

Reliability Improvement of Lithium Cells Using Laser Welding Process with Design of Experiments

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ABSTRACT

Manufacturing operations introduce unreliability into hardware that is not ordinarily accounted for by reliability design engineering efforts.

Inspections and test procedures normally interwoven into fabrication processes are imperfect, and allow defects to escape which later result in field failures.

Therefore, if the reliability that is designed and developed into an equipment/system is to be achieved, efforts must be applied during production to insure that reliability is built into the hardware.

There are various ways to improve the reliability of a product. These include:

- **Simplification**
- **Stress reduction/strength enhancement**
- **Design Improvement**
- **Using higher quality components**
- **Environmental Stress Screening before shipment**
- **Process Improvements, etc.**

This paper concentrates on ‘**Manufacturing Process Improvement**’ effort through the use of design of experiments, (DOE). Hence, improved levels of reliability can be achieved.

Most applications optimize the mean value of a response variable. Parameter design experiments are aimed at reducing variability caused by manufacturing variations. In industrial processes, controlling variability is usually much harder than controlling the mean value. And variability is often a root cause of manufacturing problems.

Optimizing the process of welding the lithium cells hermetically, by laser, have been focused in this work.

Cell cans were approximately 1.5 inch diameter, nickel-plated, cold rolled steel with the top welded on around a 0.040 inch lip.

The important characteristic measured in this work is weld penetration depth.

The key steps in this project are:

1. Identify important process parameters / factors, (controllable and un-controllable / noise), and their potential working levels that can be manipulated.
2. Design and perform ‘Fractional Factorial Experiments’ on the process.
3. Analyze the resulting data to determine the optimum operating levels of the factors such that the product's functional characteristic is optimized and has minimal sensitivity to noise.

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INTRODUCTION

The work describes and illustrates the methodology which is a systematic method of optimizing and improving of an existing production process. By optimization, the process variance will be minimized while keeping the process mean on target and minimizing sensitivity to noise.

In this experiment, it was critically important to produce hermetically welded batteries with high quality and reliability. Welds with low quality and defects resulted in electrolyte leakage causing hazardous end effects. The electrolyte, thionyl chloride in our case, is a very dangerous liquid. The goal of the work was to reduce the variance of the weld penetration depth, also to reduce scrap, rework, and keep the process under control. The distinctive features of this quality/reliability control method are experimental design using 'Fractional Factorial Experiments' and the analysis of 'Signal-to-Noise Ratios', (s/n).

The Fractional Factorial Experimental designs provide an economical way of simultaneously studying the effects of many production factors on the process, and variance.

The s/n is a measure of the process variability. By optimizing the process with respect to the s/n, we ensure that resulting optimum process conditions are robust and stable, meaning that they have minimum process variation. An experimental design has been brought to the forefront of process design, and improvement, and especially to the area of product design. The validity of well-designed multifactor experiments and getting engineers to use them is of even greater significance.

A detailed numerical example would help to explain the procedure and point out some concerns. I will, therefore, present a real example that illustrates the use of this method 'Design of Experiments' in a process design setting.

Before proceeding to the example, I note that the work concerns the improvement of an existing process, rather than the design of a new product. Second, the work involves factors that were studied at two levels, rather than at three levels as recommended by some statisticians [2].

As the number of factors to be considered in a factorial experiment increases, the number of treatment combinations increases rapidly. This can be seen with 2^f factorial experiments, (f factors at two levels). Along with this increase in the amount of experimentation comes an increase in the number of high-order interactions. Some of these high-order of interactions may be used as error, as those above second order would be difficult to explain if found significant. In such cases, it may not be economical to run a whole replicate of 2^f observations. Nearly as much information can be gleaned from half as many observations. When only a fraction of a replicate is run, the design is called a 'fractional replication or a fractional factorial [3].

THE PROCESS

The industrial Evarlase Model 525, CO₂ laser machine used in this process has a minimum rated output power of 575 watts. The laser output power is also stable, with a long term variation of only $\pm 2\%$ of the rated power. (Per machine manufacturer specification, time between calibrations was in months, however, application specific).

The laser cooling system is a closed loop temperature control system. At the heat exchanger, excess heat from the circulating oil is transferred to water. The electronic components and the focusing lenses of the laser are also temperature controlled by the cooling system through an accessory cooling line. The laser machine has a modular optical design that permits to be configured with either single or multiple output beams. The entire system is enclosed within one cabinet that is, there is no "umbilical" cord between the power supply and the laser itself. The power supply is controlled by saturable reactors which normally operate from a three-phase input power of 208 volts. A panel that contains pairs of switches controls various laser beam functions. These are controls for the beam's operational mode, gating of pulse bursts, pulse frequency, and pulse length.

The laser beam first encounters a water cooled 45° mirror and is reflected at a 90° angle through a tube to a focusing lens. The lens mount position is adjustable by a vernier micrometer for fine focusing or for moving the location of the focal plane. Gas is admitted to the lens housing and is conducted through a nozzle to form a coaxial jet around the emergent beam.

To produce cleaner edges on the metals, inert gases such as argon or nitrogen are used. The gas jet also serves to protect the face of the lens from back scatterer material. The laser beam is directed through two protective extension tubes, which are placed on either side of a water cooled beam bender. The lens is contained in a water cooled lens mount and connected to a coaxial gas jet assembly.

