Machining Effects on Mechanical Properties of Ni and Ti Based Superalloy Systems

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The machining effects of turning and low stress grinding Ti-834, CMSX-4®, and Haynes® 242® were examined through statistical analysis of mechanical properties from room temperature (26ºC) tensile (RTT), elevated temperature (600ºC) tensile (ETT), creep, and notched stress rupture (NSR) tests. Percent elongation (%EL), reduction of area (ROA), yield strength (YS), ultimate tensile strength (UTS), creep rupture life, and notched rupture life were analyzed for practical and statistical differences using equivalence tests. Results from Ti-834 were statistically and practically equivalent, but CMSX-4® and Haynes® 242® were largely inconclusive due to sample size. Further analysis was done on all alloys to study machining effect, and on Haynes® 242® to start a path to determining the cause of notch failure in LSG test specimen.

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HOWMET AEROSPACE

Project Background

Titanium and nickel-based superalloys are produced at Howmet via investment casting and forging. Mechanical testing is a required part of qualifying alloy heats for production and sale. For each test, customers specify parameters, properties of interest, and sample preparation methods. Turning and low stress grinding (LSG) are used to prepare Ti-834, CMSX-4®, and Haynes® 242® test specimen. LSG is currently the required machining method for tensile, creep, and notched stress rupture specimen production, however turning is a lower cost, alternative fabrication method.

Project Goal: Determine whether turning can replace LSG for Ni and Ti based superalloys without significantly affecting mechanical properties.

Approach

Statistical analysis was used to determine if machining method affects mechanical properties. Observational studies were completed before the project began with various heats, preparation methods, and sample sizes. Experimental tests reduced variability and tested within one heat. Equivalence tests compare 95% confidence intervals between two datasets to identify statistical and practical equivalence. Values were weighted if sample size was inconsistent.

$$CI = (\bar{x}_1 - \bar{x}_2) \pm t_{df}\left(1 - \frac{\alpha}{2}\right)(SE)$$

Equation 1: Confidence interval equation, where $\bar{x}$ is the mean of the dataset (1 LSG and 2 turned), t_{df} is the z value, α is the confidence level, and SE is standard error. For observational studies, a pooled standard deviation is used to calculate SE.

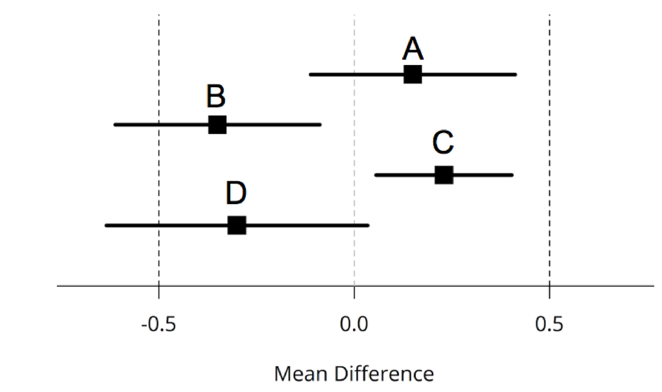

Figure 1: Equivalence test scenarios, including (A) statistically equivalent, (B) statistically and practically different, (C) statistically different but practically equivalent, and (D) not equivalent and not different, largely inconclusive. Difference in means is defined as mean LSG – mean turned. Bounds for each property were defined by Howmet.

Ti-834

RTT and ETT tests were performed on Ti-834. An observational study was conducted using a historical dataset provided by Howmet. Average values of 2-12 tests from various heats, dates, and test rings were provided. The experimental test eliminated variability due to heat, test specimen preparation, and testing environment.

