Improving and Quantifying the Process Window

Patient, systematic iterative development and evaluation are essential to successfully transitioning a process from initial demonstration to volume production

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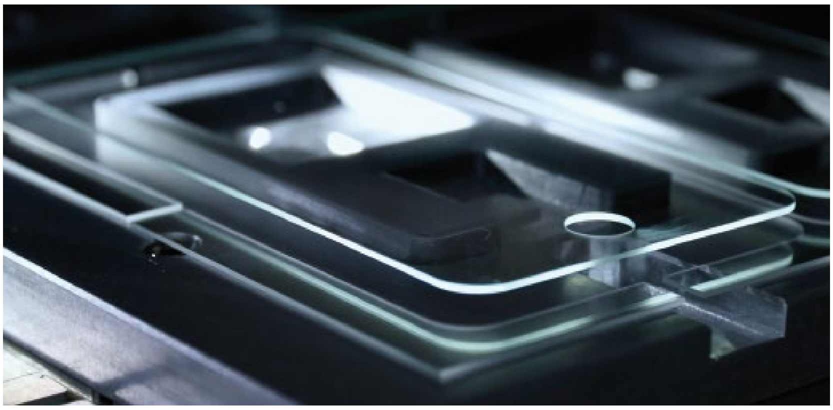

Femtosecond lasers bring numerous process-enabling advantages to precision microprocessing applications. However, taking a new, ultrafast laser-based application from a first demonstration to full-blown manufacturing at market-enabling throughput rates is usually more difficult than for longer pulsewidth lasers. This is because processes utilizing nanosecond (and longer) pulsewidth lasers can rely on a massive knowledge base, built up by laser manufacturers, systems builders and end users, over decades of application. In contrast, femtosecond laser processing is very much in its infancy, with a limited body of proven applications (or even research and development) to draw on. In this article, we describe how a process window was defined, improved, and finalized in the specific case of precision cutting of thin glass panels for display applications.

Key process variables

For any laser application, the first step is a statement from the customer manufacturer of what the process must achieve in terms of process results (e.g. the diameter, depth and position of a laser-drilled hole), process throughput, yield, and overall costs. With femtosecond lasers, there are many process parameters that then need to be thoroughly investigated before the performance (quality and yield) throughput and cost can then be realistically determined. These can include

- Fixtures (clamping, motion stages, etc.)
- Laser output parameters (pulsewidth, pulse energy, pulse repetition frequency)
- Beam delivery and focusing

These parameters must be systematically and iteratively optimized in conjunction with quantitative analysis of the results after each step. This stepwise process development is critical to attaining a quantifiable process window that is sufficiently large to operate at acceptable speed and costs, while accommodating natural process variations that can arise from factors such as changes in ambient conditions (temperature, humidity, vibrations) as well as any inevitable minor variations in the raw material (thickness, flatness, etc.). Only then can the process be confidently accepted for actual production purposes.

Glass cutting: quantifying key process results

To understand how this works in practice, consider a recently qualified application in which Coherent femtosecond lasers were utilized to cut thin (< 1 mm) sheet glass for use in displays. This producer had been cutting glass mechanically, but this necessitated post-processing (grinding) to deliver the desired cut edge quality. Also, mechanical cutting didn't have the capability to produce newer designs with curved cuts, or to accommodate non-flat glass. They therefore wanted to define a new process using a femtosecond laser, where important process definitions included edge quality, dimensions (length and width), and maximum speed (i.e., throughput).

It was quickly determined that a workstation employing high speed, motorized, *x*-*y* stages for part positioning would be required in order to meet the processing time requirements. The task was then to systematically optimize the laser beam and stage performance one parameter at a time, measuring the actual cutting in results in a meaningful statistical manner after each change.

Specifically, after each change, up to three test runs were performed typically

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totaling around hundred sample parts. After these test runs, part dimensions were measured using an optical microscope and an optical surface profilometer was employed to gauge surface quality (arithmetic roughness, R_a). At each stage, the results were analyzed statistically.

