IMPROVING DIE REWORK CAPABILITY

Opportunities for Using 3D Non-Contact Measurement Technology to Reduce Die Tryout Iterations to Resolve Dimensional Issues

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16. Abstract

This report summarizes automotive body die tryout performance, based on a survey of and interviews with die manufacturing experts from automotive body manufacturers and die suppliers, The report explores opportunities for more effectively integrating new 3D non-contact optical measurement technologies during the die tryout process to improve performance. It provides basic guidelines for optical measurement data collection for stamping dies and resultant parts as well as analysis methods.

For medium-complexity parts, the study participants estimate that a typical number of die tryout iterations is five to nine over a nine to 14 week period using typical North American tolerances and part acceptance criteria.

The key enablers to reduce die tryout time were advancements in die forming and simulation software, particularly for complex materials, as well as advancements in virtual assembly tools.

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Executive Summary

This report summarizes automotive body die tryout performance. Next, it explores opportunities for more effectively integrating new 3D non-contact optical measurement technologies during the die tryout process to improve performance. It provides some basic guidelines for optical measurement data collection for stamping dies and resultant parts as well as analysis methods.

The die tryout performance data is based on a survey of and interviews with industry participants and focuses on both performance (cost and timing) and potential enablers for improvement. The study participants include die manufacturing experts from two automotive body manufacturers and three die suppliers. Among the findings from the surveys and interviews are:

- For medium-complexity parts (e.g., front pillar reinforcement, 1.8 mm thick of high-strength low-alloy material), the study participants estimate that a typical number of die tryout iterations is five to nine over a nine to 14 week period using typical North American tolerances and part acceptance criteria. These estimates may increase to six to 11 iterations over 13 to 20 weeks for the most complex stamped parts (e.g., body sides). (See Section 2 for assumptions used to obtain these estimates.)
- In terms of key enablers to reduce die tryout time, the most frequent response was advancements in die forming and simulation software, particularly for complex materials. Another key enabler identified was advancements in virtual assembly tools.

For both simulation and virtual assembly modeling, manufacturers expect to benefit from advances in measurement technology. Optical non-contact measurement technology provides greater capability to comprehensively measure dies/tools and their resultant parts to better understand the relationship between product and die designs, die rework, and final part dimensional quality.

Utilizing these new measurement capabilities, however, requires new business processes and advanced planning to allow for efficient data collection and analysis. This report describes these processes, including requirements and planning recommendations, in order to demonstrate how this new measurement technology may be utilized.

A hood inner case study is used to demonstrate the measurement process and its potential capabilities. This case study involved the use of 3D non-contact measurement to make improvements in dimensional quality during die source tryout. A 20% savings was achieved in terms of actual versus budgeted tryout hours.

The generic business process contained in this report is aimed at helping manufacturers better understand the requirements and preparation needed to effectively use new optical measurement technology. We identify several decision points as not all applications have the same set of conditions and solutions. Additional case studies are planned to further evaluate the potential benefits of this process and to more comprehensively assess the ability to physically rework dies to desired dimensional magnitudes without adversely affecting other critical part dimensions.

1. Introduction

Stamping die tryout remains a major barrier to reducing overall body development costs and lead time. A key contributor to high tryout costs is budget overruns related to die rework iterations. Several factors contribute to the number of rework iterations including poor draw operation developments, formability challenges with complex materials, product engineering changes, and dimensional issues. In addition, the number of tryout iterations may vary significantly based on part approval criteria and tolerances. For this survey, participants were asked to identify the number of iterations assuming typical North American tolerances and part buyoff criteria. For medium to complex parts, survey respondents indicated that the typical number of die tryout iterations may range from five to nine[1].

The main focus of this research is reducing the number of these die tryout iterations related to solving dimensional issues. Several opportunities exist for reducing dimensional rework iterations. Among them are:

- Reducing the need for rework – manufacture dies capable of producing parts closer to their desired quality levels at the first panel evaluation of tryout.
- Reducing unnecessary rework – rework only those part features that have a measurable effect on the assembly.
- Reducing unsuccessful rework attempts – improve understanding between intended designs with die compensation, as-built conditions, and resultant parts to better identify what to physically change.
- Reducing unintended consequences – improve understanding of whether rework in one area of a part will adversely affect another (i.e., solve one problem, but create another).
- Reducing ineffective rework – identify *a priori* if physical die rework is capable of making a correction by some pre-specified amount. (Note: Limits may exist in which a part may be improved via physical rework.)

[1] Defining a tryout iteration is somewhat subjective and varies by manufacturer. For purposes of this report, we define a die tryout iteration as any event in which one or more dies in the die lineup (set) are reworked and a new panel is produced for a measurement inspection and evaluation.

We should note that defining what constitutes a *dimensional issue* may depend on the part acceptance criteria used. Of note, several North American manufacturers use significantly more stringent part acceptance criteria (e.g., Ppk > 1.33) than many of their global competitors and thus may go through additional rework iterations for this reason. So, for purposes of this research, we will assume that dimensional issues that are identified and require rework may be reasonably assumed to affect body assembly quality. We leave the issue of selecting appropriate tolerances and part acceptance criteria for other research (see Hammett et al., 1999).

Two potential enablers for reducing dimensional die tryout iterations are building dies that produce stamped panels closer to their desired nominal at first panel quality review and developing a more effective die rework analysis process (set of methods, guidelines, and decision criteria). This report provides a generic process that incorporates optical measurement technology to help make decisions related to these enablers. This process is illustrated through the use of a case study for a hood inner stamped part. In future reports, we intend to further evaluate and refine this business process through a series of case studies to establish methods and guidelines to help manufacturers first decide if physical die rework is feasible to improve part quality, and secondly to help identify what to physically change in the dies to reduce the number of iterations.

This report is organized as follows. Section 2 summarizes current die tryout performance and challenges from survey and interview data. It then discusses enablers to improve performance and mitigate these challenges. Among the enablers identified are advancements in optical measurement technology and software analysis tools to improve dimensional die rework decision making. Section 3 describes the usage of optical measurement technology in the measurement of stamping dies and parts (both operational and finished panels). This section includes requirements and preparation needed to effectively use this technology. Section 4 examines how these measurements may be performed and used within the die tryout process. Section 5 illustrates this business process using a case study for a hood inner stamped part. This section also provides analysis examples for evaluating die rework capability. Finally, Section 6 summarizes these preliminary report findings and discusses future research plans.

2. Survey and Interview Results – Die Tryout Performance and Challenges

To establish baseline die tryout performance data, we conducted a survey with interviews of industry participants in the research study. The survey participants include die manufacturing experts from two North American automotive body manufacturers and three die suppliers. The automotive body manufacturers primarily focus on larger structural panels and exterior parts (e.g., class A surfaces). The die suppliers in this study each produce approximately 50-60 sets of dies per year, with the majority of parts (over 70%) being moderately complex structural body parts or closures. Although the sample size for the number of participants is small, the tryout time estimates and challenges are similar to findings from past interviews and other research studies (Morgan and Liker, 2006; Baron and Hammett, 1999). Thus, we believe the findings are representative of current performance among other North American die manufacturers.

One issue in conducting a die tryout performance survey is the definition of the start of die tryout versus the end of die construction. For purposes of this survey, we define die tryout as the point at which manufacturers begin to evaluate part conformance to design in measurement fixtures based on parts produced using dies in tryout presses. A second methodological issue is accounting for differences in tryout due to part complexity and material. To account for these differences, we defined two case study parts: body side outer and front pillar reinforcement using high-strength low-alloy (HSLA) steel. Figure 1 illustrates the parts and material information given to respondents in making die tryout performance estimates.

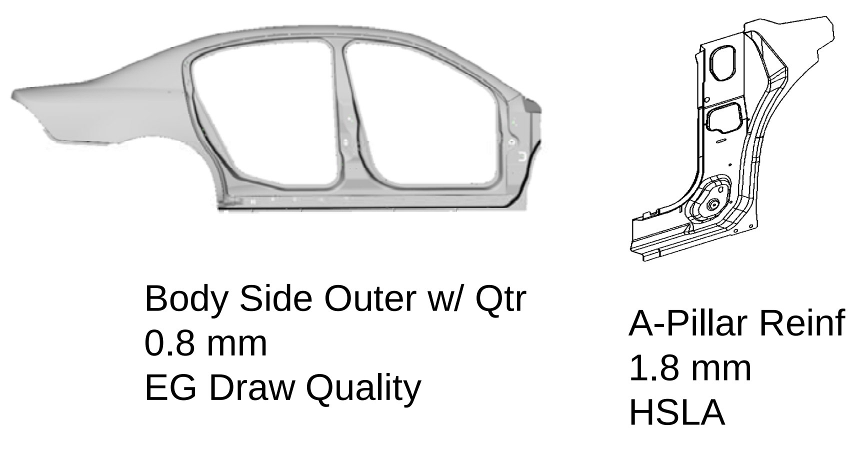


Figure 1. Stamped Parts Used for Estimating Die Tryout Performance

In addition to identifying the above two part types, respondents were also given a list of assumptions for establishing baseline performance. These assumptions were:

- The part was designed by their organization or an affiliate (partner) and they were responsible for draw development.
- The part required one set of engineering changes to be incorporated prior to shipment of dies to the production plant.
- The part was approved by the customer ("bought off") as a single stamping based on a ~five-to-ten piece sample from a single run using statistical evaluation criteria such as Ppk/Pp > 1.33. (Note: Estimates for the number of die rework iterations could vary significantly depending on criteria used for part approval.)

Many questions in the survey asked for an estimate of the typical number of die tryout trials or iterations. For purposes of this study, we defined a trial or iteration as any event in which one or more dies in the die lineup (set) are reworked and a new panel is produced for a measurement inspection and evaluation. We assume that all parts go through at least one trial in which a single part is evaluated through each die operation.