Microstructure

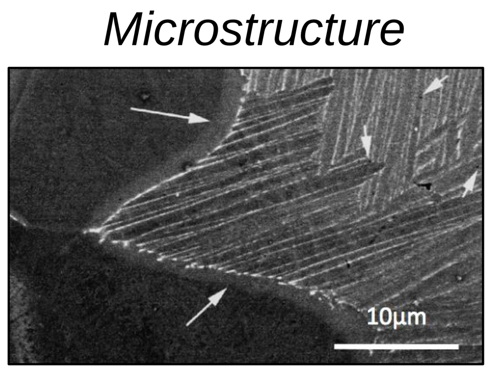

Figure 2: Micrograph of Ti-834. It is a forged, near-α precipitation strengthened Ti alloy with a two-phase microstructure known for its strength and corrosion resistance. [1]

Surface Analysis

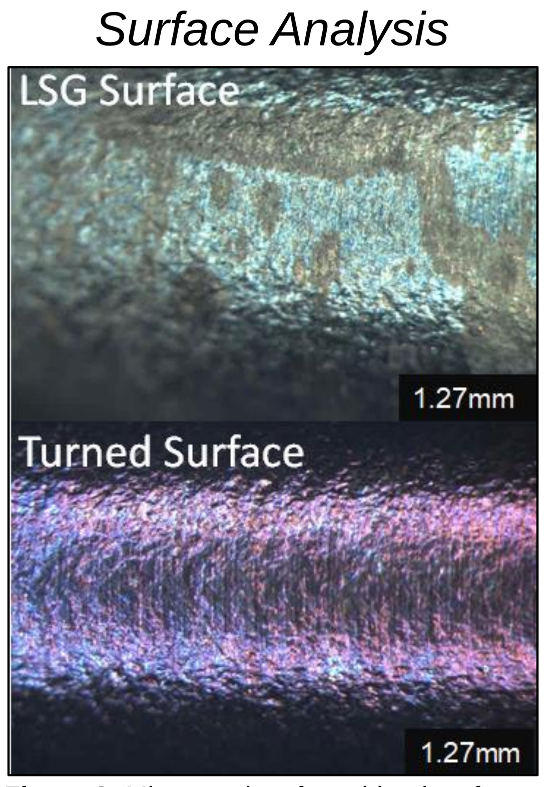

Figure 3: Micrographs of machined surfaces. The top image is a LSG specimen tested at 26ºC and the bottom is a turned specimen tested at 600ºC.

Surface Observations:

- The turned surface had some discoloration due to oxidation during high temperature testing
- The turned surface has vertical machining lines from the lathe tool

Statistical Analysis

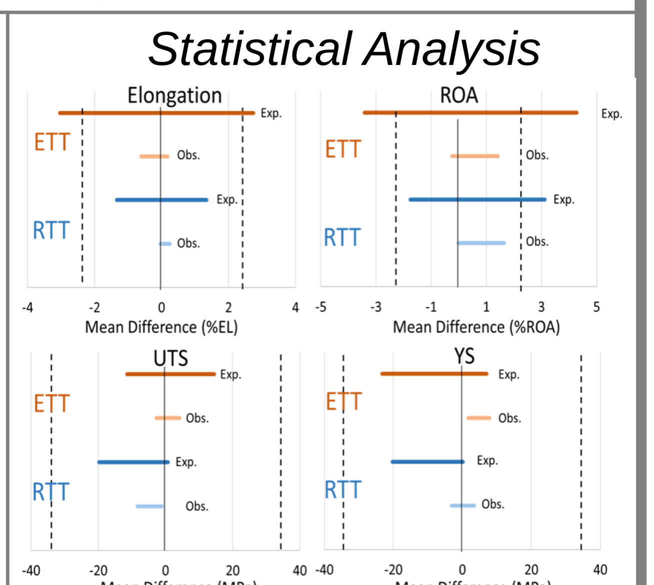

Figure 4: 95% confidence intervals for all properties evaluated after tensile testing at 600ºC (ETT) and 26ºC (RTT). Experimental sample sizes were much smaller than observational, creating a larger confidence interval. Results are summarized in Table 1.

