Hybrid strategy for enhancing the dimensional accuracy and surface finish of abrasive waterjet milled pockets

Chinmoyee Datta, D. S. Srinivasu*

Indian Institute of Technology Madras, Chennai, India

Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8 - 10, 2022 IIT Kanpur, India

KEYWORDS

AWJ Milling,
Conventional Milling,
Hybrid Milling,
Machine Vision.

ABSTRACT

Abrasive waterjet (AWJ) milling of ductile material has advantages, such as negligible heat affected zone and no burr formation against conventional milling (CM). However, AWJ milling has limitations in terms of poor milled surface quality and not complying with the intended dimensions. To address this, in this work, a hybrid milling (HM) strategy is proposed where the major stock of material is removed by the AWJ, followed by a machine vision-based pocket dimensional measurement. By considering the deviations observed from the target, the shape and dimensions of the pocket are corrected by the CM. This work uses Al-6061-T6 alloy to demonstrate the HM strategy. The results from the HM strategy show that the vision approach accurately measured the dimensions of the AWJ milled pocket. The target pocket dimensions are maintained, the surface finish is enhanced from 3.20 µm to 0.55 µm, and the tool wear is reduced drastically.

1. Introduction

Milling is one of the common processes to produce high-precision parts of different shapes and sizes in various industries such as aircraft, automotive, defense, and agricultural machinery. Among all the advanced materials, aluminium (Al) alloys are widely employed as structural materials in the aerospace and automotive industries (Demir & Gündüz, 2009). Milling Al alloys using conventional milling (CM) can generate freeform shapes, flat surfaces, and pockets with a high finish for advanced functional needs. However, while milling the ductile materials, the CM faces challenges, such as continuous chip formation, heat-affected zone (HAZ), built-up edges, and microstructural changes in the tool and the workpiece materials (Ozcatalbas, 2003). On the other hand, the abrasive waterjet (AWJ) is known to machine various advanced materials without burr and long chips at minimum thermal deformation and no HAZ. The AWJ can be employed to mill a wide range of materials (Momber & Kovacevic, 1998). However, due to the time-dependent nature of the material removal, AWJ milling faces a challenge in maintaining the desired depth and sharp edges over the machining region (Natarajan et al., 2020) Hence, AWJ milling and CM can be combined as a hybrid approach to exploit the benefits of both in enhancing the dimensional and surface quality of the pockets generated in ductile materials by the AWJs. Deep pockets (depth = 25 mm) are milled using hybrid approach where the AWJ milling achieves 36 % of that depth, and the rest of the stock is removed by CM (Viganò et al., 2018). However, to minimize the tool wear in machining ductile materials, a large stock of material needs to be removed by the AWJ, and the CM can be employed in achieving final finishing. Furthermore, post-AWJ milling, the resulting pocket dimensions need to be measured accurately so that the remaining stock and the rounded corners can be removed using CM efficiently. Thus, there is a strong need for high-precision measurement methods suitable to the machining environment. Measuring the dimensions with the traditional manual contact techniques has low efficiency due to uncertainties caused by surroundings, operator, and equipment failure (Range & Coding, 2022). The coordinate measuring machine, an expensive and contact measurement technique, may not be practical in this context (Sadaoui & Phan, 2021) To overcome some of these issues, non-contact approaches, such as confocal laser scanning microscope and optical profilometer, are used with high accuracy (Fu et al., 2018). However, optical profilometers and laser scanning

*Corresponding author E-mail: devadula@iitm.ac.in

https://doi.org/10.58368/MTT.22.5.2023.30-35

microscopes are expensive and require much time to scan. Moreover, in both methods, due to the large magnification, limited scans are possible at one go in the z-direction. Hence for large dimensions, multiple scans are needed. As a result, in the case of in-situ-based real-time measurement, achieving fast and high precision for a large dimension of the workpiece is difficult by the methods mentioned above (Adam et al., 2018). A machine vision-based system can be incorporated to measure the deviation in the dimensional measurement of the workpiece by employing an edge detection algorithm (Zhang et al., 2022) (Saif et al., 2022). From the above literature review, it is observed that limited information is available regarding shallow pocket milling in difficult-to-machine materials.

