UNIVERSITY AND INDUSTRY COLLABORATION TO SOLVE WELDING QUALITY PROBLEM USING DESIGN OF EXPERIMENTS (DOE)

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Abstract – *A local automotive seat supplier experienced a major quality problem in the fabrication of the metal seat frame used in the manufacture of the front bucket seats of automobiles. This quality concern was failure of the seat cushion weld nuts to adhere to the metal seat frame during random quality torque testing at the lower specification limit. A company executive contacted Middle Tennessee State University (MTSU) and requested a six-sigma study to determine the root causes of the problem and to work with his engineering and operations personnel to implement countermeasures. The six-sigma project team was setup by the company Project Champion and was led by the university Project Leader. The team consisted of the company welding engineer, three operations personnel, the MTSU professor, a graduate student, and three undergraduates. This paper focuses on the Design-of-Experiments portion of this project that required close collaboration between the industry and the university personnel.*

Index Terms – design of experiments, CIEC, multi-welder, six sigma

BACKGROUND INFORMATION

Problem Description

The tier one supplier to the automotive industry has a specific problem in the welding station that welds four nuts to each seat pan. The four nuts that are welded to the seat pan are not welded consistently in the welding operation. The nuts with poor weld adhesion have to be replaced down stream in the manufacturing process, thus causing added expense for repairs. The nut welding operation was producing defective welds that averaged six defects per week. Since there are four weld nuts per seat and 10,000 units fabricated per week, the defect rate per million opportunities (DPMO) is 150 DPMO which represents a sigma level of 5.1. This sigma level is consistent with most good processes; however, “zero defects” is the requirement for this important weld.

Process Description

This automotive seat supplier fabricates the upper and lower sheet-metal seat pans in one of its facilities. The lower seat support is a “cushion” pan that will be attached to guide rails using the four nuts to allow the vehicle occupant to adjust the seat. (The seat pans are moved to another facility to have the guide rails, foam and covering materials added before shipping to an automotive assembly plant). In the welding station operation, the lower cushion pan fixture rotates clockwise to align the seat frame with four projection nut welders. Each welder welds a six millimeter nut to the pan using the same basic welder equipment configuration. A weld nut is automatically fed to each lower alignment pin with a pneumatic feed system. An upper cylinder has an attached electrode that will mate with the seat pan, weld nut and lower electrode. When this cylinder is extended an electrical circuit is made which allows the welder high-current to be passed through the nut and the seat pan generating the heat necessary to weld the nut to the seat pan.

Some basic research was needed that would help the MTSU personnel better understand this welding process and define the variables that affect weld quality. Projection nut welding is completed by forming projections in one or both of the work pieces; the current path is localized at the projections [1]. Several factors and components are included in projection nut welding. A pneumatic cylinder is used to place the nut to the piece that it is to be bonded. Air pressure is then supplied to the cylinder to hold the nut in position. Current flows from a transformer through a copper shunt to the electrode. The four protrusions on each nut are then melted and fused with the sheet metal. This projection geometry permits the use of flat

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electrodes, thus producing welds at the projections. The nut welding operation uses different variables to produce a good weld or melting together (fusion) of the metals. Projection nut welders are common in the manufacturing process, but are constructed and configured in different ways. For example, MIM Industries Incorporated uses the Fanuc3i robot for part placement and uses the Dengensha projection nut welder to carry out the weld operation [2]. Even though configurations vary, fortunately the variables are common to all projection welders. These variables include air pressure for the cylinder that presses the nut onto the metal, contact points between the electrodes, weld current, and contact times as detailed below:

- Tip force – the pressure level that the electrodes contact the metal is controlled by an air pressure regulator.
- Contact points – with contact quality level dependent upon electrode condition.
- Weld current – current amperage levels controlled by a transformer and weld timer controller.
- Hold time – the amount of time the upper electrode makes contact with the nut while the current is passing through.
- Squeeze time – the amount of time the electrodes make contact before the current is passed through.
- Cool time – the amount of time the electrode makes contact while the weld is in the cool-down period [3].

From information obtained through collaborations with the company Welding Engineer, the key to making good welds is determined to a great extent by the setup levels for each of these variables with influences as indicated below:

- Tip force level – high enough to hold the projection firmly against the mating part during the weld time and to cause complete projection collapse after welding to prevent metal separation; and, low enough to give proper projection collapse without metal expulsion (influences degree of porosity in the weld "nugget") and to not affect the effective weld contact area.
- Contact point condition – use of electrodes of proper design and alloy with daily checking by operators and proper "dressing" bi-weekly by maintenance personnel.
- Weld current level – high enough to cause fusion prior to projection collapse, but low enough to prevent distortion of the weld nut shape or to prevent contamination of the nut threads with weld slag.
- Weld time – the value of weld time will be dependent on the weld current and projection rigidity; and, short enough to allow production cycle times to be accomplished to meet production throughput. (The squeeze time and cool-time are primarily used with spot welders and their effects unknown for projection welds. The DOE will be utilized to discover these effects, if any).

