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Elevating precision with next generation edge finishing technology

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Executive Summary

In this paper, TextureJet explores the use of its innovative localised Stat® platform technology utilising electrochemical-jet machining to produce repeatable and tuneable edge break finishes onto Nickel based superalloys. The edge break finishes are achieved without imparting thermal or mechanical stress onto the component, a vital consideration in safety critical applications such as aerospace where residual stress generates potential part failure sites. The results achieved using TextureJet's Stat® technology are compared to the specifications of widely used automated and manual brush deburring methods, which require an edge break radius between 150 µm – 350 µm with an allowable tolerance of ±100 µm, and an affected zone of maximum 1000 µm per side.

The results presented in the repeatability study demonstrate that TextureJet's Stat® process utilising an automated delivery system consistently achieves edge break results well within these specifications, with an average radius of 214.8 µm and affected zone of 471.9 µm achieved over 110 samples processed. TextureJet's Stat® process was assessed against the capability performance index (Cpk), with values of 1.42 for the radii and 1.67 for the affected zones showing that the process is highly capable and can consistently produce high quality and controllable edge break finishes, with scope to further improve the performance.

Comparison of the results showed that the **Stat® technology is more repeatable** than the current methods utilised in edge break finishing of aerospace components, **by 74.5%** and **44.7%** compared to **manual and automated brush deburring,** respectively.

The phase 2 testing demonstrated the capability to scale the Stat® process to repeatably machine different edge break radii across the full range outlined by current specifications. The results showed Stat® can control the edge break radius by varying the energy density, with radii of 151 and 352 µm readily achieved.

All of the results presented were achieved with pH neutral saline based electrolytes using automated delivery methods, offering distinct advantages in terms of safety, sustainability and repeatability, compared to currently utilised methods which can include the use of harsh acids, creation of airborne contaminants or a high level of manual processing.

Introduction

Edge break is simply defined as the operation to create a radius or chamfer to a specific geometry so that the converged surfaces are "broken" producing a smooth transition from one face to another. However, this definition understates its vital importance, in particular for components used in safety critical applications. Components under stress with untreated sharp edges can induce high stress concentrations which cause fatigue cracking in service and lead to complete product failure (Zecchino 2024). There are also the additional concerns of sharp edges creating a hazard in handling and difficulties in part mating where effective clearance is required.

These edge break processes need to be carried out with minimal effect on component geometry or integrity with the highest repeatability so minimising scrap and rework rates on high value components. On complex high precision parts with multiple features, edge finishing can constitute up to 30% of part costs (LaRoux K. Gillespie 1999), create bottlenecks (Kannan and Kui 2019) and be significantly impactful on yield given that by the point that edge break is required, a considerable amount of "value-add" has been invested in the part. As such, scrappage can be significantly costly, with up to 5% of manufacturing costs in German automotive and tooling industries being attributed to rejects and reworks based on edge finishing (Aurich J.C. 2006).

Typical radius or chamfer lengths on parts range from 50 µm to 1270 µm but will remain consistent along the edge coupling the two adjacent planes (Lindell 2020). Variation being defined by the designer's original intent mixed with in-service needs and current machine capabilities. Further complications occur due to the materials often used in high specification safety critical applications being difficult to work due to their physical properties and work hardening, again leading to undesirable changes in metallurgy and variance in the created geometry.

Electrochemical machining (ECM) processes have been in use in manufacturing for decades and are well understood (Serope Kalpakjian 2006) including their use for deburring and edge break applications (Kadam and Mitra 2021). Electrochemical deburring (ECD) has distinct advantages of being non-contact, with no surface damage, recast or residual stress. Coupled with the fact that materials physical properties, such as toughness or hardness, have no effect on the material removal. However, these processes are inherently difficult to employ due to the machine architecture utilising submerged technology, costly tooling, and high-cost automation. As such, outside of smaller and simple enclosed geometry components, it becomes inefficient and has the potential to affect the whole surface, so it does not allow for intimate control of what is being created due to the "one-size-fits-all" approach.

Stat® - Automated High Precision Edge Finishing System

TextureJet utilises an adaption of ECM called electrochemical jet machining (ECJM) (Speidel, et al. 2022) in its Stat® systems, shown in Figure 1, which has been developed especially for deburring and edge-break when coupled with a low cost 5-axis automation system.

Along with enabling all the commonly associated benefits of using ECM it also brings significant additional benefits. ECJM can generate user defined edge-break radius leaving behind an ideal surface finish, with the ability to vary the radius in different features and even within the same feature as part of the tool path program or nozzle design (Mitchell-Smith, et al. 2017), giving ultimate user flexibility with zero tooling costs. As a direct-write technology, it requires no masking and creates a minimal affected zone especially in comparison to incumbent technologies. Due to the unique architecture of "taking the machine tool out of the machine" it can deal with parts of any size and complexity as the delivery head (which may contain multiple jets), is remote from the machine and can be any distance from the machine making it automation and robot manufacturer agnostic, so provides the ultimate scalable automated platform for deburring across a wide range of high-value applications.

