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REAL TIME SURFACE FINISH MEASUREMENT OF STEPPED HOLDING GEAR SHAFT BY SMART SYSTEM

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Abstract: Traditionally, machining depended on post–production surface finish measurement, which resulted in rework caused by human modifications based on delayed data. This research solves this issue by developing a real–time surface finish detecting method. Our primary focus is on gear shaft fabrication using a lathe equipped with a laser triangulation sensor and a unique roughness testing algorithm. This system continually collects surface data during machining, computing average roughness (Ra) and compares it to predefined criteria. This real–time feedback system, known as the "SMART Mechanism," cuts completion time by 25–35% by eliminating distinct inspection steps. Furthermore, it reduces workpiece rejects by 20–30% while maintaining consistent quality with a 9% error tolerance for surface finish measurements. This strategy uses sensor technologies and algorithms to empower workers and speed up production with improved quality of production.
Keywords: Gear stepped shaft, distance sensors, Live surface finish measurement, productivity, operator fatigue

1. INTRODUCTION

The cutting–edge innovation of smart surface finish detection represents a groundbreaking advancement poised to transform the manufacturing landscape, particularly tailored to meet the intricate demands of stepped holding shafts. In the realm of manufacturing, achieving top–tier workpieces necessitates an unmatched emphasis on surface finish, an area where traditional methods often prove inadequate in providing immediate and comprehensive insights. Critical quality parameters, such as surface finish, commonly referred to as roughness, hinge on various factors including cutting parameters. Choices regarding cutting parameters such as feed and depth of cut significantly influence the attainment of a superior surface finish.

With the industrial sector increasingly gravitating towards automation or CNC machines to stay competitive in terms of quality, there arises a need to enhance operators' proficiency, confidence, and output to maximize labor efficiency. This underscores the significance of process parameters, which hold paramount importance for operators. Quality considerations like surface finish predominantly rely on the selection of speed, feed, and depth of cut. Empowering operators with real–time information about the workpiece enables them to make informed decisions, progressively elevating the workpiece into the quality realm rather than risking rejection. However, the existing feedback systems for making decisions regarding workpiece dimensions are lacking in continuity. While various methods exist for measuring surface finish, there's a notable absence of emphasis on its live, real–time availability.

R. Ramesh et al. uses Support Vector Machines (SVM) excel in tackling intricate multi–dimensional parametric challenges that traditional analytical methods find daunting. The intelligent support system for controlling surface finish aids operators in estimating surface finish based on specific feed rates, spindle speeds, and depths of cut. In cases where the predicted output fails to meet the required surface finish standard, operators can define alternative operating conditions. Once satisfied with the parameters, operators can apply them to achieve the desired finish. [1] This method is exclusively employed on CNC machines, as it's not compatible with general–purpose machines. The intelligent system defines cutting parameters and integrates them into the CNC machine for processing. However, it lacks relevance for general–purpose machines and doesn't provide direct guidance to operators.

Xiaoyan Guan et al. states method based on the concept of sensor utilization and specific experimental conditions, the overall design of the detection system is formulated, followed by research into the spatial positioning algorithm and surface measurement algorithm of the workpiece under examination. The algorithm is employed to compensate for and rectify errors. The adequacy of the framework is verified by estimating the surface dimensions of the workpiece. Subsequently, the spiral roundabout run–out error is utilized as an example to validate the recognition framework. The results indicate that the estimation error remains below 5%, affirming the high accuracy of the framework. However, it's important to note that this method is deployed solely for surface dimensions, not surface finish, despite considering various points along the length.[2]

S. Lakshmana Kumar et.al in a separate study proposes, a polynomial insertion is utilized to enhance the data density of the conventional GG technique, thereby improving LT's data acquisition accuracy. These techniques are then applied to on–machine measurements of the American Petroleum Institute (API) thread and the screw rotor, respectively. Experimental results demonstrate that the method significantly enhances the measurement accuracy of free–form curved surfaces using LT. Furthermore, the improved laser spot center extraction algorithm is better suited for free–form curved surfaces with smaller and more uniform curvature changes.[3]

ZhixuDong et.al vision system is used to capture the SEM images of the machined surface. Two–layered pictures of the Nimonic263 combination's machined surface are utilized for surveying example surface profiles during complete the process of turning. Surface harshness is distinguished in recreated pictures of examples under various processing settings utilizing imaging advancements. In this exploration, surface is extricated through a strategy that joins 2D surface pictures with the wavelet change method. The 2D wavelet transform can break down a machined surface image into multi resolution representations of various surface attributes, proving valuable for surface evaluation. The study involves analyzing the disparity in histogram frequency between an illuminated region of interest (ROI) and rotated surface images. [4] Characterization of the Machined Surface is done after manufacturing by images simulation. The surface roughness is not aimed at live manufacturing and continual feedback system for effective communication with operator.

In–Process Surface Roughness Adaptive Control (ISRAC) system for turning operations using an Artificial Neural Network (ANN) is one of the method developed for roughness measurement by Julie Z. Zhang et.al. This system incorporates two subsystems: the Neural Network–Based In–Process Surface Roughness Prediction (INNSRP) and the Neural Network–Based In–Process Adaptive Parameter Control (INNAPC). The INNSRP subsystem predicts surface roughness during the finish cutting process with an accuracy of 92.42%. The development of regression models, derived from experimental tests in turning operations, is a common practice for predicting the outcome. Basically, it is not operator friendly. [5] LT contour data obtained by applying different spot center extraction algorithms. (a) Traditional GG method; (b) variable threshold sub–pixel GG method is only on machine off manufacturing measurement and it sis operator friendly once work piece changes its profile.