Table 1: Conclusions from tensile tests. (+) indicates LSG value was higher than turned. Green is an acceptable difference, and yellow is inconclusive. Reference Figure 1 for type explanations.

	n (LSG/Turned)	Elong	ROA	UTS	YS
600ºC Experimental	4/4	D	D	A	A
600ºC Observational	29/176	A	A	A	C
26ºC Experimental	5/5	A	D+	A	A
26ºC Observational	28/167	A	A	C	A

Statistical Observations:

- ETT experimental test was inconclusive (due to sample size)
- The experimental results with conclusive intervals were consistent with the observational study
- Other tests were practically and statistically equivalent
- Machining methods did not affect mechanical results

Ti-834 Conclusion:
It is recommended to switch from LSG to turning.

CMSX-4®

RTT, ETT, and creep tests were performed on CMSX-4®. Observational tests were not performed, as Howmet has not previously turned the alloy. The experimental test used material from the same heat to avoid variability due to heat, test specimen preparation, and testing environment.

Microstructure

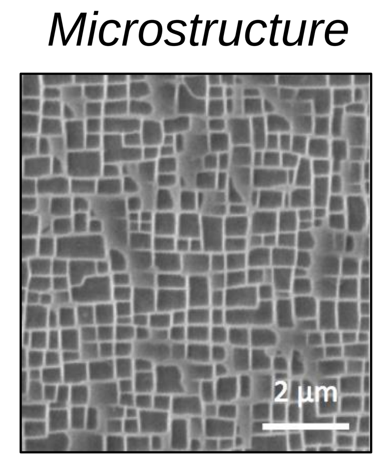

Figure 5: Micrograph of CMSX-4®. It is a cast, single crystal Ni alloy with 9.6% Co and a two-phase γ-γ' cuboidal microstructure. [2]

Surface Analysis

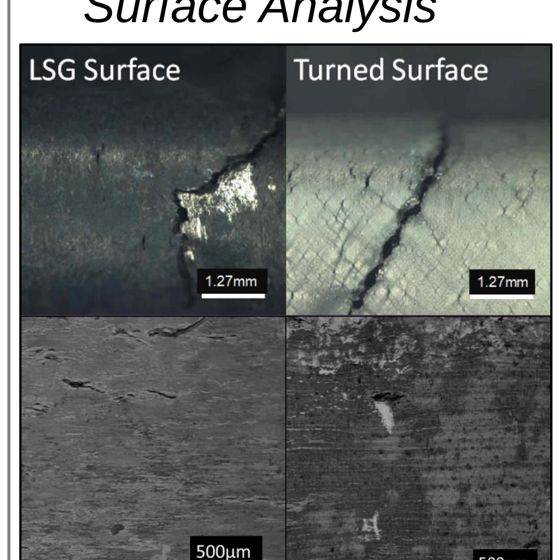

Figure 6: Micrographs of machined surface (top) and SEM images (bottom) of machining layer effect on creep specimen after testing.

Surface Observations:

- Machining lines were less distinguishable in the LSG specimen
- The LSG specimen has a more random machining pattern