Survey participants were asked questions along three general themes: (1) die tryout performance (estimated timing and hours spent in die tryout), (2) issues/challenges that significantly increase or decrease the number of tryout iterations, and (3) key enablers for reducing die tryout time and rework hours. Results for the first two question themes are presented next.

2.1 Die Tryout Performance Survey Results – Rework Trials, Lead Time, and Hours

Survey respondents were asked to identify typical and high estimates for number of rework iteration trials, tryout time, and man-hours per rework trial. These estimates were based on two baseline parts: front pillar reinforcement and body side outer (see assumptions in prior section). The results are summarized in Table 1.

Table 1. Summary of Die Tryout Time and Iterations

Part	Baseline Material	Time in Tryout (weeks)		Number of Trials		Estimated Man-Hours per Trial
		Typical	High Estimate	Typical	High Estimate	
Front Pillar Reinforcement	1.8 mm thick, HSLA	9	14	5	9	150
Body Side Outer	0.8 mm thick; Draw Quality	13	20	6	11	200

In addition to these estimates, survey respondents identified several factors that may increase die tryout time. For example, the majority of participants indicated that some newer, highly complex materials are likely to increase the typical number of rework iterations by three or more. Related to this concern, the majority of respondents indicated the quality of the formability prediction software used has a significant effect on the number of trials.

Two other key issues identified are engineering changes and buyoff procedure. Both the die suppliers and body manufacturers noted the importance of avoiding engineering late changes to reduce tryout time. In terms of reducing rework iterations, the majority of respondents indicated a potential savings of one to two iterations by “buying off” parts that meet functional requirements at the next level or final assembly. These findings are consistent with prior research supporting a functional build strategy (Hammett et al., 1999) versus relying solely on trying to achieve Ppk statistical criteria for all stamped part dimensions (PPAP, 2002).

Based on these results, significant opportunity exists to reduce the costs of die tryout through reducing the number of trials and iterations. Ideally, most die manufacturers would like to reduce the total number of rework trials to one or two. Still, even if using conservative estimates, the potential savings from a more effective die tryout process that reduces the average number of trials by three has the potential to save each manufacturer more than $1M per year for every 50 sets of dies produced (assumptions: 3 rework trials x 50 sets of dies for a part x 150 man-hours/part x $50/man-hour = $1.1M).

2.2 Enablers for Reducing Die Tryout Iterations

The above challenges facing stamping die manufacturers are well-known. The more pertinent issues are determining the future enablers to reduce die tryout efforts and how to support their implementation. To identify and prioritize enablers, respondents were asked to rate several of them using a scale from 1-5 (1-strongly disagree, 2-disagree, 3-neutral, 4-agree, and 5-strongly agree). The results are summarized in Table 2.

The highest-rated enabler identified was advancements in die forming and simulation software, particularly for complex materials. As discussed later in this report, advances in machining and die construction capabilities can result in the construction of dies very close to the CAD die design. However, given springback and other complexities in sheet metal flow, producing dies to their tool design nominal condition does not necessarily result in panels at product design nominal condition, particularly for complex parts and materials. Thus, one implication is that tryout hours would be reduced by the greatest amount if math-based modeling tools were better able to support the development of die designs that were capable of producing parts closer to design product intent.

Table 2. Survey Responses of Enablers for Reducing Die Tryout Time

Enablers to Significantly Reduce Die Tryout Costs	Freq Median	Low	High
1. Advancements in Die Forming and Simulation Software for complex materials.	4.88	4	5
2. Improvements in Die Manufacturing Capabilities.	4.13	4	5
3. Advancements in New Technology/Processes to measure dies/tools (e.g., 3D Non-Contact).	4.33	4	5
4. Advancements in Technology/Processes for 'reverse engineering' (e.g., die duplication, digitizing prototype tools, etc.).	4.33	4	5
5. Advancements in Measurement Technology/Processes to measure stamped parts more comprehensively (e.g., 3D non-contact).	4.25	3	5
6. Advancements in Virtual Assembly Tools that use data from actual stamped parts in their evaluations.	4.25	3	5
7. Improvements in Physical Build Evaluation Processes.	4.00	2	5
8. Improvements in more effective Dimensional Criteria.	4.33	4	5
9. Improvement in management and execution of existing processes.	3.75	3	5
10. Better communication and mutual trust relationship with my customer.	4.75	4	5
11. Reduction in the current number of late engineering changes.	3.75	3	5

In addition to the above, participants were asked to identify the three most critical enablers needed to improve die tryout performance. Again, the most frequently reported response was advancements in die forming and simulation software, particularly for complex materials (see enabler 1 in above table). Other commonly cited enablers were advancements in virtual assembly tools, advancements in 3D non-contact measurement technology, improvements in physical build evaluation processes, and better communication and trust between supplier and customer.

A critical supporting element in achieving several of these key enablers is advancements in optical measurement technology, related software, and processes for measuring dies/tools/parts. The next section describes a generic data collection process that includes requirements and preparation needed to utilize this technology effectively.

3. Process for Measuring Stamping Dies and Parts Using 3D Non-Contact Measurement

Various 3D non-contact optical measurement systems are available for measuring stamping dies and related parts. In this section, we outline a generic process for measurement preparation, data collection, and analysis based on observations of several companies using 3D non-contact measurement technology. The tasks are listed sequentially although the order and usage of some will depend on the specific application. Within these tasks, we also identify several non-contact measurement issues that should be considered to maintain consistency of measurement between operators, facilities, etc. Of note, several of these issues are affected by the measurement equipment used and thus have varying solutions.

Figure 2 provides a high level flow of the process for measuring a single die or part. This flowchart decomposes the measurement process into three phases: pre-measurement, measurement, and post-measurement activities. The pre-measurement and measurement phases are examined in greater detail in the remainder of this section. Post-measurement analysis is examined in a subsequent section using a hood inner case study.

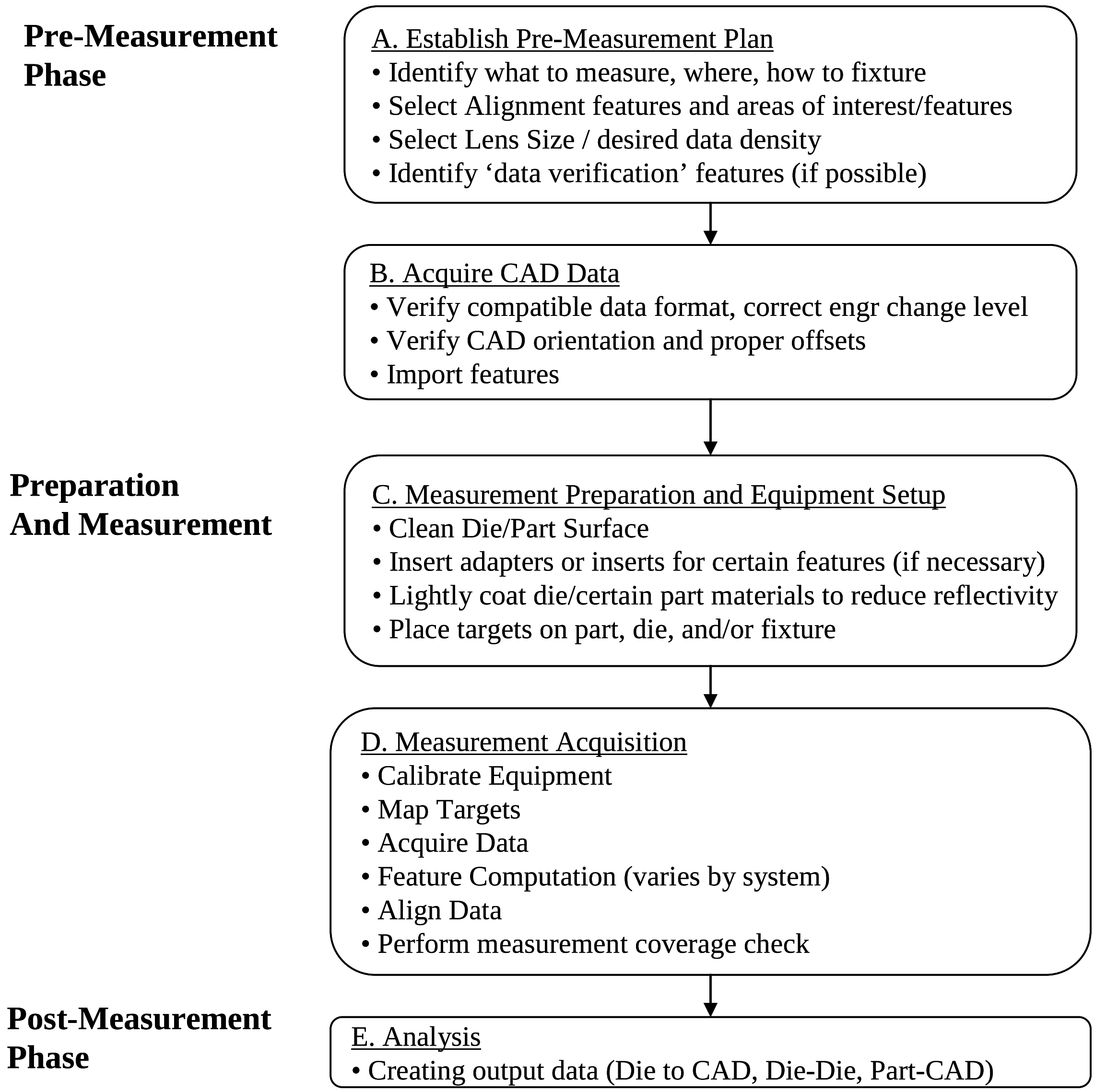


Figure 2. Sample 3D Non-Contact Measurement Process

A. Establishment of a Pre-Measurement Plan

First, a plan should be developed to clearly identify what is to be measured (e.g., die, operational panel, final panel), where it is to be measured, and how to fixture/align the part or die for measurement (i.e., how to stabilize/hold and reference the part to a body coordinate system or CAD product design). Table 3 summarizes various pre-measurement steps and our approach for these measurements in a hood inner case study.