This work proposed a hybrid milling (HM) strategy integrated with machine vision-based measurement and demonstrated by milling a 10 mm x 10 mm pocket. AWJ milling was the preliminary operation to remove the maximum stock of material. Following this, a machine vision approach was used to measure the resulting pocket's dimension. Finally, conventional milling was used to enhance the corner edge radii, dimensions, and surface quality. Furthermore, the tool wear was studied in HM and CM, where the complete pocket was milled by only solid cutting tool.

2. Experimental Setup and Methodology

This section presents the abrasive waterjet milling setup, the conventional milling setup, the machine vision-based measurement setup, and the methodology for milling pockets through HM and measuring surface characteristics.

2.1. Experimental setup employed for AWJ milling

The 3-axis abrasive waterjet machine tool (Fig.1: AQUAJET® - G3020) was equipped with an ultra-high pressure water pump that can supply water at maximum pressure (*P*) of 420 MPa at a rated discharge of 4.3 l/min employed for the AWJ milling. The abrasive feeder can supply abrasives at a flow rate ($\dot{M}$) of 0.25 - 0.5 kg/min. The positional and motion controller aided in traversing the jet up to a maximum traverse rate (V_f) of 15000 mm/min. The diameters of the orifice (d_o) and the focusing nozzles (d_f) of 0.35 mm and 1.02 mm were used throughout the experiments. The abrasive grit size was #80 (φ 180 µm).

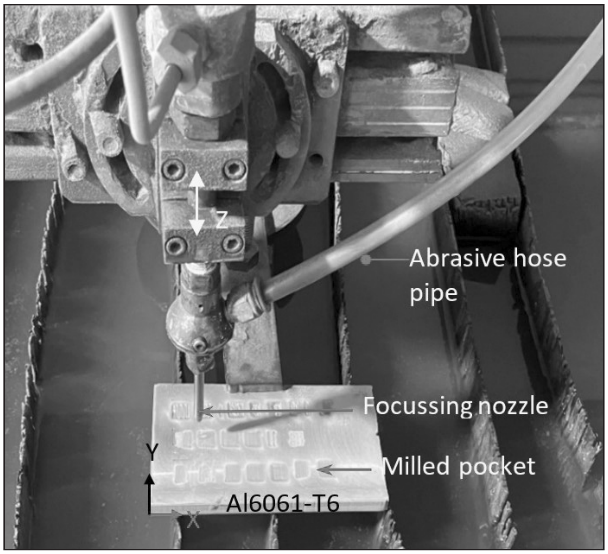


Fig. 1. Experimental setup used for abrasive waterjet milling.

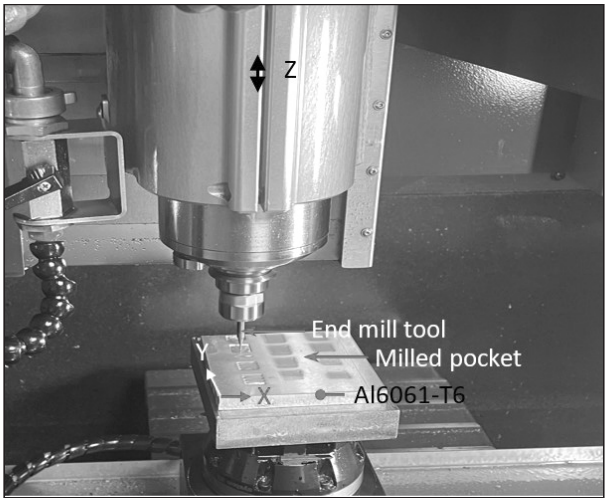


Fig. 2. Conventional milling setup for generating pockets.

- *Process parameters of AWJ milling experimental trials*

The pocket was milled by AWJ at a jet traverse speed (V_f) of 250 mm/ min, and the waterjet pressure (*P*) was kept at 125 MPa. The standoff distance (*SoD*) and the abrasive flow rate were fixed at 10 mm and 0.35 kg/min, respectively.

2.2. Experimental setup of conventional milling process

The ultra-precision 5- axes milling machine tool (Fig. 2: KERN Evo®) was employed for the hybrid and conventional milling of the pockets. The CM experimental trails employed an end mill cutter of 1.0 mm in diameter for hybrid and conventional milling. The feed rate of 100 mm/ min, the depth of cut of 0.6 mm, and the spindle speed of 10,000 RPM were considered.