Collaboration – Team Interaction & Decisions

The MTSU graduate student was setup as the team leader and had the opportunity and to apply his education in soft skills acquired the previous semester. He had to tactfully deal with the maintenance and operations personnel as he instructed them in how to setup the welder and how to collect the data needed under normal operations. Also, during the testing phase, he had to obtain safety policy from the company and teach the undergraduate students proper safety techniques in working around and with the welding equipment as well as the sheet metal and test equipment. While evaluating the initial results, it was necessary for him to collaborate with the Welding Engineer so that test methods and data analyses could be understood and any changes made based on those evaluations. Students learned how to operate the equipment by teaming with maintenance and operations technicians (a "pizza" luncheon provided by the project leader went a long way to cementing a good relationship). This collaboration was very important since valuable insight into the machine operation was provided to students for use in setting up the test runs. The operations and maintenance technicians provided invaluable insight into the operation ranges of the welder settings to the team leader as well. Everyone from MTSU understood the importance of maintenance and operations personnel experience and both groups treated one another with respect. Both university and company personnel truly learned the importance of learning from one another through honest and open collaboration.

The MTSU professor from the Engineering Technology and Industrial Studies Department at MTSU decided that a Design of Experiments (DOE) analysis would be the appropriate technology to apply as part of the overall six sigma "analysis" methodology. He contacted the company's Project Champion to obtain permission to run the test at a non-production time with the understanding the testing would provide 36 scrap parts and would require use of maintenance/operations personnel with support from the MTSU group.

- The DOE should be a 2-level, full factorial, 5-factor interaction model (current, hold time, squeeze time, weld time, and tip force) with 4 mid-points for linearity checks requiring a total of 36 experiments with one output (weld nut failure torque) per experiment. The company agreed to provide 36 cushion pans for the DOE tests.

- The welder level settings are dependent upon the actual process involved and must be determined through the collaborative process described earlier.

- Experimental data would be obtained from tests using one of the four welders (head #1) and one fixture (fixture #4). This head was chosen since the data showed it to be representative of the other welders in terms of defect rates. The fixture was chosen at random since the Welding Engineer stated that the fixture tooling appears not to be a factor that affects weld quality.

- The two levels for each variable (high value and low value) were obtained primarily from two company Maintenance Technicians on the project team based on their experiences in working with the process engineers during the original equipment installation and setup. For example, they knew the maximum current level that could be run just prior to weld nut distortion as well as the minimum current level that would produce a good weld.

- Testing was scheduled for a non-production period on a Saturday morning to be conducted by the MTSU project leader with students handling the parts for identification, welding, and torque measurement; and, with Maintenance Technicians operating the welder. The company would provide a peak-reading torque wrench for measuring the torque at which each nut weld failed (one weld nut to be checked per panel).

DESIGN OF EXPERIMENTS (DOE)

Test Method

The DOE software, Design Ease ®, used to design this experiment is a product of Stat-Ease, Inc [4]. The data sheets were generated by the software and were used on site at the seat fabrication plant to run the experiments. The data "runs" were randomized by the software to minimize any bias in the data by randomizing unknown effects external to the experiment.

Seat panels were loaded one at a time, on the same fixture (#4), and were cycled through all weld heads on the rotating multi-welder table. The automation fed nuts to each weld point, but only one weld point/head was analyzed (#1). Changes in the levels of each variable (either at its highest or lowest setting) were made through the touch-panel multi-welder station control interface (except for the tip pressure which was adjusted using a pressure valve with analog meter feedback). Four (4) tests were run at setting each variable at its mid-point to check for linearity. The maintenance technician made the setting changes as read out by the student taking data, while being monitored by the MTSU project leader. Another student loaded a panel and cycled the multi-welder through its normal operation with all other fixtures being empty. After the panel was welded, a bolt was placed into the nut to make sure it was clear of slag and not distorted, and then the panel was marked with the DOE run number for later torque measurement. The tests were performed in "run-number order to randomize the setups.

The finished panels were taken to the QC teardown area for destructive torque measurements. Torque was applied to the nut being tested until the weld failed and the nut broke loose (345 inch-pounds was the low specification limit that would assure a proper weld). The peak torque was recorded at which the weld failed. This part of the testing was quite difficult since applying torque consistently (without "jerking" the wrench or changing the rate) was not practical due to the manual nature of this process – particularly for the high torque levels. (For a more accurate output measurement, a motorized, digital device is needed. Even though some variation was introduced at this point of the testing, the DOE software provides statistical confidence intervals based upon variation). There were four (4) weld nuts of the 36 test panels run which could not be broken loose. Readings were recorded for these tests at the point the seat pan metal began deformation (at approximately 800 inch-pounds).