Table 3. Pre-Measurement Plan (Task A)

Pre-Measurement	Comments/Approach
A.1 Identify measurement location	Measuring on a factory floor may present some challenges and distractions such as limited space, light interference, vibration, temperature changes, overhead interruptions, and/or nearby aisle traffic. Creating a dedicated measuring area reduces equipment movement and provides a place for storage and network connectivity. For our case studies, we typically measured parts in CMM rooms or open areas and dies on the factory floor.
A.2 Select fixtures/ stabilize the part or die for measurement	<u>*Dies:*</u> Regardless of their size, dies may exhibit some twist/sag if they are supported only in a few locations. This error is more pronounced for dies with less structure (e.g., a draw ring). To reduce this error, we would prefer to measure dies on a surface plate. For our case studies, however, this was not feasible and thus we measured dies either on the floor using protective rubber mats or on wood blocks. <u>*Finished panels*</u>: For finished panels (with all operations complete), most manufacturers use a simple holding fixture (pins and clamps without check rails, data collection bushings, hole position cutouts, or undercut surfaces for gap and flush measurements around periphery). For some parts, manufacturers may choose to also measure in free state. This is often acceptable for less complex, rigid stamped parts. For our case study, we measured finished parts in both clamped and unclamped states (for the unclamped state, we measured parts on a holding fixture using pin locators and with the panel resting on datum surfaces. But, we did not engage clamps). <u>*Operational panels:*</u> For operational panels (panels measured after draw operations or other secondary operations), measurement fixtures often are not available. Here, there are several options including: 1. Free state aligned mathematically by features 2. Operational die 3. *Ad hoc* holding fixture (e.g., holding fixture with some details or clamps not used) For our case studies, we held operational panels in dies.

Pre-Measurement	**Comments/Approach**
A.3 Identify alignment features	Next, we must identify features on the part or die that we intend to use to align the measurement data to CAD coordinates (either die design and/or product CAD). In this study, the following approaches were used. When possible, we aligned dies using keyways and other known machined surfaces. For operational panels, we used co-holes if available. For finished parts, we used holding fixtures with tooling balls for alignment whenever possible. *Dies:* Keyways and/or known machined surfaces for X, Y & Z. Note: Some companies have been observed to use inserts for the keyways to insure viewable access for measurement. *Operational panel (die as fixture and panel with co-holes):* Known die machined surface for Z and panel co-holes for X & Y. *Operational panel (die as fixture and panel without co-holes):* Keyways for X & Y and known machined surfaces for Z. Note: We recommend verifying alignment by examining section cuts. *Finished part (with fixture available):* Fixture tooling balls or known fixture surfaces. Note: Also measured hood inner using locating pins/resting on locator surfaces, but without clamps. *Finished part (without holding fixture available):* Use part features (holes/slots).
A.4 Create feature list/ identify areas of interest	Surface data is the base measurement output with non-contact measurement systems. Acquisition of other features (e.g., holes, slots, trim edges, die pins/bushings, etc.) typically require additional effort. The features selected in our case study were based on manufacturing drawings such as GD&T. Features should be identified *a priori* to insure the operator is prepared to acquire these measurements. In some cases, measuring a desired part or die feature is not possible or it may require a special insert or device. Of note, techniques used to acquire specific feature type measurements are dependent on the equipment used. Thus, we have chosen not to include them in this report.

Pre-Measurement	Comments/Approach
A.5 Select lens size (field of view/measurement volume)	Next, we must select an appropriate lens size (field-of-view size/measurement volume). The size of the die/part and the purpose of the measurement affect lens selection. In general, different lenses result in different field-of-view size (or measurement volume). On a per-measurement-frame basis, a smaller field of view will yield greater data density and vice versa. (Note: Actual lens sizes and field-of-view size/ measurement volume vary by equipment provider.) For these case studies, we used CogniTens' medium field of view for both dies and parts. Our intent was to capture finer surface detail around the periphery of both the dies and parts and to support computational algorithms for all features. In some cases, we switched to a larger field-of-view lens during measurement for less dimensionally critical center areas of large dies and parts.
A.6 Identify double-check features	When possible, we identified die/part features to double-check the measurement alignment. In some cases, we measured die pins/bushings solely to check against erroneous alignment to CAD.

B. Acquisition of CAD Data

Although not required, we recommend acquiring the die or part CAD data in advance of measurement. This allows the operator to check alignment, data coverage (e.g., surface and computed features such as holes), and agreement between the product design and measured data at the time of measurement (e.g., this verifies that measurements are at the correct engineering change level). Some manufacturers ask operators to simply acquire data and then pass it off to a downstream user. Here, the operator may not capture the requisite data needed for alignment, or may not be able to compute all the non-surface features. Of note, even if the CAD file is not acquired in advance, alignment feature points should be provided prior to measurement.

Table 4 examines several issues related to acquiring CAD data.

Table 4. Acquisition of CAD Data (Task B)

CAD Data Acquisition	Comments/Approach
B.1 Verify compatible file format	The CAD format must be compatible with software used for measurement and post-measurement analysis. Generally, standard interchange formats for product CAD (e.g., IGES) can be used. Formats corresponding to widely-used CAD packages (e.g., CATIA, Unigraphics, etc.) also may be used. As companies use 3D non-contact measurement systems, this issue is generally resolved with simple planning.
B.2 Verify appropriate engineering change level and CAD design file	Obviously, the product CAD data must match the part being measured. Thus, engineering change level is important to verify – especially during die tryout. For dies, users must acquire CAD data matching the die surface being measured. Of note, die surfaces can go through several iterations corresponding to a single final part change level. Thus, getting data that exactly matches the die level may not be feasible. Die changes may be manually incorporated into a die without formally updating the die design or die surface file. As such, measuring actual dies relative to die design is not always useful, particularly late in tryout. As tryout progresses, we prefer to examine die measurements relative to prior die measurements (i.e., before versus after a rework attempt) or relative to product CAD coordinates.
B.3 Verify CAD orientation	CAD data should be obtained in the proper orientation. All surface deviations and feature measurements are computed relative to CAD as it is in the coordinate system. Dies are typically measured relative to die coordinates (Z is the direction of press movement; 0,0,0 is at the center of the lower die mating face to the bolster). The upper die may also have its own coordinate system with 0,0,0 at the center of the top face mating to the ram. Die coordinate systems usually differ from product CAD and may change between die operations. Thus, analysis is complicated if comparisons are being made from die-to-die or die-to-product. Here, the machined surfaces may need to be offset in Z and/or rotated about Y (tip angle). The machined surface position and tip angle of each die in a lineup should be identified. Note: Measurement outputs (*.stl files) may be transformed later to a new coordinate system if transformation coordinates are known (using CAD software, for example, to transform a file from the coordinate system of one die to another).

CAD Data Acquisition	Comments/Approach
B.4 Verify proper offset (if necessary)	The CAD offset must be accounted for if the CAD is offset from the die/part being measured. For parts, sheet CAD, or one-sided CAD, this may present a side-of-metal issue. Here, the CAD has 0 mm thickness causing confusion as to which side of metal is represented. This problem is more pervasive with part data though it may exist with die CAD data. For instance, it may lead to some confusion as to whether sheet CAD represents the lower or upper die surface.
B.5 Import features (if available and required)	Depending on the system, desired features (e.g., alignment points or dimensional monitoring points) may be imported into a measurement project file. Importing features from a repository reduces the effort required by the operator to look up feature coordinates and enter them manually. Pre-loaded features also are useful to direct the operator's measurement (feature acquisition can easily be overlooked). Finally, the operator can actively compute and review features to potentially diagnose setup or alignment errors.

In addition to the above, some potential challenges may result based on the format of the die CAD data. For example, die data may be in the form of (1) a full die design file or (2) a die machining file. We recommend using the full die design file, which typically contains the die working surface as well as pierce/trim features, keyways, pins/bushings, stop blocks, etc. These features are needed for alignment and measurement, plus they provide verification items to double-check measurements. Of note, these files may also contain wiring, sensors, gaging, cylinders, and other information that is not needed for measurement. Thus, they do require some manipulation or file cleanup to select the desired information.

In contrast, a die machining file contains only the die-machined working surface used for NC machining. In our experiences, the base die design is not always updated to reflect morphed surfaces (developed for formability/springback), trim/pierce features, or engineering changes. Thus, using a die machining file as the process standard limits downstream analysis capabilities. Furthermore, the operator must get die alignment information (e.g., keyway or Z surface coordinates) from a source other than this file.

C. Measurement Preparation and Equipment Setup

Preparation and equipment setup is critical to accurately and efficiently measure dies and parts. Table 5 summarizes key steps and issues in the measurement preparation and equipment setup phase. For these case studies, most measurements for either a die or part involved part measurement and equipment setup times ranging from approximately 20 to 40 minutes. Of note, the amount of setup time may be reduced if the equipment is applied in a more permanent setting.

Table 5. Measurement Preparation and Equipment Setup (Task C)

Measurement Setup	Comments/Approach
C.1 Clean dies/parts	An initial step in setting up a measurement is to clean the die/part surface and alignment features (e.g., holes) of any oils, metal shavings, or debris.
C.2 Add adapters or inserts (as needed)	If required, adapters or inserts may be needed for certain alignment or part dimension features. Some examples include: ▪ Keyways ▪ Plates or magnets for under-side surfaces ▪ Weld studs (e.g., for assemblies)
C.3 Apply light surface coating or spray (if necessary)	For dies and certain materials such as aluminum, a light surface coating is needed to reduce the reflectivity of the surfaces being measured. Highly reflective surfaces, such as a machined die surface, almost certainly require surface preparation. Adapters and parts may or may not require surface preparation depending on the system used and the surface finish. For these case studies, we prepared dies and aluminum parts with a light coating of MagnaFlux developer spray (about 10-30 microns) to reduce surface reflectivity. Of note, the required spray thickness can vary by system and surface conditions, but will likely fall in this range. This amount generally is considered insignificant for die and part measurement though it may limit the ability to do virtual spotting.