2.3. Machine vision-based measurement setup and methodology

The milled pocket's dimensions were measured with the help of an indigenously developed machine vision setup (Fig.3). The machine vision setup comprises an industrial CMOS camera, low distortion lens of less than 0.1 % distortion percentage, bar light (combination of LED sources) illuminating system, image acquisition device that is pc and software. The camera's resolution is greater than 12 MP. The camera's pixel size is greater than 3 microns, and an image transfer rate of 30 fps. Milled surface images were captured while bar light illuminated the milled pocket at various positions on the axis of the camera. The light source to object distance, grazing angle, and inclination angle of striations were considered, as they affect the image surface's greyscale values. Image pre-processing was done to remove the noise present in the captured image. The entire image was converted to binary form by creating a mask using image thresholding. Since the image was read by MATLAB® software while processing the image, it followed the pixel coordinate system when scanning the image to detect the edge. The pocket edges were marked, and the dimension of the marked lines was measured. The measured dimension achieved was in pixel dimension. Therefore, the camera was calibrated for converting the image pixel values into the physical dimension (mm). From the camera calibration, the scaling factor was evaluated as 0.015 mm/ pixel, 64 pixels in 1 mm of a scale. That scale image was captured at the same camera resolution condition. Finally, the scaling factor was multiplied by the measured pixel dimension to evaluate the length and width in mm units.

2.4. Methodology for measurement of surface characteristic

Once the milled pocket achieved the required length and width with the help of HM, an analysis of surface texture was employed. The pockets were scanned using a confocal laser microscope (LEXT® OLS4000) to measure the surface texture parameter- 2D roughness. The methodology of the whole work is presented through the flowchart (Fig 4).

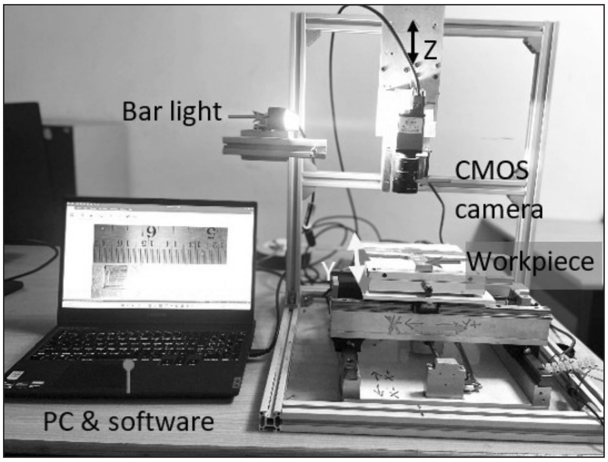


Fig. 3. Machine vision setup used for measurement of pocket dimensions.

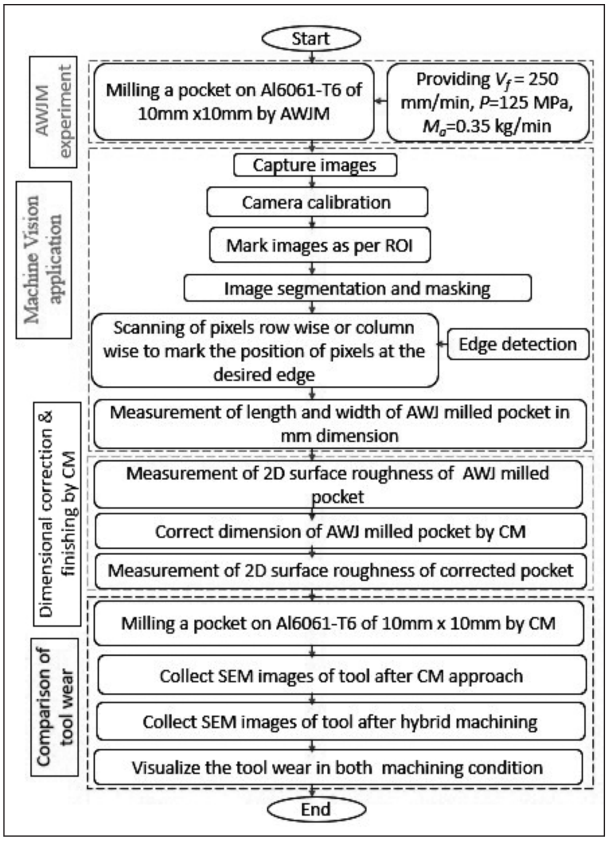


Fig. 4. Flowchart of the methodology followed.