Statistical Analysis

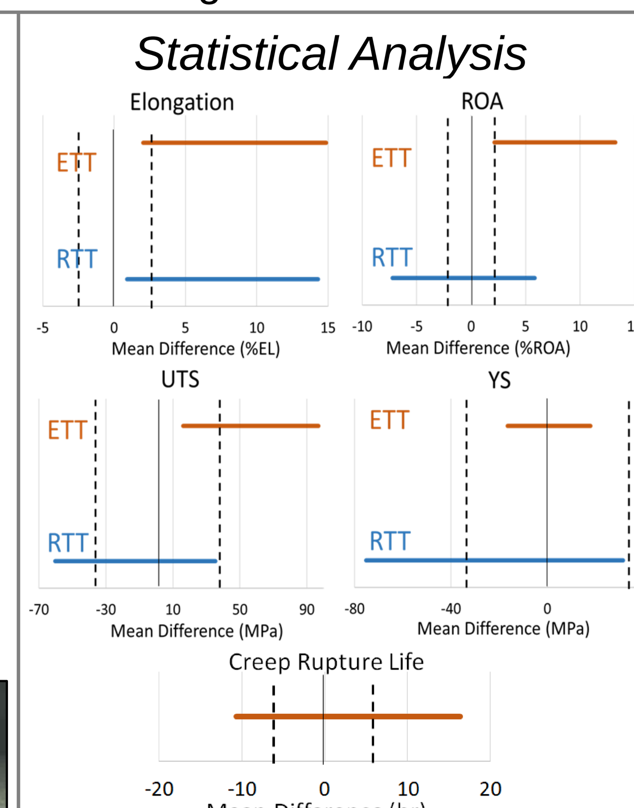

Figure 7: 95% confidence intervals for all properties evaluated after tensile testing at 600 ºC (ETT) and 26ºC (RTT) and creep testing at 871ºC and 607MPa. Results are summarized in Table 2.

Table 2: Conclusions from tensile and creep tests. (+) indicates LSG value was higher than turned. Green is an acceptable difference, yellow is inconclusive and red is unacceptable. Reference Figure 1 for type explanations.

	n (LSG/Turned)	Elong	ROA	UTS	YS	Creep Life
600ºC Tensile	4/4	B+	B+	B+	A	
26ºC Tensile	4/4	B+	D	D-	D-	
871ºC Creep	5/5					D

Statistical Observations:

- ETT: unacceptable to switch machining method
- RTT: inconclusive
- Creep: inconclusive
- Sample size caused wide confidence intervals

CMSX-4® Conclusion:
Machining method does not yet exhibit a statistical effect on mechanical properties. More testing should be done with a larger sample size because initial testing discourages turning the alloy.

Haynes® 242®

NSR tests were performed on Haynes® 242®. An additional study was conducted using a dataset provided by Howmet, and rupture life and failure mechanisms were examined using statistical and SEM analysis. The experimental study used material from the same heat and looked at rupture life variability between machining methods. Notch failure has historically been an issue, so emphasis was placed on finding its source.

Microstructure

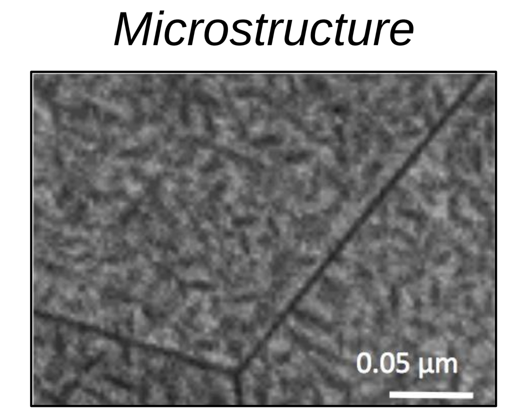

Figure 8: Micrograph of Haynes® 242®. It is a forged, precipitation strengthened Ni alloy with 25% Mo. It has coherent BCO precipitates in an FCC matrix. [3]