Figure 1. *(a) TextureJet's Stat® system (right) coupled with PrecisionJet 5-axis automation system (left), which has been developed to create controllable and repeatable edge breaks on any conductive material. (b) Stat® System being utilised to edge break complex geometry.*

The work presented in this paper demonstrates the distinct advantages of utilising TextureJet's system for creation of industry specification edge-break features in comparison to commonly used methods. The result achieved using TextureJet's Stat® technology are compared to a repeatability study conducted as a collaboration between Safran Aircraft Engines Poland and Rzeszow University of Technology (Falandys, 2023) on the widely used automated and manual brush deburring methods.

Methodology

The purpose of testing was to demonstrate the capabilities of ECJM delivered through the TextureJet Stat® system for edge-breaking, benchmarking performance for this application in achieving repeatable and scalable results.

The edge break study was carried out over two phases. The first phase was designed to demonstrate that Stat® could produce the required edge break finishing to meet specifications, and investigate the process quality in comparison to current methods by carrying out a repeatability study. Current specifications in aerospace applications achieved by utilising brush deburring allow for a tolerance of ±100 µm, requiring an edge break radius between 150 µm – 350 µm (Falandys, 2023), with an affected zone of 1000 µm per side taken as the maximum allowed for the purposes of this study. The second phase then focussed on the flexibility of the technology to create different edge break finishes illustrating the ability to fine tune the process to the design intent.

In order to carry out the two phases of testing, TextureJet's Stat® system was utilised, with the articulation provided by PrecisionJet which provides 5-axis of motion (Figure 1), using a 3-axis gantry coupled with ITS technologies 2-axis gimbal, and TextureJet's Ultra B-483 proprietary pH neutral saline based electrolyte solution.

Stat® uses a jet of electrolyte which is expelled from a nozzle and impinged on an opposing surface**.** An electrolytic cell is then formed between the nozzle and the surface allowing for highly localised and controllable anodic dissolution (Figure 2). Due to the spot size of the jet, extremely high energy density is created leading to high material removal rates (MRR), coupled with high flow flushing, consistent and repeatable high precision geometry can be created. Stat® allows for several machine parameters to be adjusted, including nozzle size and shape, power, flow rate, translation speed and electrolyte, so a range of parameters were trialled in order to optimise the machine strategy for the required edge break specifications. A holistic approach is required to tune all of the parameters, so customer specification is achieved and best described by the term energy density, which accounts for both the power, nozzle size used and processing time of any given point along the edge, as described by eq. (1) below.

$$Energy\ Density\ (J\ cm^{-2}) = \frac{Power\ (W)\ *\ Nozzle\ Diamater\ (mm)}{Nozzle\ Area\ (cm^{2}) * Nozzle\ Translation\ Speed\ (mm\ s^{-1})} \qquad (1)$$

Inconel 718 was selected as the test substrate, due to its extensive use in aerospace applications where edge break finishing is widely utilised to avoid imparting stress onto the surface of safety critical components under cyclic loading conditions. The samples were cut using wire EDM leaving the as processed finish.

The machined sample edge breaks were measured using an Alicona G5 infinite focus, which uses focus variation to analyse both the thermographic topography colour maps and radius (edge break) profiles following the EN ISO 21920-1:2021 and EN ISO 25178-606 standards. The edge break analysis allowed for measurement of the radius size, affected zones on each face and angle between the faces. Two repeat measurements were carried out, with the results averaged to reduce any positional bias.

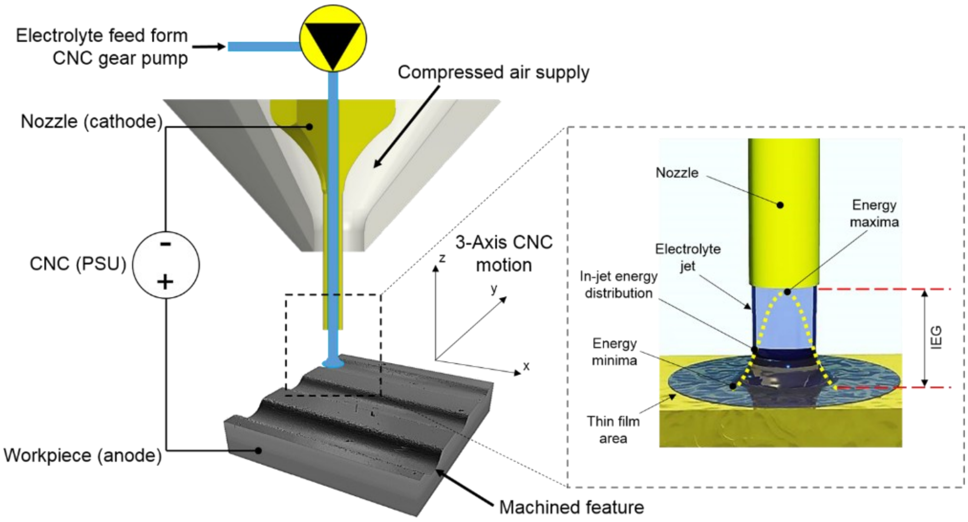

Figure 2. ECJM end-effector in an anodic dissolution configuration as used herein (left). Schematic diagram of the standard Gaussian type current density profile within an incident jet during processing with ECJM (right).