Measurement Setup	Comments/Approach
C.4 Place targets on part, die, and/or fixture	For manual 3D non-contact measurement systems, measuring dies and stamped parts usually requires targets. The number and spread of these targets will vary depending on the part, application, measurement system, and lens size used. For some applications, targets may be incorporated directly into part measurement fixtures. If using automated systems, they may be built into the cell design. Still, targets usually are required for die and operational panel measurements. For these case studies, we used a manual system and placed targets on all dies and parts measured.
C.5 Prepare for virtual die assembly (optional)	If the intent is to perform a virtual die alignment, some additional planning and work are needed. The complete die – upper and lower in the closed position – will need to be prepared with targets and mapped. Measurement does not take place with dies in the closed position. Here, only the targets are mapped to be able to later reposition the upper (or lower) die measurements to their closed-die positions. Afterward, the upper and lower dies must be separated and prepared with additional targets suitable for measuring the die working surfaces. The mapping should include targets on the outside of the die for virtual die assembly. Care also should be taken to capture die alignment features.

D. Measurement – Data Acquisition

The specifics of acquiring measurement data are determined largely by the measurement system used. Still, the measurement process for manual 3D optical measurement systems typically follows the steps outlined in Table 6:

Table 6. Measurement Data Acquisition (Task D)

Measurement Acquisition	Comments/Approach
D.1 Map targets	A global mapping of the targets usually must be performed. Calibrated scale bars (and perhaps a special origin marker depending on the measurement system) should be placed within the setup area. Care should be taken such that the scale bars are stable, do not obscure any targets, and do not disturb the setup when removed after mapping. One must also place special unique targets throughout the mapped space. Propriety system software (from the equipment provider) is used to compute the position of each target in the mapped space along with errors (overall error, scale bar error, weak or bad targets, etc.). The acceptability of a given mapping should be determined by pre-established limits for error and the ability of the operator to overcome weak or missing targets. Note: This mapping step may be eliminated for certain small part applications.
D.2 Calibrate equipment (if necessary)	The optical head should be calibrated to the operating environment temperature. Calibration compensates for the temperature of the optical head, not the temperature of the target die/part. Data is collected per a calibrated standard. Proprietary algorithms tune software parameters that are used to adjust measurement data for the temperature of the optical head. This calibration step is recommended, though it can be skipped if the head temperature is still within an acceptable temperature range of its previous calibration.
D.3 Acquire data	3D non-contact measurement involves taking a series of "pictures" over the entire area of interest as well as any alignment or dimensional monitoring features. Data may be collected in any order, though we recommend beginning with alignment features or areas of the setup that could be easily disturbed (for example, by loose clothing or by having to lean over the setup when positioning the optical head). Actual data collection time varies by the size of project, number of special features, and operator skill.

Measurement Acquisition	**Comments/Approach**
D.4 Reposition or adjust part/die	*Parts:* To measure some part dimensions or alignment features, the part may need to be adjusted or moved during measurement. For instance, if measurements are needed on two sides of a part, the part may need to be flipped over during measurement. With proper target planning and mapping, most systems will accommodate such issues. *Dies:* For dies, some movable parts may need to be activated or de-activated to provide measurement access. For example, to completely measure a draw die, a traveling draw ring may need to be measured as well as the punch. Here, the ring in the raised position will obscure the draw punch and must be lowered. Conversely, the ring in the lowered position is obscured by the punch and must be raised (particularly if data is needed on the side walls of the draw bead). In our case studies, we addressed this issue by charging/de-charging the ring depending on which portion of the die was being measured. Charging the ring, however, can damage the die or even be dangerous if charged when the die is in the open position. Formal procedures should lay out specific guidelines in this case.
D.5 Compute features	This task will vary by the measurement system used.
D.6 Align data	Raw measurement data is not aligned in any known orientation. Thus, data must be aligned to CAD for reporting and analysis using the alignment features selected during pre-measurement. A transformation of the data must be applied by features and/or targets to known CAD features or known X, Y, and/or Z nominal values. Alignment is perhaps the most critical decision in measurement. See section 3.2 for a more complete discussion.

Measurement Acquisition	Comments/Approach
D.7 Perform measurement coverage check (optional)	Next, we recommend that the operator check if data coverage is complete and aligned with CAD. Sometimes data coverage is too thin to compute certain feature deviations or a part may fail to align with the pre-selected alignment features. During tryout, particularly when a die or part is being measured for the first time, it is recommended that additional time is spent checking for data coverage and that all desired features compute. In some cases, operators may want to create a few section cuts and/or a surface deviation color map to satisfy that the data is sufficient and aligned properly. For these case studies, we checked for sufficient data coverage by trying to compute all predefined feature deviations prior to closing a part measurement project. Of note, in some cases we were unable to obtain all desired feature measurements. Depending on the system used, one visual check for data coverage is to produce a color map before closing the project file. This may quickly show inconsistencies in part CAD change levels, alignment issues, or feature measurement problems.
D.8 Perform measurement clean up (as required)	For most applications, some data will be collected on unintended areas. For example, data may be collected in clamped areas, non-critical fixture surfaces, or non-critical die surfaces. For these case studies, we typically had to delete some point cloud data in these unintended areas. Of note, many software reporting tools (such as CogniTens Coreview) have tools to compute the percentage of a measured surface within a deviation range (e.g., percentage of surface with 0.25 mm of CAD design nominal). These results may be skewed if non-essential part or unintended die surface data is included in the measurement output.

E. Post-Measurement Analysis

The collection of 3D non-contact measurement data offers the potential for numerous analyses. We demonstrate several of these methods through the application of a hood inner case study in a later report section. Additional dimensional analysis processes using 3D non-contact measurement also are discussed in Hammett et al., 2006.

3.2 Die Alignment

Alignment, though not difficult, is perhaps the most debated issue when questions arise related to data integrity. With advanced planning, alignment for a single measurement is generally straightforward. However, alignment consistency over multiple measurements (of the same die and/or multiple dies in a lineup) can easily be broken. In addition, features for a die alignment may be different from those that are used for machining setup or die positioning in the press. A well-defined strategy minimizes alignment differences that different operators may employ (e.g., selection of different Z surface features by different operators).

In establishing a die alignment strategy, several challenges and issues must be resolved. First, since dies may have several known X, Y, and/or Z features, the possibilities for alignment are numerous. One strategy is to establish an alignment method that most closely represents the die positioning in the press (e.g., use of bottom of shoe for Z and keyways for X and Y). One can argue that alignments other than this introduce errors as the relationship between the die base features and the alternative alignment features is unknown.

Alignment error minimization objectives also must be balanced with the practicalities of 3D measurement. Optical measurement is easiest to apply to top-side die features. However, the positioning of keyways and/or other desired alignment features often are not on the top side or easily accessible for visual measurement. One company was observed to resolve this issue by using an adapter tool that fit into the keyway to align in X, Y, and Z. Here, the adapter is positioned off of the keyway and bottom die surface and juts out from underneath the die making it readily accessible for visual measurement.

Another issue is alignment robustness. 3D non-contact systems typically are most reliable at measuring surfaces; other features rely on algorithms to detect and compute features (e.g., hole centers and diameters). Thus, a robust alignment strategy would:

- Utilize surface features for X, Y, and Z alignment
- Have top-side accessible Z surfaces
- Have extra alignment points available (versus a strict 3-2-1) in the event that specific alignment features cannot be computed or to perform alignment sensitivity checks.

3.3 Part Alignment

Similar to dies, part alignment is essential to allow for comparison between the actual part surface/holes/trim edges and the product design. There are several options available for part alignment. These include using:

- Known dimensions on the fixture (e.g., tooling balls or known surfaces)
- Specific features on the part (e.g., 3-2-1)
- Multiple point iterative alignment
- Best fit iterative alignment

For these case studies, we aligned finished stamping panels using known dimensions on the holding fixture. If holding fixtures with known features are not available, manufacturers typically select specific part features and perform a mathematical alignment. This is often acceptable, particularly for less complex, rigid stamped parts.

For operational panels (panels measured after draw operations or other secondary operations), measurement holding fixtures with known features (e.g., tooling balls) typically are not available. Rather, measuring operational panels typically involves alignment using one of the following:

- Free state aligned mathematically by features
- Operational die
- *Ad hoc* holding fixture (e.g., holding fixture with some details or clamps not used)

For our case studies, we measured operational panels in dies to hold/stabilize the panel and specific features on the part and/or die for alignment. For drawn panels, we measured on the draw punch as it provided sufficient support for nearly the entire panel. Of note, a panel may exhibit some springback and thus require the aid of shims to locate by part form. The use of shims, of course, should be avoided if possible because they are dependent on the operator (e.g., different operators may use different placements and numbers of shims).

One way to simplify alignment of operational panels is to use co-holes on the part. This also may be more accurate than using die features such as keyways for X and Y alignment. Of note, we would still use die surface features for Z alignment.

In the case where a draw operational panel was measured for machining the second die in a lineup, we measured the operational panel on the draw punch die to simulate panel nesting in the secondary die. This approach is believed to reduce nesting and spotting effort as compared to a process where the second die is machined to math nominal. (Note: The drawn operation panel is not likely to look like part math despite the draw development modeling.)

4. Die/Part 3D Non-Contact Measurement Evaluation Die Tryout Process

Figure 3 illustrates the general die tryout flow at the construction source and potential break point opportunities for measuring dies and parts. If prototype dies or carryover dies are available, die and part measurements could begin earlier to support draw die development.

