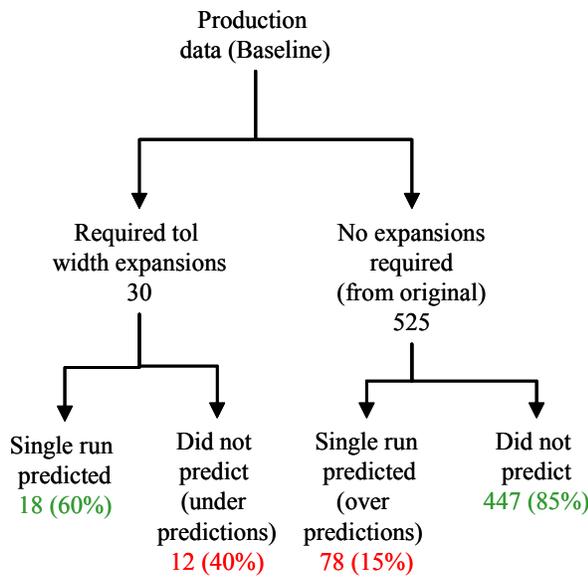


Figure 3. Single Run Tolerance Expansion Recommendations versus Production Needs

These results contrast with the estimates that were obtained using the proposed multi-run methodology. Figure 4 shows that there were 2% of false alarms or over-predictions and the errors in the estimation or under-predictions were 7% for the proposed methodology.

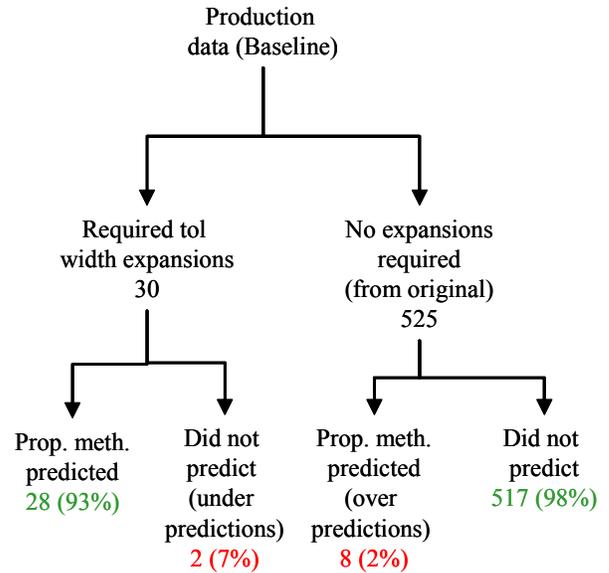


Figure 4. Proposed Multi-Run Tolerance Expansion Recommendations versus Production Needs