To weld metals with a laser beam, it is necessary for the beam to have a sufficient power density to produce a molten puddle in the material. This is accomplished by either increasing the laser output power or by focusing the beam with a lens of very short focal length. The same condition may be accomplished by operating the laser in a pulsed mode.

If the laser is operated at 575 watts a lens of 2.5 inch focal length or less is required for metal welding. This produced a beam focused to an area of about 0.005 inch in diameter, which will have a high enough power density to melt most metals. The gap (distance between cover and can) must be small so that the energy does not escape without welding. Since the beam profile is usually 'Gaussian' (most of the energy is in the center), the maximum gap must be 10 to 15 percent of the optical spot size for best results.

The process that was studied involved Lithium Battery cans hermetically welded by laser machine. A brief

description of the manufacturing process follows. The battery assembly is transported by a conveyor system through a turning fixture in order to form 45° phase at the lip of the can. Then, the battery is transferred to the laser welding machine's rotating table which has four holders. The laser beam of approximately 600 watts with a 2.5 inch lens, produce a hermetic weld in a few seconds on the battery cans, which are rotated by the holders. An important quality characteristic of a welded can is the penetration depth of the weld. The target value for the penetration depth is 0.60 millimeters. Deviations below the nominal value are considered to be undesirable. Thus, an ideal welding process would yield battery cans with a penetration depth of 0.60 millimeters, [Figure 1](#).

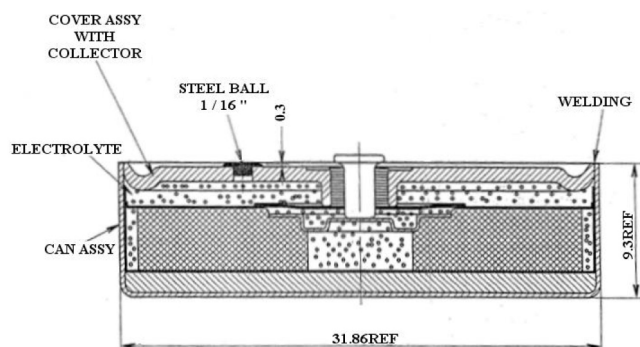


Figure 1. 1/6 D Cell Assy.

THE EXPERIMENT

In this experiment, engineering department has identified seven controllable factors, and four noise factors which could affect the quality and reliability of welding process.

The search would be for the levels of controllable factors that are least influenced by changes in the noise factors.

It will also be investigated to know which factors to adjust when the weld penetration depth deviated from the target, control limits of the process control charts, and which direction to adjust them.

The seven controllable factors of the laser welding process were:

A. Flow rate of the protection gas, lt/min. (Laser welding is performed in an environment of inert gas flowing over the work surface, which acts as a shield against plasma oxidation and absorption).

B. Type of case material; C.R.S 1008-1010 tempered or not.

C. Pulse frequency, (Hz).

D. Ratio between pulse time and welding time.

E. Welding speed, (cm/min).

F. Type of protective gas, (Argon or Helium).

G. Power of the laser beam, (Watts). The laser is operated at about 600 watts, which will have a high enough power density to melt the metal.

In addition to the main effects of these factors, the engineers decided that the following factors / conditions will be difficult, and/or not cost effective to control during production, and therefore, treated them as noise factors. Thus, engineers sought to find combinations of the levels of 'Controllable Factors', A, B, C, D, E, F, and G that would yield to a penetration depth of 0.60 mm, while being insensitive to 'Noise Factors' H, I, J, and K [2].

H. Pressure of the case to the cover.

I. Optical Lenses' cooling system temperature.

J. Optical cleanliness.

K. Holders stability and uniformity.

The two levels of each factor, Controllable and Noise, studied in the experiment are given in [Table 1](#).

Table 1. Levels of Factors Studied in the Experiment.

Code	Factors Controllable and Noise	Low (-)	High (+)
A	Flow Rate of protection gas, (lt/min)	10	15
B	Type of case material	Not Tempered	Tempered
C	Pulse Frequency, (Hz)	400	500
D	Ratio between pulse and welding time	70/30	75/25
E	Welding Speed, (cm/min)	30	40
F	Type of Protective Gas	Argon	Helium
G	Power of the Laser Beam, (Watts)	590	610
H	Pressure of the case to the cover	Exist	Not Exist
I	Optical Lenses' Cooling System Temperature	Hot	Cold
J	Optical Cleanliness	Low	High
K	Holders stability, uniformity	Exist	Not Exist

THE DESIGN LAYOUT

Engineering department decided to study the effects of seven factors, each at two levels [1].

The full factorial experiment to explore all possible factor-level combinations would require $2^7 \times 2^4 = 2048$ experiments.

Considering the cost of material, the time, and the availability of facilities/resources, the full factorial experiment is prohibitively large. Also, from statistical considerations it is unnecessary to perform the full factorial experiment because processes can usually be adequately characterized by a relatively few parameters [1, 3].

The 'Fractional Factorial' design used for this study is a one-fourth fraction of 2^7 as the inner array, and a one-fourth fraction of the full 2^4 design as the outer array.