Quality and Consistency of Machined Components and Products

Measurement Science and Standards in Forensic Firearms Analysis

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Delivering consistent value to customers for machined products

- Machining produces high geometric *accuracy* and low surface *roughness*, leading to high quality and value to the customer
- Increasing the quality or consistency of machined products increases their cost, which detracts from their value
- The quality, consistency, and cost of machining depends on a complex combination of the performance of process steps and equipment.
- Manufacturers manage this complex combination to increase value to customers while minimizing cost.
Manufacturing of complex, high-value products are expensive and time consuming, requiring lengthy trial-and-error procedures and resulting in wasted resources due to uncertainties in:

- Material properties/behavior under manufacturing conditions
- Manufacturing processes
- Performance of manufacturing equipment

Resulting from:

- Lack of strong metrology infrastructure
- Lack of robust and optimized process control technologies
- Variations in manufacturing system response due to varying manufacturing environmental conditions
Technical Approach - NIST Role

Develop/improve knowledge
Performance Evaluation – Metrology – Data

Represent knowledge
Models – IT – Standards

Integrate/use knowledge
Manufacturability Analysis – Optimization – Control - Diagnosis

Smart Manufacturing Processes and Equipment
Basic Machining Process

Schematic of an image of an orthogonal cutting process. The equipment produces the relative motion between the workpiece and the tool. The process removes material in the form of a chip, creating an accurate and smooth surface on the workpiece.
Machining Equipment Metrology

• **Machine Tool Performance Standards** – provide consistent measures of motion errors, which enables manufacturers to evaluate production quality limits.

• **On-machine metrology** – enable complex part certification by assessment of measuring capability (uncertainty) of machine tools through development of relevant ISO standards.
Standards Enable Error Segregation

Many error sources with complex task-specific effects

- Geometric Errors
- Stiffness & Hysteresis
- Axis of Rotation
- Thermal Errors
- Machine Dynamics
- Contouring

Spindle Error Motion
Predicting machining tolerances

- Aggregating the measured errors provides a threshold for achievable tolerances
- Variations in process performance degrade tolerances from this theoretically achievable threshold
Machining Process Metrology

Schematic of an image of an orthogonal cutting process.
Machining Process Metrology

High speed cameras acquire gigabytes in a second
Imperfections in process performance include surface deformation, tool deflection, and wear.
Machining Process Metrology

Advancing competitiveness of generalized scientific process models requires:
- Advanced simulation tools
- Data on phenomena during material processing
- Material properties under manufacturing conditions

Process characteristics:
- Strain 200 % to 2000%
- Strain rates: $10^3$ to $10^7$ s$^{-1}$
- Temperatures: 100 to 1000 °C
- Heating rate: up to $10^6$ C/s

NIST Pulse-heated Kolsky Bar
- Unique capability to heat sample to 1200 K in less than 0.5 s
- Strains up to 50%
- Strain-rates up to 8000 s$^{-1}$
- Thermal camera
- High-speed visual camera
Worn tools degrade surface quality

(a) Flank face
Flank wear
Rake face

(b) Rake face
Crater wear
Flank face

(c) Chipped cutting edge
Rake face

(d) Thermal cracking
Rake face

(e) BUE
Rake face

(f) Rake face
Flank face
Industry uses process planning and modeling to produce parts to specification.
Machining Process Models

Model-based optimization optimize for:

- Tool path
- Tool selection
- Feeds/speeds
- Coolant strategy
- Sequence

Power and Forces

Spindle Error Motion

Surface Roughness

$y = 11.233x$

Feed rate (mm/rev)

Roughness Ra (µm)

$Ra = 11.233f$
Quality Control of One Process Step

(a) Graph showing average diameter, $\bar{x}$ (average of averages)
- Upper Control Limit for $\bar{x}$, $UCL_{\bar{x}}$
- Lower Control Limit for $\bar{x}$, $LCL_{\bar{x}}$

(b) Graph showing range, $R$ (average range)
- Upper Control Limit for $R$, $UCL_R$
- Lower Control Limit for $R$, $LCL_R$

Manufacturing Engineering and Technology, Sixth Edition
Serope Kalpakjian and Steven R. Schmid

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Products Need Many Process Steps

Machine 2: Mill, drill, ream, plunge mill

Machine 3: Drill, ream, plunge mill

Machine 4: Drill, bore

Machine 5: Drill, bore

Machine 6: Drill, ream, bore, mill

Machine 12: Bore

Machine 11: Drill, ream, bore

Machine 10: Bore

Machine 9: Mill, drill, ream

Machine 8: Mill

Machine 7: Drill, ream, bore

Wash

Machine 13: Finish hollow mill, finish gun ream, finish generate

Machine 14: Ream, tap

Machine 15: Hone, wash, gage, bore, mill

End

Assemble

Assemble

Assemble

Air test
Aggregate Control of Quality

(a) Unstable

(b) Stable
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- Changes in process steps and equipment to maintain quality and consistency focus on aspects related to the product function.
- Any aspects of product characteristics *related to forensics but unrelated to function* may or may not be controlled.
Questions and Discussions