Phase 1 testing

Inconel 718 samples measuring 30 mm x 30 mm x 7 mm were processed using TextureJet's Stat® and 5-axis PrecisionJet accessory (Figure 1), with a 0.5 mm round nozzle applied at a 45° angle relative to the substrate and centred about the edge to be machined, as shown in Figure 3. Centring was achieved by utilising Stat® touch off technology, whereby the nozzle is used to probe the surface and record the positional data. This process was carried out on both faces of the edge to be broken to determine the exact point at which the two faces meet and find the centre of the edge. A repeatable standoff distance was then applied between the nozzle and workpiece along the toolpath determined in CAM. An energy density of 36.6 kJ cm^{-2} was used throughout phase 1 testing in order to achieve a consistent finish. A total of 110 samples were processed for testing, with three 5 mm tracks processed on each edge of the machined sample and the remaining unprocessed regions serving as the control (Figure 3). The processed samples were then measured and analysed using a Bruker Alicona G5 with two repeat measurements taken on each edge.

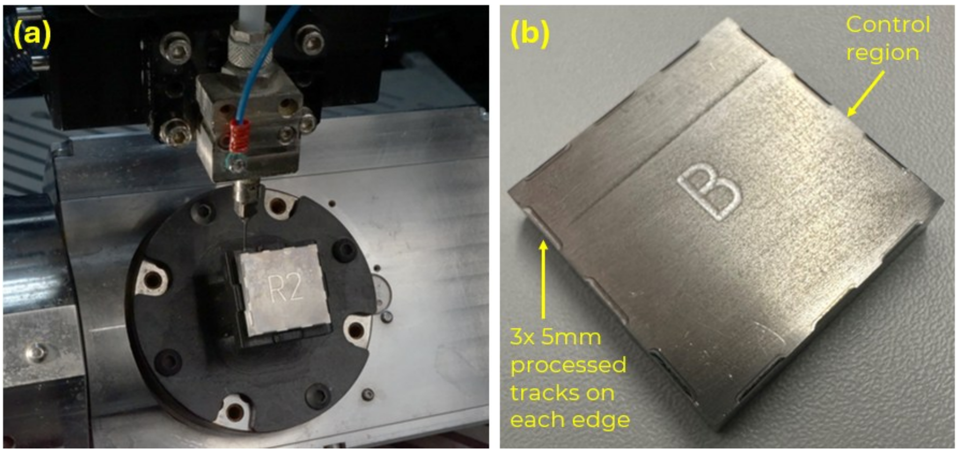

Figure 3. (a) PrecisionJet 5-axis with direct write structuring (DWS) head at a 45° angle to an Inconel 718 sample demonstrating edge-breaking finishing using TextureJet's Stat® system. (b) Three 5 mm Stat® processed region and unprocessed control region of Inconel 718 sample edges.

Phase 2 testing

The aim of the second phase of testing was to show the flexibility of the technology to create different sized edge break finishes. To achieve this, the same experimental setup as described in phase 1 was used, with the translation speed varied. ECJM is an energy based process, so based on Eq. 1, it was expected that a faster speed would result in a smaller radius and the slower speed would produce a much larger radius. Using this concept, the speeds were varied to demonstrate that Stat® could readily scale the edge break radius to create radius at both ends of the 150 µm – 350 µm specification.

Results and Discussion

Phase 1 – Repeatability

The repeatability study was carried out on Inconel 718 with 110 edges processed and measured. The average edge break radius and affected zones for the processed samples are shown below in Table 1 in both microns and thou, and Figures 4 - 5. Examples of the measurement thermographic topography colour maps and edge break profile analysis have been shown in Figures 6 - 8. The processed edges were compared to the current industry specification (Falandys, 2023), with a targeted radius of 250 µm and an accepted tolerance of ±100 µm. The affected zone was only specified to be a maximum of 1000 µm of each face, so an affected zone of 500 µm was targeted with an accepted tolerance of ±250 µm.

Table 1. *Results of surface measurements on the machined and control sample edges*

Measured feature	**Control**		**Processed (36.6 kJ cm^{-2})**	
Units	**(µm)**	**(thou)**	**(µm)**	**(thou)**
Edges Measured	6		110	
Average measured edge break radius	25.7	1.011	214.8	8.457
Standard deviation in edge break radius	8.2	0.323	15.2	0.598
Radius - Process capability potential (Cp)	-	-	2.20	
Radius - Process capability performance (Cpk)	-	-	1.42	
Average measured affected zone	-	-	471.9	18.579
Standard deviation in affected zone	-	-	44.3	1.744
Average difference between left & right affected zones	-	-	24.9	0.980
Affected Zone - Process capability potential (Cp)	-	-	1.88	
Affected Zone - Process capability performance (Cpk)	-	-	1.67	