Notch Failure Analysis

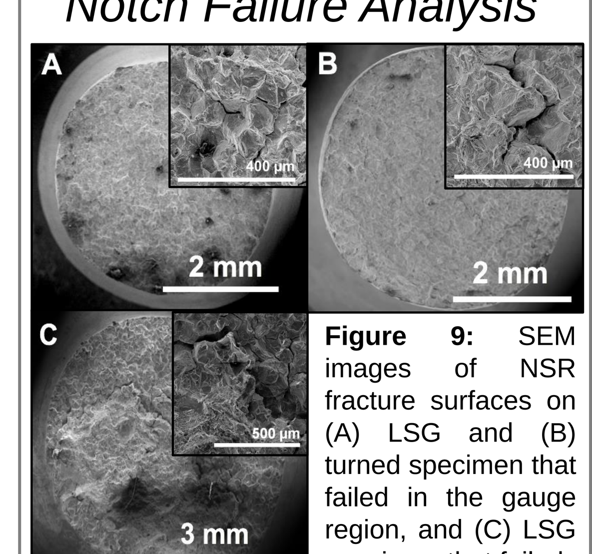

Figure 9: SEM images of NSR fracture surfaces on (A) LSG and (B) turned specimen that failed in the gauge region, and (C) LSG specimen that failed in the notch. (A) and (B) exhibited a brittle, intergranular fracture, while (C) exhibited both an intergranular, brittle fracture region and a transgranular, ductile fracture region.

Surface Observations:

- Both machining methods exhibited failure with brittle, intergranular fracture mechanisms
- Notch-failed surface had non uniform failure types

Statistical Analysis

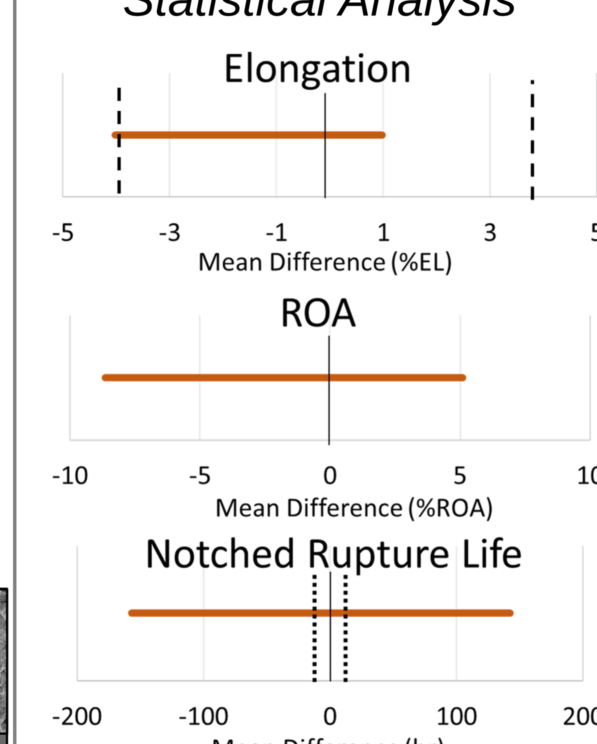

Figure 10: 95% confidence intervals for all properties evaluated after NSR testing at 649ºC and 621MPa. Values were reported for all tests that did not fail in the notch.

Statistical Observations:

- % Elongation: Type D, inconclusive
- % ROA: no bounds given, inconclusive
- Notched rupture life: Type D, inconclusive
- 4/8 of the LSG specimen and all 7 turned specimen failed in the gauge region
- Sample size caused wide confidence intervals that spread outside of the given bounds

Haynes® 242® Conclusion:
It is recommended to switch from LSG to turning, but geometric measurements of each notch should be taken to understand variability.

Conclusions and Recommendations

Based on the results from the equivalence tests, turning can replace LSG for Ti-834. It cannot be concluded whether turning can replace LSG for CMSX-4® creep testing, as the sample size in the experimental studies was too small to determine a practical difference. It is not recommended to replace LSG with turning for CMSX-4® tensile testing, as the results were statistically and practically different. For NSR testing (Haynes® 242®), LSG should be replaced with turning, as LSG showed more frequent notch failure. It is recommended that additional NSR (Haynes® 242®) and creep (CMSX-4®) testing should be done to help quantify the difference in mechanical properties. For NSR tests, statistical results were inconclusive due to the small sample size. Geometric measurements should be taken on each test specimen and correlated with mechanical properties. Until rupture life becomes consistent within a machining method, it should not be permanently replaced with the other, as the ideal machining method has not yet been determined through statistical analysis.

Acknowledgements

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2. N. S. Husseini et al, "Mapping single-crystal dendritic microstructure...," Acta Materialia, vol. 56, no. 17, pp. 4715-4723, 2016.
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