PROCESS CAPABILITY IN HEAT TREATING

Developing the statistical tools necessary and applicable quality characteristics can be a major challenge for gas carburizing and similar operations.

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nternal and external demands are increasingly placed on automotive manufacturing, which results in heat treaters seeking innovative means to adapt quality tools to their processes. This paper describes the statistical methodology that we have developed to improve overall quality in our heat treat operations and to track process capability.

Quality tools have been used in our carburizing operations for several years, but one element missing until recently had been the ability to quantify with capability indices the effectiveness of using such tools. The challenge became how to implement an effective SPC/SQC methodology for heat treat furnaces given the following constraints:

- Furnaces run several different “recipes” on different components
- Components are made of different materials (whose chemistry varies with heat number and/or supplier)
- Each component has a different heat treat specification
- Routine destructive inspection is cost prohibitive

To meet this challenge we employ a methodology of placing a standard size test bar in each carburizing load. It is routinely analyzed to determine effective case depth (ECD) and other more qualitative microstructural criteria. Resulting ECD data are then used as a guide to adjust furnace atmosphere parameters. Although establishing an absolute direct correlation between the test bar ECD and that of the parts has been elusive, we can predict whether or not a load is heat treated to specification. Furthermore, the statistics allowed a specification for the test bar ECD to be established and consequently, the ability to compute capability indices for the furnaces.

Gear carburizing process

Routinely, six different recipes are run in several integral quench, endothermic gas atmosphere batch furnaces to gas carburize various gear components. These components are assembled into a safety-critical product and have stringent min-

imum/maximum effective case depth (ECD) requirements. The components are worm, spur, and spur rack gears weighing between 1.4 and 8.2 kg (3 and 18 lb) and are carburized to ECDs ranging between 1.1 to 1.6 mm (0.045 and 0.065 in.).

To expedite inspection and to minimize the scrap lost in destroying actual parts, a 25 mm in diameter, 51 mm long (1 x 2 in.) cylindrical test bar is heat treated with every load. Quantitative inspection — measuring the required ECD to 50 HRC — is then limited mostly to the bar. An added advantage of using the test bar is eliminating steel chemistry fluctuation effects by employing single-heat test bar stock for several years. In addition to enabling statistical quality control (SQC) functions, the data are also used to adjust the furnace’s atmosphere as explained below. In essence, this achieves statistical process control (SPC) from a resulting characteristic.

A partial setback in using the test bar method was that attempts to establish direct correlation between bar and actual part ECD were largely unsuccessful. As it turned out, it was not possible to predict the exact ECD of actual parts. Fortunately, judicious analysis of the data afforded a near 100% confidence that the parts were heat treated within specification, resulting in the ability to compute furnace capability, demonstrating that the process is indeed capable by calculated C_p and C_pk values well above a value of 1.

Statistical data handling

To achieve confidence in the test bar inspection method, sufficient paired data (bar ECD and actual component ECD) was gathered. A key element
was limiting the bar data used for statistical analysis to only loads that knowingly produced parts within specification. This was done to eliminate misuse of data that may have been associated with “special cause” problems, i.e., only normal variation was present in the analyzed data.

In practice, the mean bar ECD vs. cycle duration should follow the line labeled “target” shown in Figure 1. For each cycle or recipe, the overall (all furnaces included) statistical mean test bar ECD can be calculated. This value then becomes the target for each cycle or recipe.

All furnaces can run any one of the six recipes at any time. To track furnace performance with only one statistical chart — independent of cycle duration — a normalization step was utilized. The resultant test bar ECD value obtained for a particular recipe was divided by that cycle’s mean target value to yield a ratio that fluctuates around a value of “1.” Resultant ratios were plotted on Individual/Moving Range (I/MR) charts (Fig. 2, 3).

By detecting trends in the I/MR charts, our practice is to make relatively small changes in the parameter that electronic controllers use to calculate carbon potential (or dewpoint) from oxygen probe signals. This parameter reflects the value for atmosphere carbon monoxide content, which is normally not measured. For our equipment this parameter is known as the “process factor.” This approach has been found to be an effective and efficient method to regulate the overall system with one parameter. Caution must naturally be exercised to not intentionally vary process factors outside a meaningful range. Typically, adjustments are not made unless control chart data reflect that the process is “out of control,” based on standard control chart interpretation rules that depend on the number of plot points being considered. Figure 4 shows an example where the factor was changed, and how the chart reflects the effect.