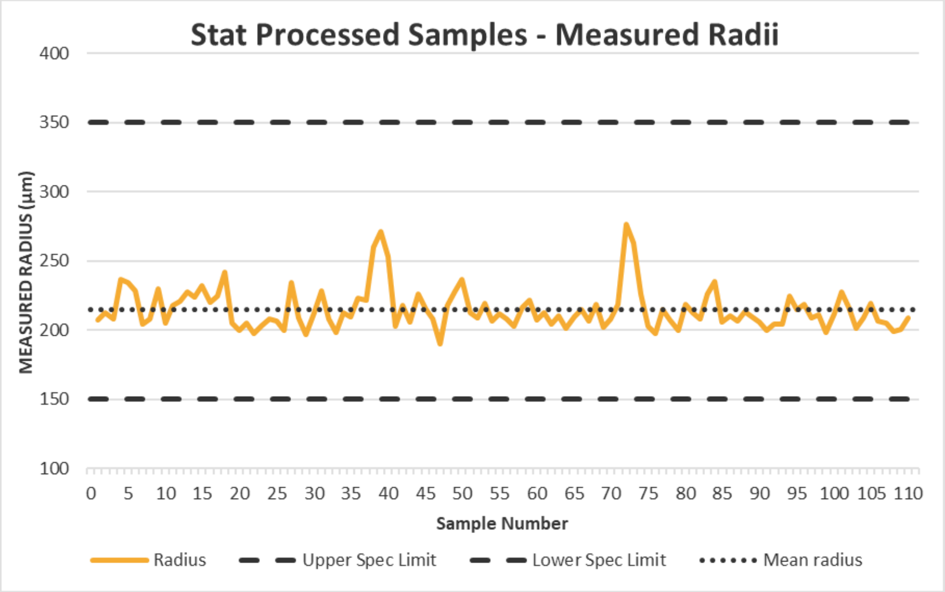

Figure 4. *Measured edge break radii for the samples processed using TextureJet's Stat® system to assess the process capability and performance of the technology.*

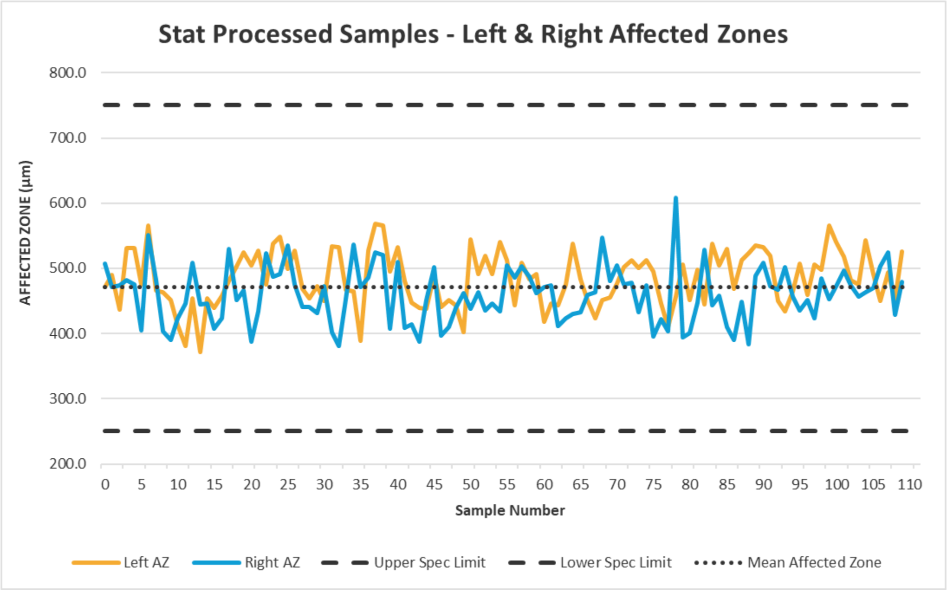

Figure 5. *Comparison of the measured left (yellow) and right (orange) affected zones for the samples processed using TextureJet's Stat® system to assess the process capability and performance of the technology.*