The type of statistical analysis was the widely used set of process capability indices called C_p. This index, or ratio, is a mathematical comparison of the acceptable range of a process metric (e.g., part length) to a multiple of the standard deviation of the actual results. Where there is an upper specification (USL) limit, but no lower limit – as in for example, edge surface roughness – a variant called C_pU or CU is used. And where it is possible that the mean of the measured parts and the mean of the USL and LSL may not coincide, an additional parameter that incorporates this offset is also used, called C_{pk}, to more fully evaluate the process. Simply stated, higher C_p ratios indicate a more robust process with higher yields. For example, a C_{pk} value of 1.33 represents a process yield of 99.99 %. For critical dimensions in mass produced parts, an excellent target for C_{pk} is in the 2.0 – 2.5; values over 3.0 may indicate an overly constrained process with unnecessary costs. For a parameter with only a USL (or LSL), as in the case of edge roughness, then a C_pU value around 1.5 is an accepted target level. Coherent thus set out to optimize the cutting process towards these target values.

Process optimization

The first test runs did not deliver acceptable results and capability indices for the part dimensions as well as the roughness, R_a. Several process parameters were investigated and optimized to improve the quantitative process window. For surface roughness we found that the way the glass was secured to the *x-y* stages, as well as the sequence of the cuts, were very important. Specifically, we realized that if the edges could move against each other after cutting, then an otherwise acceptable edge quality could be compromised by this abrasion. Similarly, we soon determined that the critical part dimensions (length, width) primarily involved a trade-off between *x-y* stage speed and dimensional tolerances: faster speeds directly reduced the observed *C* indices. The fast cutting of corners was a particular challenge because of so-called "following errors."

The qualified process

The modifications of the fixturing to prevent the possibility of the cut edges grinding against each, and changes to the *x-y* stage speed encompassed a total of five sets of test runs as we steadily improved the *C* indices. Acceptable performance was eventually achieved in a sixth set of runs. This extended set of runs covered three days to ensure it was also robust to any effects due to shutdown and startup. By acceptable, we mean both the *C* values for the three critical parameters – length, width, and roughness – as well as achieving these at a cost-enabling speed (i.e., throughput).

Fig. 1 summarizes the three days of statistical (normalized) data for the glass panel width and shows the process capability indices calculated from this data. This example illustrates the importance of examining both C_p and C_{pk}. The spread of the actual results is very narrow, yielding C_p value of 3.34, which would indicate a process that is better than needed, and potentially more costly than needed. However, to get this narrow spread, there is also an acceptable offset in the process mean versus the specification mean. The true process capability is therefore better expressed by C_{pk}, and the measured 2.68 for this parameter was determined to be an excellent value. And just as important, it was obtained at a customer-acceptable speed.

Fig. 2 summarizes the normalized statistical data for the edge roughness. With only an upper specification limit for R_a, the C_pU and C_{pk} parameters are the same thing. In this case, a value of 1.6 is just above the 1.5 value needed to guarantee six sigma performance.

Summary

In conclusion, in precision applications, femtosecond laser processing offers the potential of unique and often critical advantages. But to fully exploit this potential, each new application must be carefully developed in a disciplined and systematic approach.

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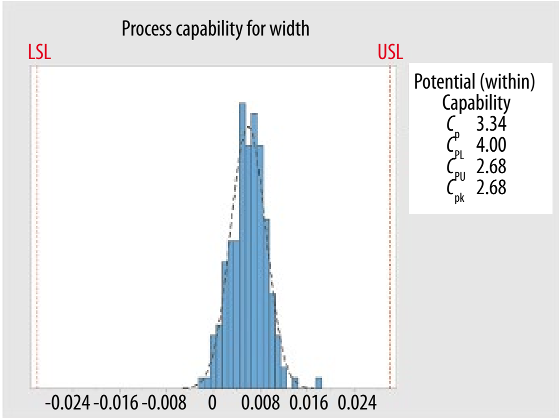

Fig. 1 Normalized statistical data acquired for width of the processed glass parts.

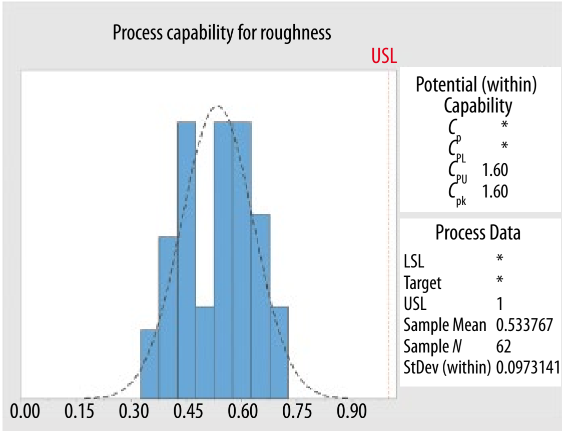

Fig. 2 Normalized statistical data acquired for edge roughness (R_a) of the processed glass parts.

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