Test Results

- The ANOVA for the model indicated the model itself was significant with an "F-value" of 13.11.
- Weld current, weld cycles, tip force, and the interaction between squeeze time & weld time are probable significant factors. A notable exception was hold time which was not a significant factor.
- The "curvature" was not significant; however, the model "lack of fit" was significant. It is desirable to have a model that fits in order to predict performance at various levels of variable settings. (Several "transforms" were attempted to get a better fit, but none were found that gave a good fit while maintaining insignificant curvature).
- The model "Predicted versus Actual" showed some correlation, but not strong enough for reliable predictions.

The Welding Engineer suggested combining the squeeze time & weld time into a new single variable "time," and dropping the hold time; and, re-run the DOE as a 3-factor interaction model (weld current, time, and tip force). The new data gave the following improved results:

- The ANOVA for the new model indicated the model itself was significant with an F-value of 136.8.
- Weld current, time, tip force and the interactions between weld current & time, and time & tip force are probable significant factors.
- The "curvature" and "lack of fit" were not significant, even after the confidence level was changed from 95% to 99%; however, the "Normal Plot of Residuals" did not look "normal."
- To improve the "Normal Plot of Residuals" the data was transformed by a "power transform," which provided better results. The other model parameters still remained at relatively the same significance levels as the previous model. <u>This analysis means that this last model is robust and can be used to reliably predict output torques for various level settings of the variable factors.</u>

DOE Conclusions & Recommendations

The Tip Force variable directly affects output torque and is a significant contributor to weld strength. Surprisingly, the output torques improved as the tip pressure was reduced (just opposite to what the team thought intuitively). In fact, the present setting of 70 pounds per square inch pressure is a primary contributor to low torque failures particularly at the low weld current settings that are often run. It is recommended that this pressure should be lowered to a value based on the desired throughput time and welder amperage desired as follows:

- To obtain the lowest weld time of 4 cycles (1/60th of a second per cycle), set the tip force to 35 psi (one-half the original setting) and weld current to 12,100 amps. The DOE model predicts within 99% confidence that the lowest individual torque reading will be 400 inch-pounds (higher than the 365 inch-pound low limit specification) with a population mean reading of 500 inch-pounds.

- For lower weld current and a more typical setting of weld time of 10 cycles, set the weld current to 11,350 amps at the 35 psi tip force recommended above to achieve the same torque output values.
- After a trial set of parts are run, it may be found desirable to raise the tip force to the mid-point setting of 52.5 psi. For this setting the weld current must be increased to 12,500 amps at a weld time of approximately 11 cycles to obtain the output torque ranges stated previously.
- Leaving the tip force at its current setting of 70 psi must be compensated by an increase in current and in weld time. To achieve the same torque values stated previously, the weld current should be set to approximately 14,000 amps with a weld time of approximately 15 cycles.

For a weld that will not break loose until the surrounding metal fatigues, the weld current should be set at 15,000 amps, with tip pressure at 35 psi and weld time at 30 cycles. If this outcome is desired, another set of trial parts should be run to confirm good weld nut quality (i.e. no weld slag or nut deformation). For improved throughput and improved weld nut quality (no deformation or slag), it is recommended that during this trial run, the weld time should be experimentally decreased until the yield point is determined.

SUMMARY & CONCLUSIONS OF COLLABORATION

As a result of the University and Industry project team collaboration, the company made a successful "running change" to immediately reduce welder tip force to eliminate the defective welds. The low torque issue is solved and the multi-welder is currently running close to "zero defects" (missing weld nuts due to automation feed problems are being addressed currently by the six-sigma team). Without the University team members, there would have been no DOE, and without the Industry team members there would have not been a successful DOE. Neither group could have accomplished this part of the quality improvement program without the other. The industry Project Champion provided the resources needed by the team; the Welding Engineer provided the technical welding expertise and critical information needed to revise the DOE model to a robust version that allows reliable (99% confidence) prediction of output torques versus variable setting levels; and, the maintenance technicians were invaluable in determining the high/low level ranges for test purposes and for running the welding automation. The university project leader provided the technical expertise needed to setup the DOE and to coordinate testing with all members of the Project Team; and, the undergraduate students worked diligently with the maintenance technicians in actually performing the tests and measurements. The graduate student project leader is continuing with this project to address issues in setup standards & control, preventive maintenance (PM), and Total Productive Maintenance (TPM). The students were also able to learn about how a tier 1 supplier to automotive OEM's operated. The company personnel were able to learn how sophisticated statistical software could be successfully applied to solving their problem and were quite delighted with the results.

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