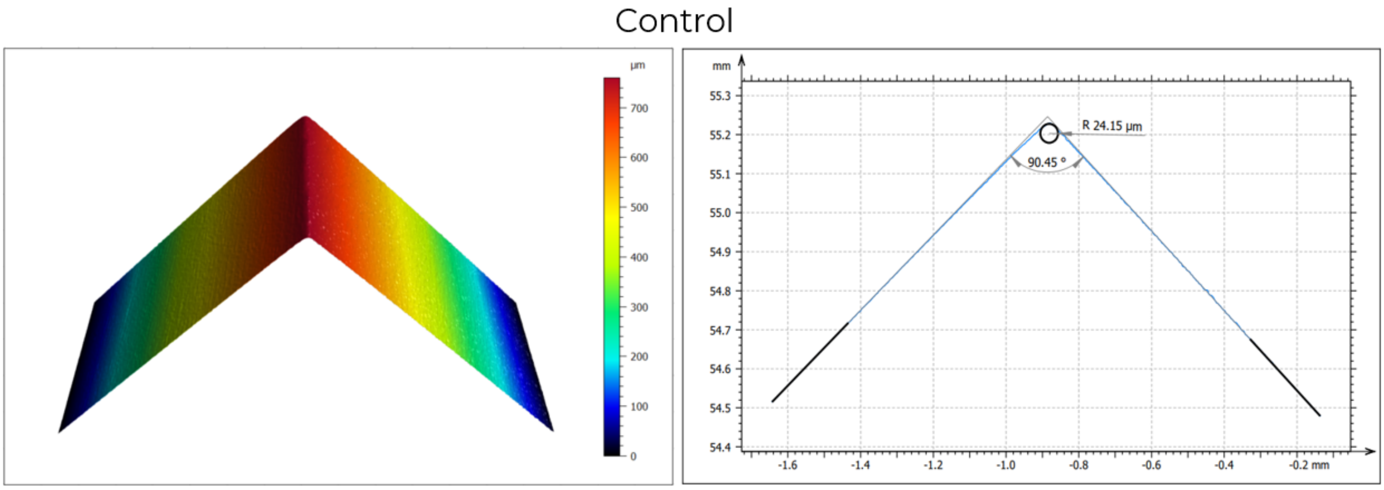
Control

Figure 6. *Surface measurement heat map (left) and edge analysis (right) displaying edge angle (90.45°) and radius (24.15 µm) prior to processing with Stat®, and used as the control for comparison.*

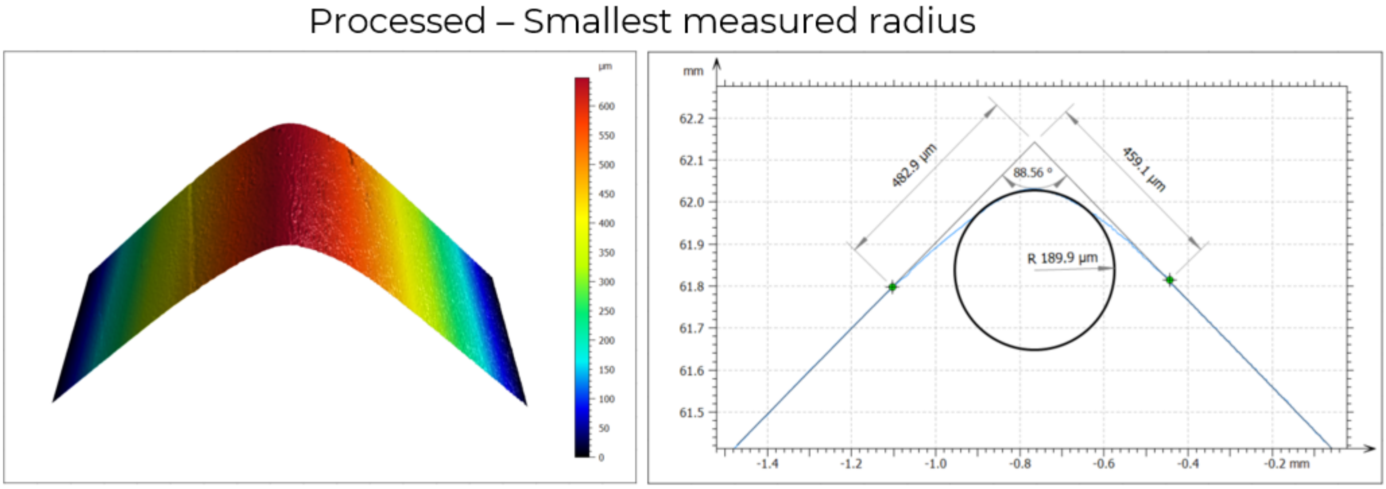
Processed – Smallest measured radius

Figure 7. *Surface measurement heat map (left) and edge analysis (right) for the smallest measured radius in the study, showing the edge angle (88.56°) and best fit radius (189.9 µm) and average affected zone (471.0 µm) after processing with Stat® using an energy density of 36.6 kJ cm^{-2}.*