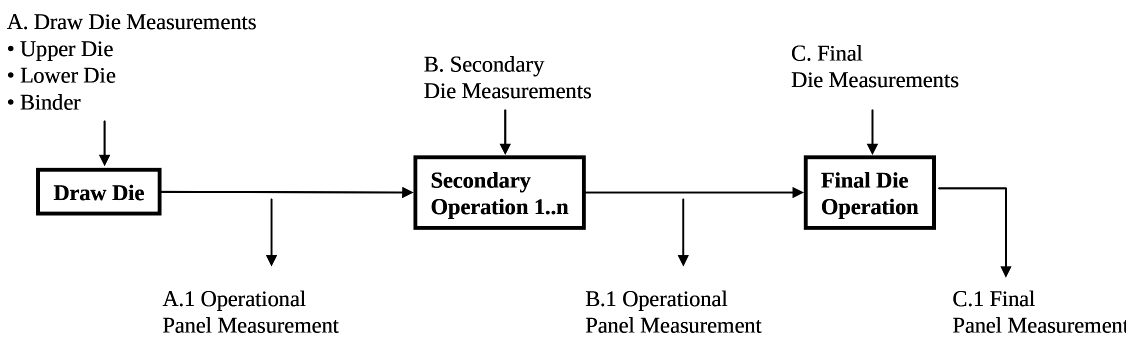


Figure 3. Die/Part Measurement Points

Traditionally, manufacturers measure dimensions on only finished panels (after completing all operations). Thus, the approach shown above will involve additional effort and should be pursued when the potential savings in terms of die rework efforts are projected to outweigh the additional costs of measurement. For the purposes of this report, we assume that such opportunities exist, particularly for complex materials and historically difficult parts to get approved dimensionally.

In a generic process for such a part, one approach is to first tune the dies to resolve formability concerns until a panel is ready for inspection (i.e., first panel review on gage). At this point, one could measure the draw dies (upper, lower, and binder) and the drawn operational panel. These measurements may be used to evaluate draw panel shape to product CAD design. Of note, before making draw die rework decisions, a manufacturer may wish to explore how the panel changes in secondary operations (either using the subsequent production trim dies or perhaps via laser trimming). In addition to evaluating operational panels to product design, drawn operational panel measurements may be used to evaluate springback prediction models for either evaluating rework alternatives or improving future model prediction. In addition, operational panel measurements may be used for secondary operation tune-in (machine secondary die operation based on an operational draw panel).

Once a drawn panel is deemed acceptable, manufacturers would then complete the remaining operations and measure the final panel using 3D non-contact systems. This finished panel would serve as the baseline condition for analysis and part quality assessment. The measurement of secondary die operations would then be done on an as-needed basis for problem diagnostics.

5. Case Study Hood Inner Stamped Part – Observations and Analysis

We now illustrate the above processes using a case study for a hood inner part. For this case study, we measured both dies and parts at first panel review when a split-free panel was produced and ready for measurement. As expected, certain areas of the part were not dimensionally acceptable and required rework. This particular rework iteration involved changes to the draw die as well as two secondary trim die operations. Figure 4 summarizes the measurements taken before and after the rework loop. Of note, operational panels were not measured after the rework iteration. Since all three dies in the lineup were reworked, we focused on the physical changes in the dies (primarily the draw and final trim operation) and the resultant effect on finished panel measurements using their checking fixture.

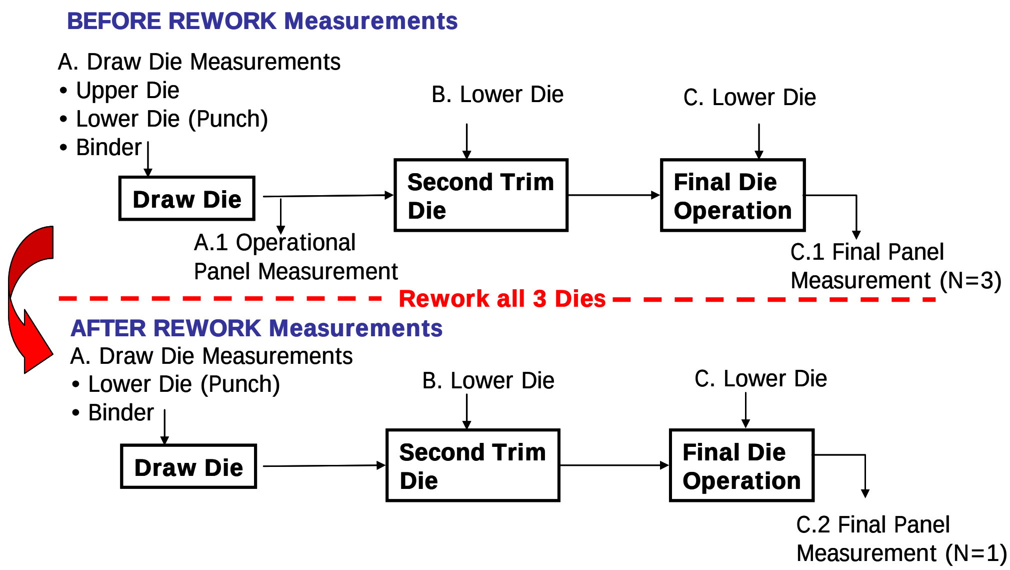


Figure 4. Hood Inner Case Study Measurements

5.1 Baseline Condition – Dimensional Concerns at First Panel Review

To evaluate the baseline part dimensional quality condition, three finished panels were measured. Measurements were taken by loading the parts in their check fixture and taking measurements in both the clamped and unclamped conditions. The results are shown in Figure 5.

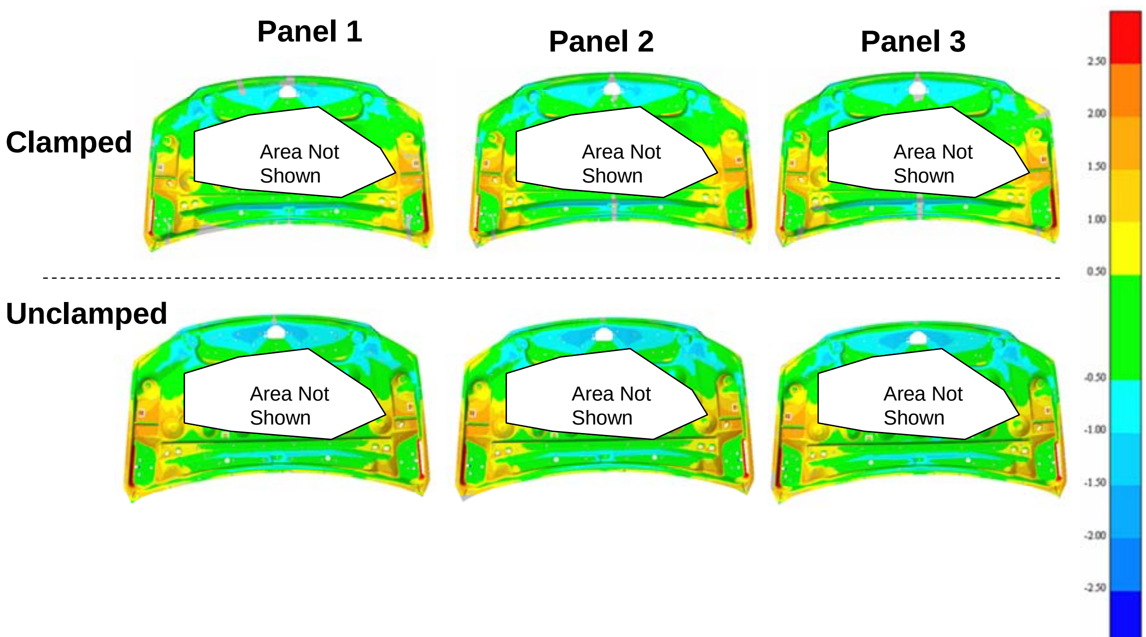


Figure 5. Hood Inner – Three-Piece Sample

Overall, the panel fit reasonably well using locating holes and net surfaces. The following Delta color map compares the average panel in the clamped versus the unclamped state. Over 99% of the surface moved less than 0.25, suggesting that the clamps themselves had minimal effect.

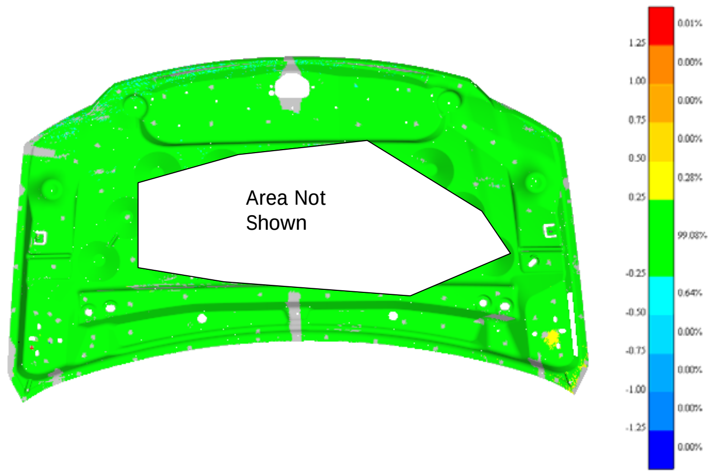


Figure 6. Delta Color Map: Clamped Vs. Unclamped Panel

Figure 7 shows average and range color maps for the three-piece sample for the clamped condition. In terms of mean conformance to CAD nominal, about 60% of the total part surface was within 0.5 mm, with 80% within 1 mm. The variation in the three-piece sample was also very low; all range measurements were less than 0.25 mm (for either the clamped or unclamped condition).