I/MR charts are also a powerful means to achieve quality assurance functions. By establishing ±3σ control limits, parts are acceptable when the test bar ECD ratio falls within the control band. This precludes sacrificing parts to destructive inspections. When values fall outside of the band, our quality system mandates that an actual part be sectioned and checked for specification conformance. Each furnace has its own statistical control

![Fig. 1 — Target test bar ECD values for each cycle have been established from averages from all furnaces (red line). The other two lines shown are the averages for furnaces 2 and 6 for the year 2001.](image)

![Fig. 2 — I/MR chart and histogram indicates process variation for Furnace 1 in 2002. Data outside the UCL represent special cause events such as after burn-out effects, weekend shutdown effects, or thermocouple failure among others.](image)

![Fig. 3 — I/MR chart and histogram indicates process variation for Furnace 2A in 2002.](image)
band, which will vary with furnace conditions within a given time period. The widths and location of the control limits with respect to the target will vary in time and from furnace to furnace. However, the most desirable condition is to have a band as narrow as possible, and centered with respect to the process target (not the actual statistical mean). Therefore, for added quality, a single control band is imposed on all furnaces, based on the actual historical best limits obtained. That is, control band evaluation of each furnace revealed that at least one of them was capable of a centered control band with a 0.92/1.08 LCL/UCL. This band, designated as the process control band, is thus the standard imposed on all furnaces. It provides the principal guideline to adjust the process and establish the limits for which an inspection “reaction” is necessary, i.e., an actual part from the load must be inspected.

Over the years, it has been observed that unless a malfunction occurs due to an assignable cause, the loads in most cases meet specification even when the test bar ECD ratio falls outside of the control band. Serious malfunctions, such as an oxygen probe failure or a large leak, result in large departures from the control limits, in which case carbonized components are historically of unacceptable quality.

**Calculating capability**

The absence of a direct correlation between test bars and part ECDs precludes using the part heat treatment specifications for determining capability. Yet even though the exact ECD for the actual parts is not known, the statistical methodology works remarkably well as evidenced by two facts: the absence of heat treat related functional problems with our products, and the vast majority of “out of control” loads (without apparent assignable cause) actually do check within specification upon inspection. This latter fact is understandably a product of imposing an aggressively narrow control band on the process. Not only does this raise the overall quality, but these outlier data make it possible to establish a specification and thus calculate process capability.

Whereas we work with an imposed control band (the process control band) of 0.92 to 1.08 (“1” being the target), we usually observe actual control limits — actual ± 3σ of a particular furnace data population — that

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Table 1 — Outlier values for each cycle observed since 1997

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<th>Minimum</th>
<th>Maximum</th>
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* Less than 2 data points in this group.

range between 0.89 and 1.12. This implies, and is in fact observed, that there will be data points outside the process control band, thereby creating the need to destructively inspect some loads. For our operation this represents approximately 1.5% of the loads and the generation of approximately 30 outlier paired data points (test bar data and actual part data) per year. On average, 20 out of these 30 points correspond to loads within specification as evidenced by destructive evaluation. The remaining points correspond to loads for which an assignable cause is known. In these cases, the parts will be outside of specification and are either reworked or scrapped. In general, destructive inspection of loads that show conformance is undesirable, but as explained below these data are key to establishing specification limits. In addition, it is a small investment toward making a robust quality system.

A summary analysis of the 100+ outlier paired data (corresponding to loads confirmed to be conforming) collected over the past five years is shown in Table 1. Because these data come from in-specification loads, the highlighted values (minimum) and (maximum) can be considered a specification range for the process. Using these specification limits, the capability of our furnaces can now be calculated, as shown in the examples of Individual-Moving Range (I-MR) charts and corresponding histograms for two furnaces (Fig. 2, 3). The capability indicators $C_p$ and $C_{pk}$ provide targets to meet and justifications for making improvements on those furnaces whose indices deteriorate over time.

Concluding remarks

The volume of work in the open literature covering SPC applications in heat treat is not very large, and our experience tells us that the number of industries applying SPC to heat treating is still limited. The methodology we have outlined here is but one of the possible applications of SPC in heat treating.

Because our quality inspection system is and has for many years been robust, we knew that the statistical percentage of nonconforming product leaving our heat treat process would be quite small or actually nonexistent. By ascribing capability indices to it, we can now put actual numbers to the process. For example, a $C_{pk}$ of 1.5 is equivalent to a statistical probability of 3.4 nonconformances per million. Actually in our case, as explained earlier, the approval criterion does not rest on the specification limits described, but rather on the practice of observing whether the data fall within the process control limits. Departures from these limits trigger the inspection of an actual part thereby diminishing further the statistical 3.4 ppm nonconformance probability. Naturally, even higher $C_{pk}$ values mean fewer ppm.

Other SPC applications in carburizing are currently being studied. These include statistical analysis of enriching gas usage, actual atmosphere gas make up and carbon potential (with routine 3-gas analysis), and others. The ultimate goal is naturally to achieve capability in the process variables so that the output is stable and conformant. With enough confidence in stable processes, an immediate achievable benefit would be to reduce the “cost of quality” by shifting time and manpower upstream into value added areas of the heat treat process.

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