3. Result & Discussions

This section describes the observations on the AWJ milled pocket, measured dimensions on the AWJ milled pockets by employing the machine vision approach, determination of correction on the dimensions, and correction realization by the post-conventional milling, enhancement of the surface roughness resulted by the AWJ milling. Finally, the tool wear analysis between HM and CM was presented.

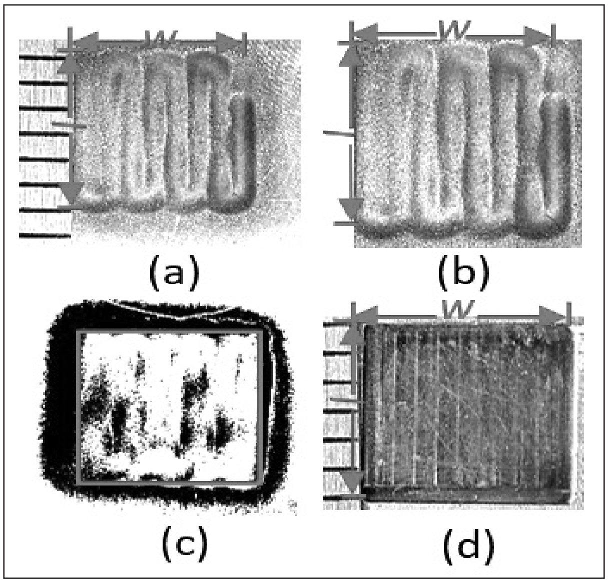


Fig. 5. Captured images using the machine vision setup (a) AWJ milled pocket, (b) region of Interest, (c) image processing, (d) corrected dimension by CM.

3.1. Observations on the AWJ milled pocket

From the AWJ milled 10 mm x 10 mm pocket at the above-mentioned process parameters, the erosion depth (=0.43 mm) was observed as shallow at 125 MPa waterjet pressure and 250 mm/min traverse rate. At the pocket corner, the jet slows down its traverse rate during the traverse direction change, creating a rounded edge due to the effective jet radius (Fig. 6(a)). Furthermore, the low-energy stray abrasive particles made the corner radius blunt.

3.2. Dimensions measured through machine vision setup

The edges of the AWJ milled pocket were detected using the machine vision approach (Fig.5(a)). From the image processing algorithm, the region of interest (ROI) was extracted (Fig. 5(b)). Image masking and segmentation were done (Fig. 5(c)) in the image processing step, and finally, the edges were detected. From this, it was determined that the length and width of the pocket were 9.76 mm and 9.62 mm, respectively. To achieve the required dimension of 10 mm x 10 mm, the remaining material was removed and finished using the CM process by following a zig-zag path (Fig 5(d)).

3.3. Measurement of corner edge radii

Following the AWJ milling, hybrid milling, and conventional milling, the radii of the milled pockets' four corners were measured (Fig. 6). The average corner edge radius in each pocket milling mode was evaluated (Table 1).

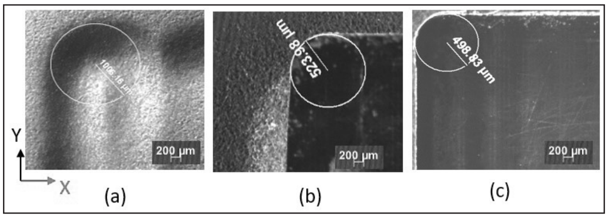


Fig. 6. Corner edge radius calculation (a) AWJ milled pocket, (b) Corrected milled Pocket, (c) Conventionally milled pocket.

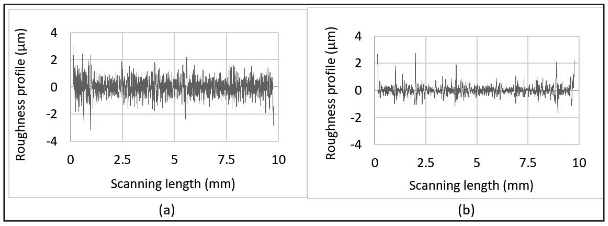


Fig. 7. Evaluation of roughness profile (a) AWJ milled pocket, (b) milled pocket by hybrid approach.

Table 1
Measurement of corner edge radius.