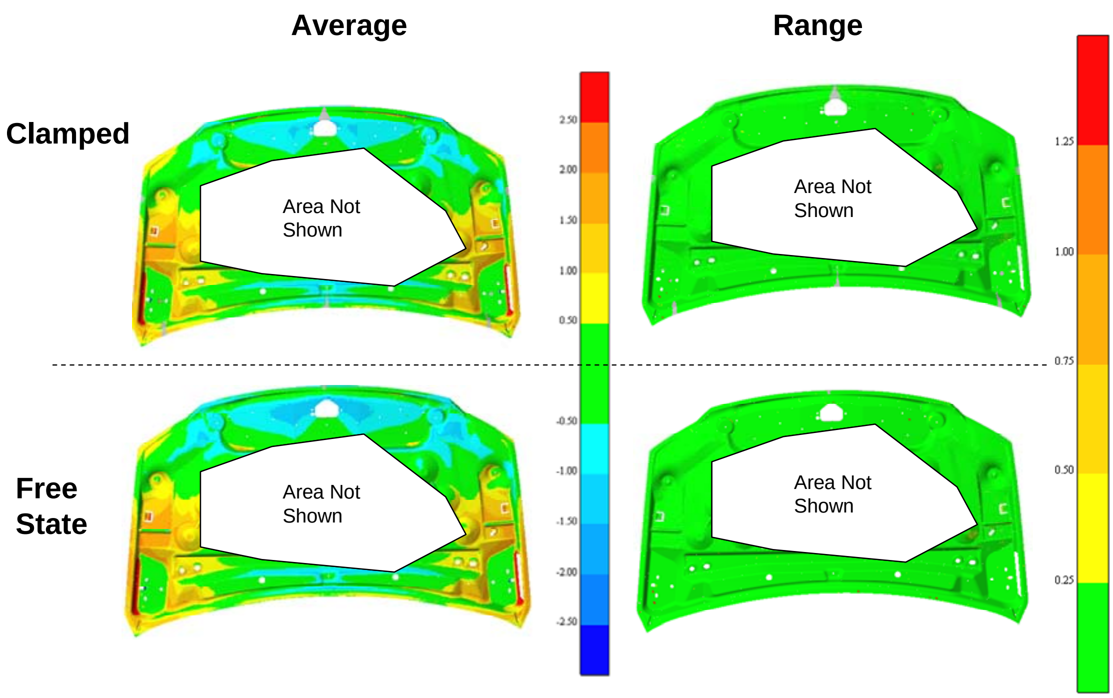


Figure 7. Hood Inner: Average – Range Map

The results of this initial assessment were that these panels were consistent (i.e., low variation) but off nominal, particularly in a few key dimensional areas. For instance, the outer flange area was 0.5 – 1.5 mm up (high relative to car position). Related to these measurements, the panel was crowning (see Figure 8). Of note, the mean deviations from side to side for this initial panel review were fairly symmetric. In other words, the mean deviation patterns on the LH side of the panel were similar in direction and magnitude to mirror points on the RH side (same X and Z body coordinates, but opposite Y coordinates).

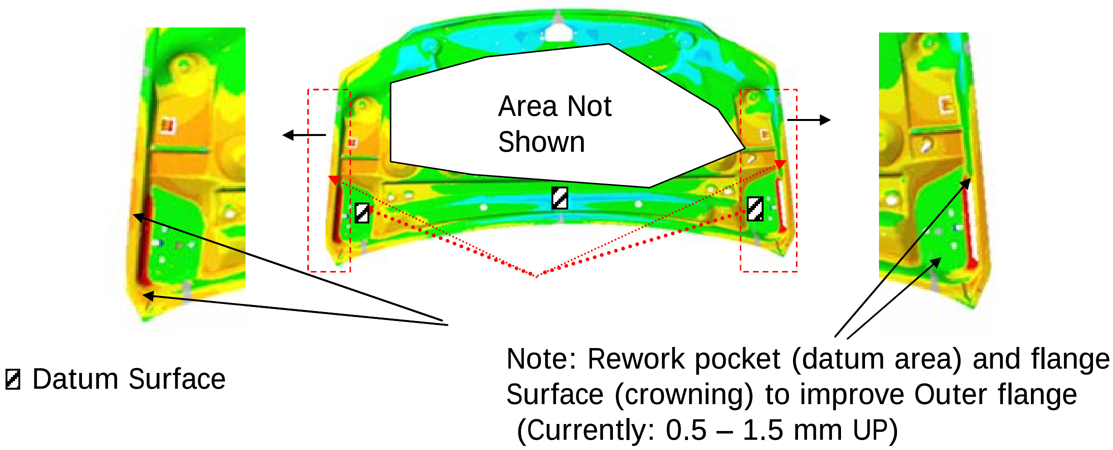


Figure 8. Hood Inner – Rework Areas

In addition to the panels, we also measured the draw die (upper, lower, and punch) and trim dies. For example, Figure 9 shows the surface color map for the draw die lower (punch). The die surface is fairly consistent with the desired surface after construction. About 66% of the surface was within 0.2 mm of its desired tool design.

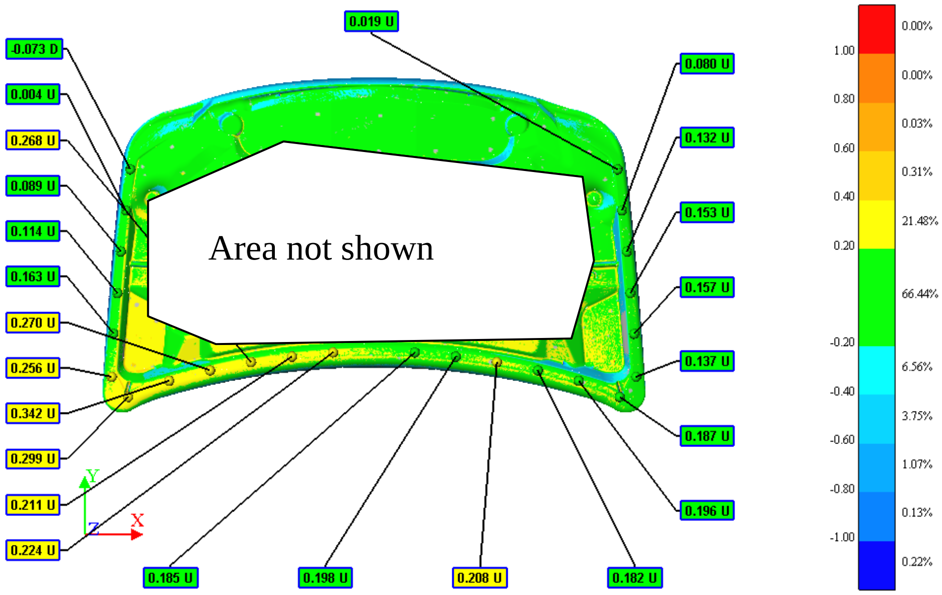


Figure 9. Draw Die (Punch)

5.2 Post Rework – Die Changes

For this particular case study, all three dies in the lineup were reworked to improve the outer flange area. The most significant changes occurred on the draw die punch. Figure 10 shows the revised punch die after rework. Of note, several areas were reworked away from the original die design in an attempt to improve the final part quality.

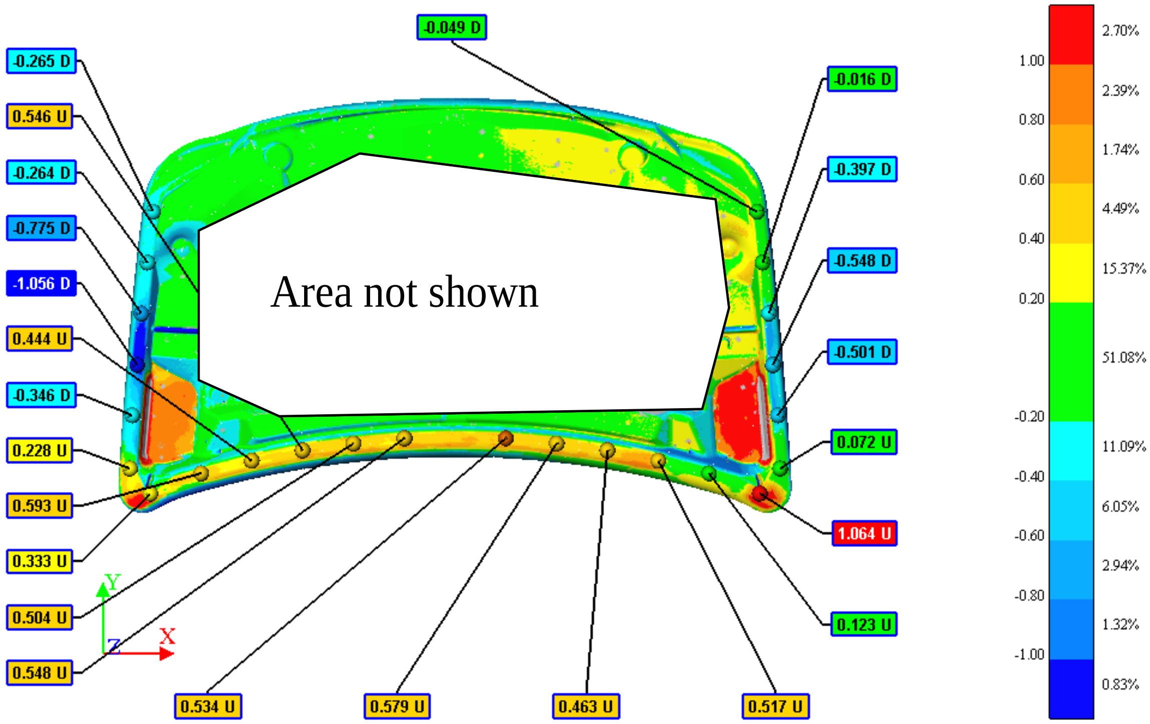


Figure 10. Draw Die (Punch) after Rework

Figure 11 shows the difference in the draw die punch surface before and after rework. Of note, the non-rework areas were very consistent suggesting a consistent alignment between the two die measurements (about 73% of the overall surface changed less than 0.1 mm after rework).