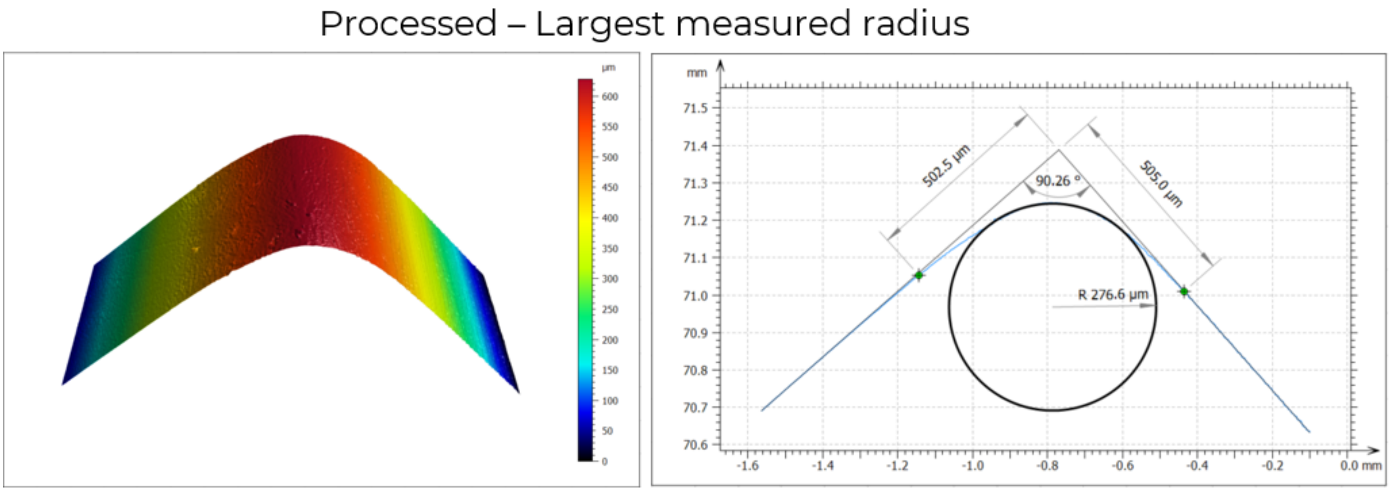

Figure 8. *Surface measurement heat map (left) and edge analysis (right) for the largest measured radius in the study, showing the edge angle (90.26°) and best fit radius (276.6 µm) and average affected zone (503.8 µm) after processing with Stat® using an energy density of 36.6 kJ cm*$^{-2}$.

From the phase 1 repeatability study, the results show that the Stat® process is highly capable of performing precise edge break finishing with all 110 samples processed well within the specification for both the measured radius and average affected zones. This is further supported by the capability performance (Cpk) values of 1.42 for radii and 1.67 for the affected zones, demonstrating the process can consistently produce high quality and controllable edge break finishes. The capability potential (Cp) of 2.20 and 1.88 for radii and affected zones respectively, shows that process has the capacity to be further improved. This can be readily achieved through optimisation of the energy density to increase the radii to closer to the 250µm mid spec as shown in the phase 2 scalability testing, and adjusting the nozzle geometry and alignment.

Comparing the Stat® results with the brush deburring results presented in Falandys 2023, shows that through the use of the Stat® system there is an increase in repeatability of 44.7% and 74.5% compared to laser-assisted robot automated brush deburring and manual brush deburring respectively, which provides increased confidence in the finished component edge, and would enable a step change in consistency and precision of edge break dimensions after processing within the required specification. This addresses a key pain faced in edge breaking within the aerospace industry, which traditionally uses manual methods leading to issues in repeatability and feature non-conformance (Kannan and Kui 2019).

In addition to the benefits offered by the Stat® process in repeatability, the material removal mechanism offers advantages in avoiding imparting stress onto the component as there are no thermal or mechanical forces imparted on the surface (Liao, et al. 2021). The Stat® process also offers advantages for safety and environmental considerations relative to other edge breaking processes. Examples include the closed loop Stat® system preventing exposure to airborne dust particles such as those generated during abrasive blasting and brushing (LaRoux K. Gillespie 1999). The pH neutral solutions used are significantly safer to work with and dispose of than acidic solutions used in electropolish or purely chemical methods. The automated solution eliminates the need for slow and laborious manual finishing, reducing risk of injury from manual strain and significantly improves the associated issues of repeatability. The inherently localized nature of the technology removes the need for masking, streamlining processing and reducing waste generation. In addition, TextureJet's 5-axis system provides high precision automation at a significantly lower cost than incumbent 5-axis machines used commonly in CNC operations.

Phase 2 - Flexibility

Our aim in evaluating the relationship between processing speed and best fit radius was to demonstrate how readily the edge break radius can be scaled using Stat® to meet user needs by aiming to machine edges with radii at the minimum (150 µm) and maximum (350 µm) range of the specification.

Theoretically by increasing the energy density applied, for example by decreasing processing speed, should result in an increased edge break radius. The energy density applied to the surface can be tuned in multiple ways, including varying the current, nozzle size or processing speed. Here processing speed is used a continuous variable as a means to control edge break radius, showing the process offers the user a high degree of control over the processed edge radii using Stat®. The results of the phase 2 testing are shown in Table 2 and Figures 9 - 10.