	Mode of Pocket Milling		
	AWJ	Hybrid	Conventional
Corner edge radius (µm)	980	492	488

As the AWJ milling is a time-dependent operation, and at the corners, the jet decelerates, it dwells more time, resulting in over erosion. Hence the corner edge radius was increased. Most of the material was removed by AWJ to reach the required dimension of the pocket. Thus, only the edges needed to be corrected by the CM, which also helps to reduce the tool wear. However, while milling pockets entirely by the CM method, the tool removes all the targeted material, resulting in high tool wear.

3.4. Surface roughness analysis

Figure 7 shows that the surface roughness value was less in the hybrid milling approach than the roughness value achieved in the AWJ milling method. The average surface roughness (R_a) value of the AWJ milled pocket was 3.20 µm, and the R_a value of the pocket milled by the HM was 0.55 µm. As a result, the surface finishing was improved considerably (by 82 %) after employing the hybrid milling approach rather than milling by AWJ alone.

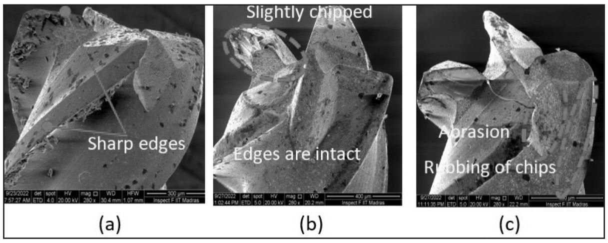


Fig. 8. Tool wear analysis of end mill cutter
(a) before milling,
(b) after correcting AWJ milled pocket,
(c) after milling pocket entirely by CM method.

3.5. Tool wear observations

The comparative analysis of the pockets milled in the HM, and the CM revealed that nearly the same depth of pocket of 0.7 mm was maintained. Figure 8 depicts the end mill tool's scanning electron microscope (SEM) images in both cases. Figure 8(a) shows the SEM image of the tool in its initial condition, and it was clear that all the edges were sharp at that condition. It was observed that after correcting the pocket, which was milled by the AWJ method using the CM approach, the tool was slightly chipped off in one of the edges (Fig. 8(b)). However, all the other edges were sharp and intact. After milling the pocket entirely with the CM method, there was abrasive wear at the cutting edges (Fig. 8(c)), and scratch marks were visible due to the rubbing of the chip over the tool.

3.6. Comparison study on cycle time

The comparative analysis of cycle time in both the HM and CM approach revealed that time was saved using the HM approach. While using the HM process, the AWJ milling process took significantly less time (T_1= 34″) for a single pocket to remove a large amount of stock, and the remaining amount of material to reach the required dimension of the pocket was milled by the CM approach (T_2= 3′ 24″). Therefore, the cycle time needed for the HM approach was T_3= 3′58″. But, for milling a pocket of the same dimension and depth entirely using the CM approach, the cycle time was calculated as T_4= 7′56″. Therefore, the total cycle time required for milling pockets in bulk using the HM approach will be significantly less than the CM approach.

4. Conclusions

The present study proposed a hybrid milling approach that exploits the complementary benefits of the abrasive waterjet and the conventional hard-cutting tools for generating pockets in ductile behaving Al6061-T6 alloy. From the current study, the salient results are concluded as follows:

- The HM enhanced the quality (in terms of dimensional and surface) of the pockets milled by only AWJ. The tool wear on the solid cutting tools is reduced considerably as they are employed as complementary tools for material removal.
- The machine vision approach was demonstrated as an efficient, accurate, in-situ, and non-contact dimensional measurement technique, and it is proved to be a workable industrial solution.
- By the HM approach, the nominal dimension of the pocket was achieved successfully, and the pocket corner radius was reduced by 50 % compared to the AWJ milling and improved pocket dimensional accuracy.
- The surface roughness of the milled pocket decreased by 83 % in hybrid milling compared to AWJ milling.
- Tool damage was minimal in the hybrid milling compared to conventional milling.

Detailed experimentation is required to analyze the AWJ and conventional milling process parameters' effect on the respective milled surface quality, corner/edge radius, and pocket dimensions toward achieving optimized part quality. Furthermore, the work will be extended to modify the indigenously built machine vision setup with the arch-type module for illuminating the workpiece efficiently. The setup will be integrated with the AWJ machine tool along with the hermetically sealed compartment to protect from any dust or moisture.

Acknowledgments

The author would like to acknowledge the financial support from the Prime Minister's Research Fellows (PMRF) scheme and the Department of Science and Technology (DST) [ECR/2017/003357].