The most significant changes occurred in the outer flange area (to remove crown effect) and in the hinge pocket. The hinge pocket surface was shifted up after rework to create a shallower draw. The goal was to shift the hinge pocket up, thereby shifting the outer flange area down, to get the desired final measurement result. Because this hinge pocket area represents a primary up/down datum location, dimensional changes to this area may not be observed in reviewing finished part measurements using the check fixture to hold the part.

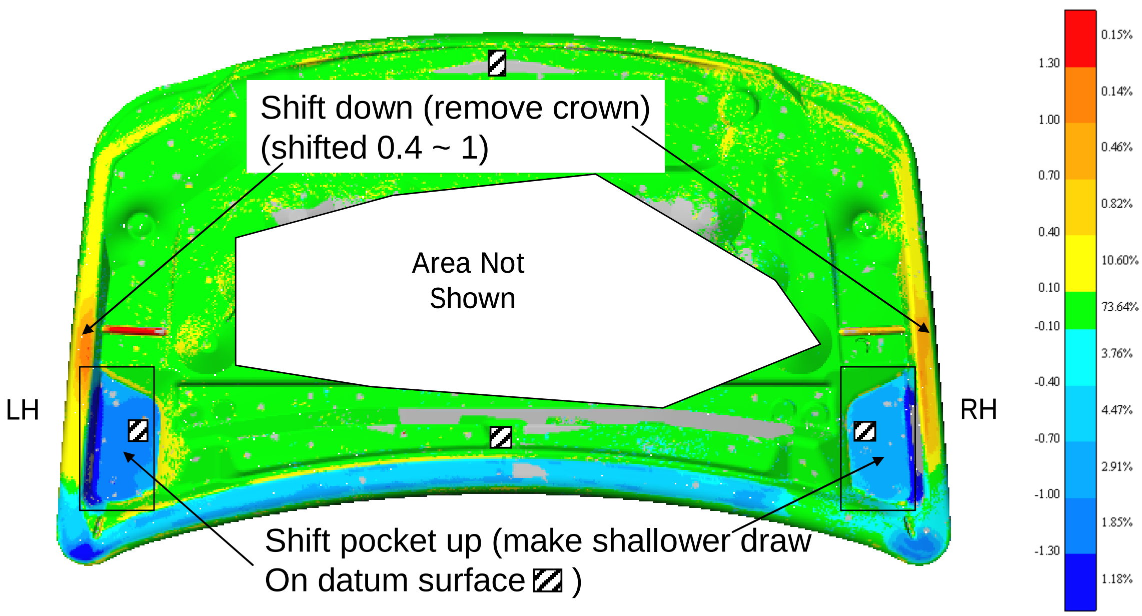


Figure 11. Change in Punch Die Surface – before and after Rework

One observation is that the manual rework activity in these areas resulted in less symmetry between the LH and RH sides' corresponding points. In this case, the LH side was shifted more (~1.1 mm versus ~0.8 mm). In addition, we may observe that in the back of the hood, the rear RH flange was changed less than the rear LH flange area. In some cases, the amount of rework to the die surface between RH and LH mirror point locations varied by as much as 0.5 mm.

Similar changes may also be observed by comparing the final trim die before and after rework (see Figure 12). Figure 13 shows the differences from before to after rework. Here, one can observe the areas adjusted down for the crown and the movement in the hinge pocket area to make a shallower draw. Similar to the draw die, rework was not symmetric between RH and LH mirror point locations.

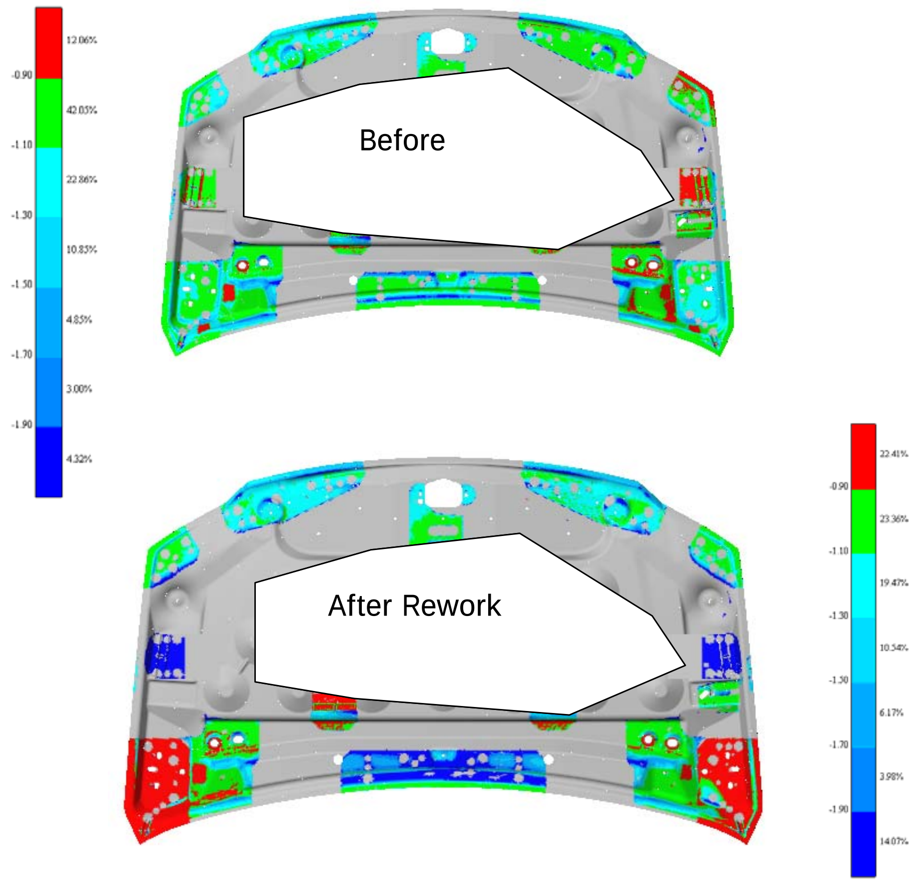


Figure 12. Final Trim Die – before and after Rework

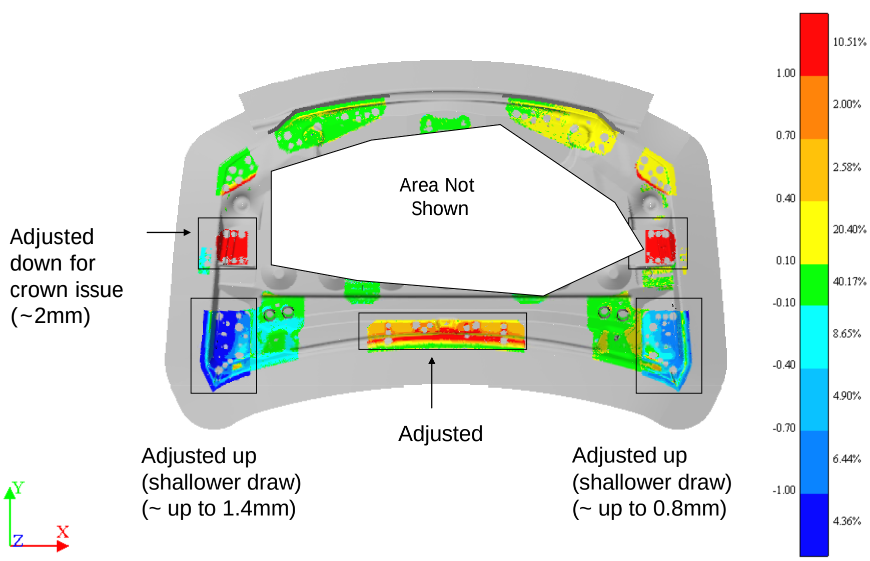


Figure 13. Change in Final Trim Die Surface – before and after Rework

5.3 Case Study Findings – before and after Panel Measurements

The final dimensional effects are shown in Figure 14. Here, we may see coordinated changes to the panel dimensions related to the rework areas. However, we may also observe that some areas that were not changed in the physical dies shifted during the rework process. This demonstrates a common challenge of die rework in trying to avoid unintended consequences.