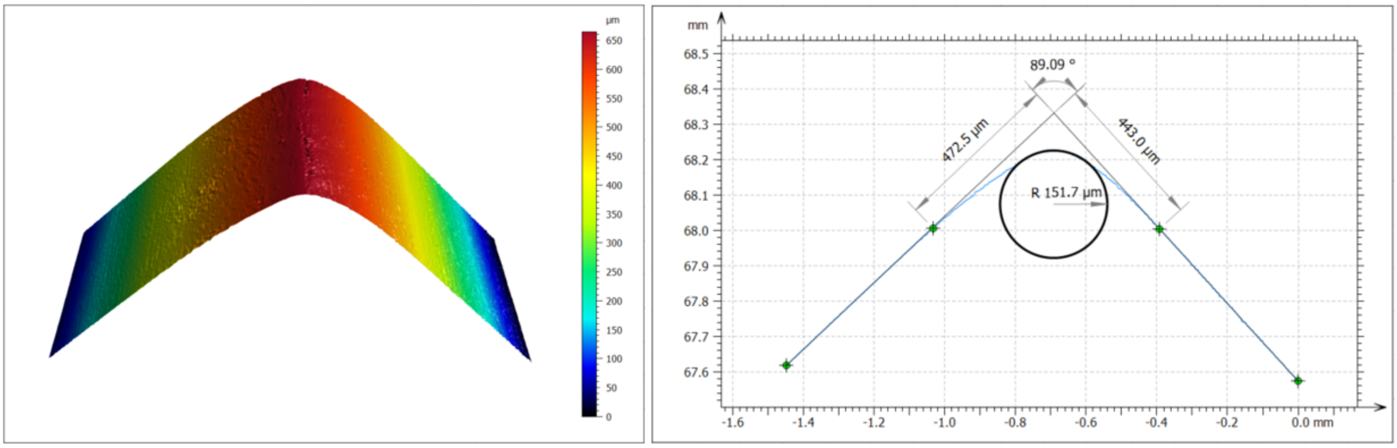
Processed – Scaling to minimum spec

Figure 9. *Surface measurement heat map (left) and edge analysis (right), displaying the edge angle (89.09°), best fit radius (151.7 µm) and average affected zone (457.8 µm) after processing with Stat® during phase 2 trials using a 0.5 mm diameter nozzle at an energy density of 27.4 kJ cm*$^{-2}$.

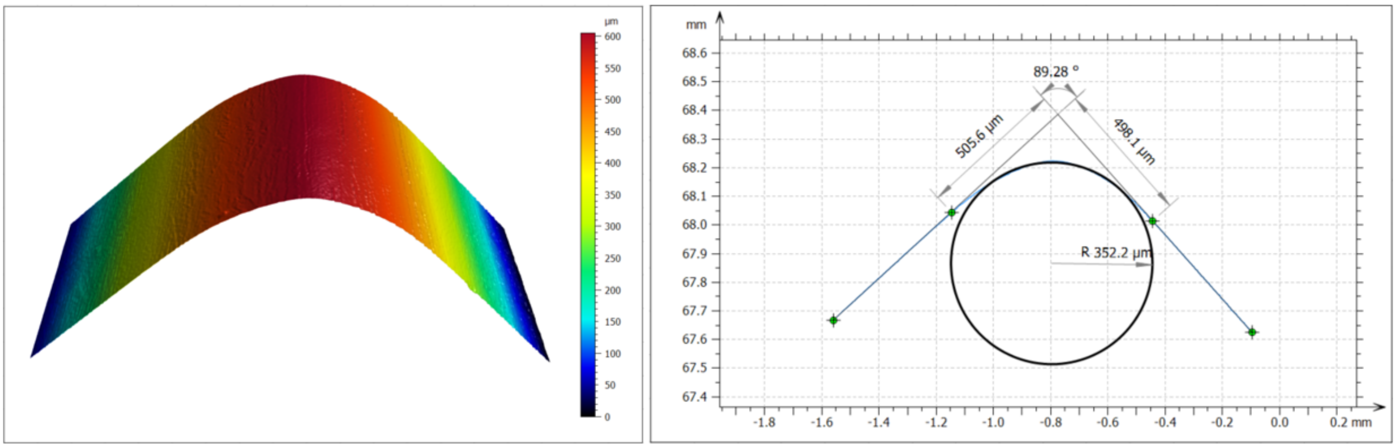
Processed – Scaling to maximum spec

Figure 10. *Surface measurement heat map (left) and edge analysis (right) displaying the edge angle (89.28°), best fit radius (352.2 µm) and average affected zone (501.9 µm) after processing with Stat® during phase 2 trials using a 0.5 mm diameter nozzle at an energy density of 57.1 kJ cm*$^{-2}$.

Table 2. *Effect of varying the energy density to scale the edge break radius.*

Parameter		Measured feature	
Edges Measured		6	
Units		**µm**	**thou**
Nozzle	**Energy Density**	**Average Edge Break Best Fit Radius**	
0.50 mm	27.4 kJ cm^{-2}	152.1	5.988
0.50 mm	57.1 kJ cm^{-2}	352.2	13.866

The phase 2 results demonstrate the Stat® process can be readily scaled, with the capability to vary multiple parameters including power, translation speed, electrolyte and nozzle selection to allow for a range of processing requirements to be met. Compatibility with multi-axis machine tools, gantry system and robotic arm delivery systems allows for further flexibility to selectively process edges of complex geometries of any size components.