References

Adam, A., Yusof, Y., Iliyas, M., Saif, Y., & Hatem, N. (2018). Review on manufacturing for advancement of industrial revolution 4.0. *International Journal of Integrated Engineering*, *10*(5), 93-98. https://doi.org/10.30880/ijie.2018.10.05.015

Demir, H., & Gündüz, S. (2009). The effects of aging on machinability of 6061 aluminium alloy. *Materials and Design*, *30*(5), 1480-1483. https://doi.org/10.1016/j.matdes.2008.08.007

Fu, S., Cheng, F., Tjahjowidodo, T., Zhou, Y., & Butler, D. (2018). A non-contact measuring system for in-situ surface characterization based on laser confocal microscopy. *Sensors (Switzerland)*, *18*(8). https://doi.org/10.3390/s18082657

Momber, A. W., & Kovacevic, R. (1998). Material-Removal Mechanisms in abrasive water-jet machining. *Principles of Abrasive Water Jet Machining,* 89-162. https://doi.org/10.1007/978-1-4471-1572-4_5

Natarajan, Y., Murugesan, P. K., Mohan, M., & Liyakath Ali Khan, S. A. (2020). Abrasive Water Jet Machining process: A state of art of review. *Journal of Manufacturing Processes*, *49* (November 2019), 271-322. https://doi.org/10.1016/j.jmapro.2019.11.030

Ozcatalbas, Y. (2003). Chip and built-up edge formation in the machining of in situ Al4C3-Al composite. *Materials and Design*, *24*(3), 215-221. https://doi.org/10.1016/S0261-3069(02)00146-2

Range, L., & Coding, M. (2022). *High Precision Visual Dimension Measurement Method with Large Range Based on Multi-Prism and M-Array Coding*.

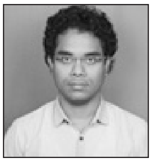
Sadaoui, S. E., & Phan, N. D. M. (2021). Touch Probe Measurement in Dimensional Metrology: A Review. *International Journal of Automotive and Mechanical Engineering*, *18*(2), 8647-8657. https://doi.org/10.15282/ijame.18.2.2021.02.0658

Saif, Y., Yusof, Y., Latif, K., Abdul Kadir, A. Z., Ahmad, M. binti I., Adam, A., & Hatem, N. (2022). Development of a smart system based on STEP-NC for machine vision inspection with IoT environmental. *International Journal of Advanced Manufacturing Technology*, *118*(11-12), 4055-4072. https://doi.org/10.1007/s00170-021-08095-y

Viganò, F., Parenti, P., & Annoni, M. (2018). Hybrid Abrasive Waterjet and Milling Process. In *Hybrid Machining*. https://doi.org/10.1016/b978-0-12-813059-9.00007-5

Zhang, W., Han, Z., Li, Y., Zheng, H., & Cheng, X. (2022). A Method for Measurement of workpiece form deviations based on machine vision. *Machines*, *10*(8), 718. https://doi.org/10.3390/machines10080718

Chinmoyee Datta is currently pursuing a direct Ph.D (MS+PhD) program in the Mechanical Engineering Department under the Prime Minister's Research Fellow (PMRF) scheme in the manufacturing section of the department of Mechanical Engineering, Indian Institute of Technology Madras, India. Currently, she is working on machine vision-based 3D reconstruction of machined surfaces towards the evaluation of the surface texture parameters.
(E-mail: chinmoyeedatt19@gmail.com)



Dr. D. S. Srinivasu is an Associate Professor in the Department of Mechanical Engineering at Indian Institute of Technology Madras, India. He received his Ph.D from Indian Institute of Technology Madras (IIT-Madras) in 2008. He worked as a Post-doctoral Research Fellow at Nottingham University, UK for 3½ years (2008-2011). Following it, he worked as a Senior Research Fellow at KTH-Royal Institute of Technology, Sweden for 3½ years (2011-2015) before joining IIT Madras. His research interest includes in particular – machining of 3D-surfaces on advanced engineering materials (super alloys, shape memory alloys, high entropy alloys, diamond, engineering ceramics, engineering composites), abrasive waterjet machining, novel tool path strategies, optimization, process modelling and simulation, machine tools, and in general – conventional and unconventional machining processes, machine tool metrology, micro machining.