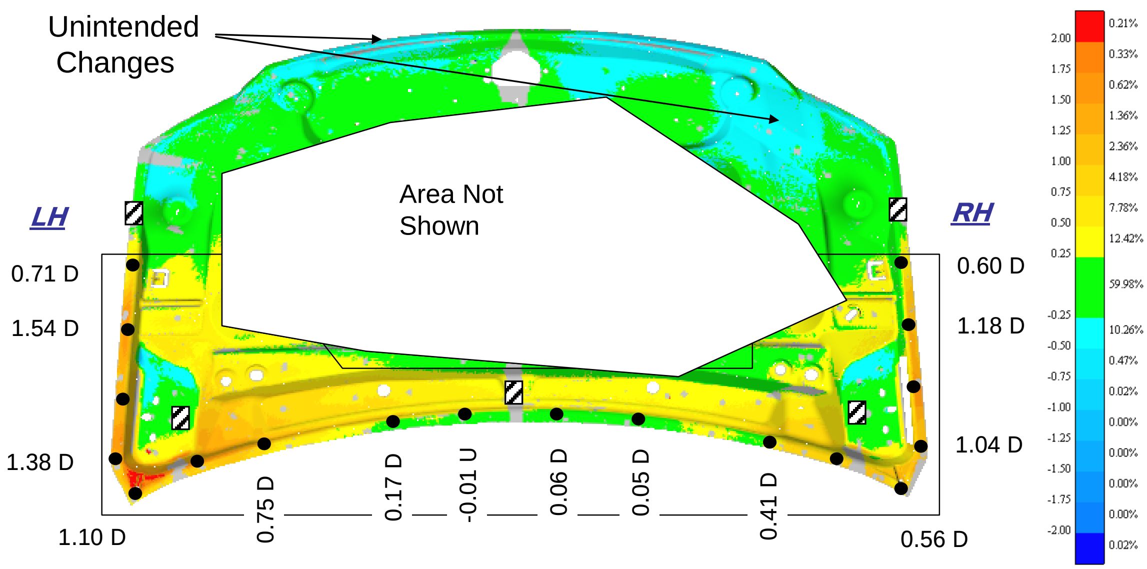
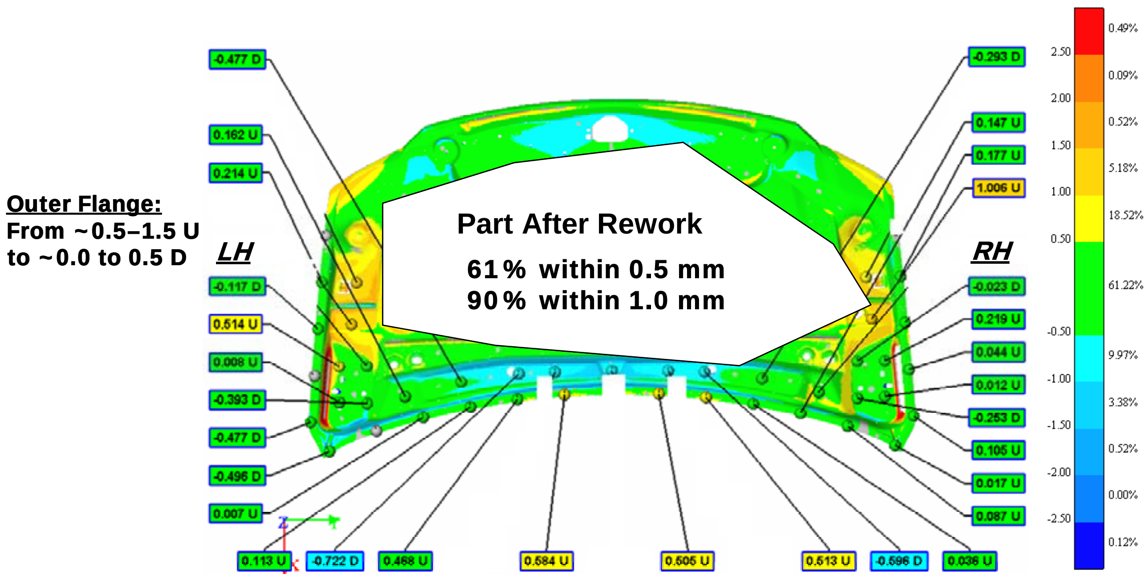


Figure 14. Dimensional Change – before and after Rework (Difference)

Figure 15 summarizes the final part relative to its product CAD design nominal. In this case, the rework iterations were able to change several of the areas of dimensional concern. However, the overall conformance of the entire panel surface to nominal was similar before versus after rework.



Note: Before Rework: ~58% within +/- 0.5mm; ~86% within +/- 1.0mm

Figure 15. Dimensional Comparison – before and after Rework

This case study demonstrates the application of 3D non-contact measurement in support of die tryout for measuring dies and parts. Of importance, the physical changes in the dies before versus after rework had corresponding effects on the final part dimensions in the key areas of interest. Still, some unintended consequences were observed in terms of overall panel dimensional conformance.

This particular case study involved fewer rework iterations than noted in the survey estimates. Several factors may have contributed to this finding including the use of soft tools to reverse engineer the initial die designs, less stringent buyoff criteria, and experience by this manufacturer in producing this type of panel. Thus, one should not infer that these improvements are solely the result of using the above process. More case studies are needed to demonstrate that consistently fewer rework iterations may be achieved.

6. Conclusions and Future Research

This report provided a summary of automotive body die tryout challenges and recommendations for integrating the use of 3D non-contact optical measurement technology to improve performance. The report provided some basic guidelines for measuring stamping dies and resultant parts using this technology.

A hood inner case study was used to demonstrate the process and its potential capabilities. This case study involved the use of 3D non-contact measurement to improve dimensional quality during die construction source tryout. Although this report contains only a single case study, a 20% savings was achieved in terms of actual versus budgeted tryout hours.

Additional case studies are needed to further evaluate the potential benefits of this process and to more comprehensively assess the ability to physically rework dies to desired dimensional magnitudes without adversely affecting other critical part dimensions. This will be the subject of subsequent reports.

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Appendix – Die Tryout Performance Survey

I. Company Background Questions.

1. Which of the following categories best describes your organization? (Please check one)
   Tool and Die Manufacturer with No Stamping Production
   Tool and Die Manufacturer and Stamped Supplier
   Tool and Die Operation within an Automotive Manufacturer

2. Approximately, how many sets of dies do you perform die tryout on each year?
   ___Sets of stamping dies per year

3. Of the following types of stamped parts you manufacture, please allocate the percentage of your output across the categories listed below. (Responses should total 100%. E.g., 20% small; 70% moderate; 10% closures)
   ___Small, structural body panels
   ___Moderate – complex structural body panels
   ___Closures and Exterior Panels

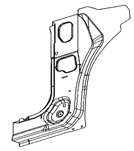
4. Of the dies you tryout in a typical year, please estimate the following.

   ___ percentage of dies that you also performed die machining and construction
   ___ percentage of dies that you also designed internally (within your organization)

II. Die Tryout Baseline Case Study

5. Given the following two case study parts (body side outer and front pillar reinforcement),

Body Side Outer w/ Qtr
0.8 mm
EG Draw Quality



A-Pillar Reinf
1.8 mm
HSLA

Please complete the following matrix using these ASSUMPTIONS:

- Each die is designed by your organization or affiliate in which you are responsible for draw development (i.e., exclude the case of die duplication or existing die replacement)
- Each part requires *one* set of engineering changes to be incorporated prior to shipment.
- Each part is approved by the customer ("bought off") as a single stamping based on a ~5 pc sample from a single run and statistical evaluation criteria such as Ppk/Pp > 1.33.

	Time in Tryout (weeks)		Number of Trials		Man-Hours
Part and Material	Typical	High Estimate	Typical	High Estimate	Estimated Hours per Trial
Body Side Outer (0.8 mm, Draw Quality)					
Front Pillar Reinforcement (1.8 mm, HSLA)					

- ***Note: Please include the first die tryout trial in your response.***
- ***Trial ~ any event in which 1 or more dies in the lineup are evaluated in a press and a new finished panel is produced.***

6. Please select the response that best describes the effect on the 'typical number of Trials' when one of the baseline assumptions is changed for the Body Side Case above only. *Options: Reduce 3 or more trials, Reduce 1-2, No effect, Increase 1-2; Increase 3 or more*

Utilize a slightly more complex material in which you have some experience.
Utilize a significantly more complex material.
Draw development is provided by your best customer (most desirable to supply dies).
Draw development is provided by your worst customer (least desirable to supply dies).
Dies/Parts were designed using the best formability prediction software available.
Part is bought off as part of an assembly in which you are responsible for all major parts.
Typical Number of Engineering changes occurs for your best customer.
Typical Number of Engineering changes occurs for your worst customer.
Stamped Parts are bought off by your best customer.
Customer representative approving your part has significant experience in die making and its challenges.

III. Enablers

7. The following are intended to identify what you consider the key enablers for reducing die tryout time and man-hours. For each of the following, please rate using the following scale.

1-Strongly Disagree; 2-Disagree; 3-Neutral; 4-Agree; 5-Strong Agree or Not Applicable.

Enabler
A. Advancements in Die Forming and Simulation Software for complex materials are critical to significantly reduce Die Tryout Costs.
B. Improvements in Die Manufacturing Capabilities are critical to significantly reduce Die Tryout Costs.
C. Advancements in New Technology/Processes to measure dies/tools (e.g., 3D Non-Contact) are critical to significantly reduce Die Tryout Costs.
D. Advancements in Technology/Processes for 'reverse engineering' (e.g., die duplication, digitizing prototype tools, etc.) are critical to significantly reduce Die Tryout Costs.
E. Advancements in Measurement Technology/Processes to measure stamped parts more comprehensively (e.g., 3D non-contact) are critical to significantly reduce Die Tryout Costs.
F. Advancements in Virtual Assembly Tools that use data from actual stamped parts in their evaluations are critical to significantly reduce Die Tryout Costs.
G. Improvements in Physical Build Evaluation Processes are critical to significantly reduce Die Tryout Costs.
H. Improvements in more effective Dimensional Criteria are critical to significantly reduce Die Tryout Costs.
I. Improvement in management and execution of existing processes are critical to significantly reduce Die Tryout Costs.
J. Better communication and mutual trust relationship with my customer are critical to significantly reduce Die Tryout Costs.
K. Reduction in the current number of late engineering changes are critical to significantly reduce Die Tryout Costs.
L. Other:
M. Other:
N. Other:

Comment (OPEN) – Given the above enablers, identify the three most critical (you may include any additional enablers you identified).

1st Most Critical

2nd Most Critical

3rd Most Critical

8. The following questions are intended to evaluate your current efforts in utilizing the above enablers for reducing die tryout time and man-hours. For each of the following, please rate using the following scale.

1-Strongly Disagree; 2-Disagree; 3-Neutral; 4-Agree; 5-Strong Agree or Not Applicable.

Evaluation of current efforts utilizing the above enablers.
My company is effectively utilizing:
Die Forming and Simulation Software.
Die Manufacturing Technology.
Technology/Processes to measure dies/tools.
Technology/Processes for 'reverse engineering'.
Technology/Processes to measure stamped parts.
Virtual Assembly Tools that use actual stamped part measurements.
Physical Evaluation Processes and Dimensional Criteria.
Management and execution of existing processes.
My company has excellent communication with our customers.
Other:
Other:

9. OPEN: What are the most critical actions *within your organization's control* needed to reduce die tryout costs (and still meet part quality/functional requirements)?

10. OPEN: What are the most critical actions *by your customers (either external or internal)* needed to reduce die tryout costs (and still meet part quality/functional requirements)?