The phase 2 results showed the effectiveness of using energy density to control the edge break radius, closely matching both the minimum (152.1 µm) and maximum (352.2 µm) radii of the Falandys, 2023 specification. Stat® has the capability to vary multiple parameters including power, translation speed, electrolyte and nozzle selection, so allows for a range of processing requirements to be met. Compatibility with multi-axis machine tools, gantry system and robotic arm delivery systems allows for further flexibility to selectively process edges of complex geometries of any size components.

Conclusion

The results of the work conducted clearly demonstrates that TextureJet's Stat® platform technology is able to controllably and repeatably generate edge break features in an automated fashion, with the ability to scale the size of the radius and the affected zone as required by the designer intent and operational needs. This is illustrated by the capability performance (Cpk) values of 1.42 for radii and 1.67 for the affected zones, with further scope to improve the performance as shown by the capability potential (Cp) of 2.20 and 1.88 for radii and affected zones, respectively. This can be readily achieved by using the scalability of the technology to further optimise the energy density to increase the radii to the 250µm mid spec, as demonstrated in the phase 2 scalability testing, and increasing the affected zones by modifying the nozzle geometry and alignment.

The repeatability study showed that implementing TextureJet's Stat® system would enable an increase in repeatability and overall tighter tolerances of 44.7% compared to laser-assisted robot automated brush deburring and 74.5% compared to manual brush deburring. This would lead to significant savings due to reduction in both reworking and scrappage experienced with current methods. This is particularly beneficial with the high cost of scrapping manufactured components with significant value added from a multitude of preceding processing steps.

The two phases of testing carried out have highlighted the repeatability and scalability of the Stat® process for edge breaking. The wide range of tuneable variables available to Stat®, which are not exhaustively explored here, is indicative of the range of edge break finishes which could be obtained in future using the technology to fit specifications outside of the investigated processing range. Use of larger nozzles, increased power or processing time allows for larger radii or chamfer finishes to be generated, and alterations to the processing angle or nozzle profile further adds to the tuneability of the process and presents opportunities to develop new and highly curated edge profiles to maximise component performance.

Though beyond the scope of this investigation, Stat® has previously demonstrated capabilities in processing a wide range of conductive metal surfaces including stainless steels, aluminium alloys, and specialized alloys such as Haynes 25. As a result, the capability shown here to impart a broken edge onto Inconel 718 can readily be applied to a wide range of other metals.

Future Work

The next steps with the technology is to apply the ability to create modified and highly tuneable surface profiles to more complex geometries than those explored herein, as well as investigate use of alternative methods of tuning Stat® processing results, such as increasing the radii through the energy density, altering nozzle design, which have been previously established to affect geometries of areas processed with Stat® for other applications but have not yet been applied to an edge breaking context.

References

Aurich, J.C., SpanSauber. 2006. Untersuchung zur Beherrschung der Sauberkeit von zerspanend hergestellten Bauteilen, Ergebnisworkshop, Lehrstuhl, für Fertigungstechnik und Betriebsorganisation, Technische Universität Kaiserslautern.

Falandys, K., Kurc, K., Burghardt, A., and Szybicki, D., 2023. "Automation of the Edge Deburring Process and Analysis of the Impact of Selected Parameters on Forces and Moments Induced during the Process." *Applied Sciences*.

21920-1:2021, EN ISO. n.d. "Geometrical product specifications (GPS) — Surface texture: Profile — Part 1: Indication of surface texture."

Kadam, S.P., and Mitra, S., 2021. "Electrochemical Deburring - A comprehensive review." *Materials today: proceedings* 141 - 148.

Kannan, S., and Kui, L., 2019. "Experimental investigation of surface integrity during abrasive edge." *Journal of manaufacturing processes* 40-51.

Gillespie, L.K., PE, CMfgE. 1999. *Deburring and Edge Finishing.* Society of Manufacturing Engineers.

Zhirong, L., LaMonaca, A., Murray, J., Speidel, A., Ushmaev, D., Clare, A., Axinte, D., and M'Saoubi, R., 2021. "Surface integrity in metal machining - Part I: Fundamentals of surface." *International Journal of Machine Tools and Manufacture.*

Lindell, K. 2020. "Edge Break Analysis for 3D Optical Metrology." *Quality Magazine*, 3 August.

Mitchell-Smith, J., Speidel, A., Gaskell, J., and Clare, A., 2017. "Energy distribution modulation by mechanical design for electrochemical." *International Journal of Machine Tools and Manufacture* 32 - 46.

Kalpakjian, S., Schmid, S.R., 2006. *Manufacturing Engineering and Technology.* Pearson Prentice Hall.

Speidel, A., Bisterov, I., Saxena, K.K., Zubayr, M., Reynaerts, D., Natsu, W., and Clare, A., 2022. "Electrochemical jet manufacturing technology: From fundamentals." *International Journal of Machine Tools and Manufacture.*

Zecchino, M., 2024. "4D-InSpec-White-Paper-Edge-Break-Measurement-that-Pays-for-Itself." *https://4dtechnology.com/.* 22 July. https://4dtechnology.com/wp-content/uploads/2021/02/4D-InSpec-White-Paper-Edge-Break-Measurement-that-Pays-for-Itself.pdf.

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