Gaowei Ye et.al in another research endeavor the evaluation of surface roughness resulting from a Teflon turning operation using CNC and conventional machine tools is explored. The findings reveal that surface roughness achieved when turning Teflon on CNC is smoother compared to conventional lathe machining. Moreover, a surface roughness recognition model named Deep CORAL AlexNet is proposed, leveraging deep transfer learning on color images to discern surface roughness levels with high accuracy in various light settings. However, while these methods provide valuable insights into data processing and measurement techniques, they do not address the need for continual surface finish feedback during live manufacturing.[6]

To address this gap, an innovative approach has been developed, employing a sophisticated algorithm and sensor setup to continuously monitor and evaluate the surface finish of stepped holding shafts in real–time throughout the manufacturing process. This system offers instantaneous feedback on surface status influenced by current feed speed and depth of cut, distinguishing it from conventional offline and direct measurement techniques.

2. METHODOLOGY

This intelligent configuration ensures the ongoing provision of feedback on surface finishes during active manufacturing processes. The technology combines a laser triangulation sensor with a meticulously crafted algorithm to continuously collect real–time data on surface finish under various cutting parameter conditions across different manufacturing stages. [7] Following this, the system associates the detected surface finish values with predefined Master Data for consistent comparative assessment. This instantaneous feedback facilitates an accurate evaluation of the workpiece's condition concerning

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the finished surface—whether it's semi–finished or rough, amidst any potential surface irregularities. Consequently, this offers real–time guidance to the operator, aiding them in selecting appropriate cutting parameters iteratively within the manufacturing cycle.

- Experimentation module
  - Sensor module

In this method of surface roughness measurement, the workpiece is secured onto the machine and precisely aligned with its central longitudinal surface line. A laser line triangulation sensor is used to measure distances precisely at the midpoint of the workpiece held by the machine[8, 9]. The sensor possesses the capability to move horizontally, backward, and forward along the single–point cutting tool utilized by the operator. Furthermore, the sensor can adjust its height to accommodate changes in the workpiece. The distances between various adjacent points measured by the sensor on specific sections of the workpiece surface being produced serve as indicators of the surface finish.

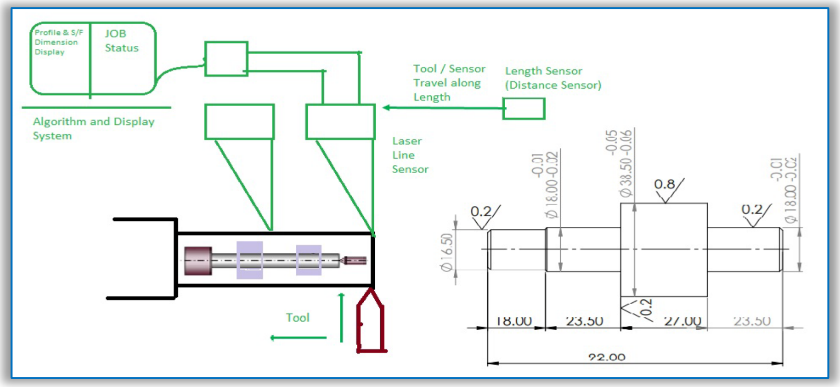


Figure 1. Showing SMART live surface finish testing Module

- Data recording and feeder Module

The output from the sensing module, ranging from 0 to 10 V, is automatically calibrated by the sensor and transmitted to an analog to digital converter. This output from the sensor module is recorded using a converter module and linked to a feeder module. Within this feeder module, a code is developed to accumulate the digital values representing distances from the workpiece. The recording and feeding of values, processed through the conversion and feeder modules, are implemented sequentially as each section of the workpiece is completed. A setting for Phase wise data recording and feeding is introduced up to job completion and signifies a transition to prioritize S/F requirements.

- Data processing and collating module

The information obtained from the feeder, which supplies surface finish data, undergoes processing within the processing module. This involves comparing real–time data values with standard data values for each section. Specifically, the distances between adjacent points along the length are computed using the built–in Raformula.[10] This processed data is then forwarded to the collating module, where it is compared with real–time values.

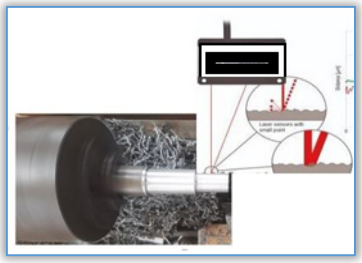


Figure 2. Actual process of surface finish

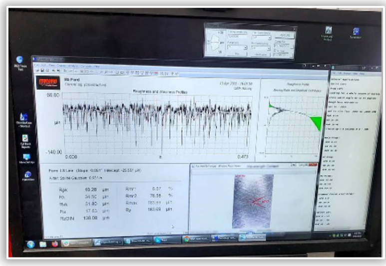


Figure 3. Surface finish Display system measurement

- Communication module

The display offers real–time guidance and control prompts for ongoing processing. It consists of a single–window screen featuring standard drawing images with sequentially labeled sections. Within this interface, the operator inputs the required standard surface finish value in one box and observes the real–time value in another. A single dialogue box in active mode provides surface finish status over the desired length of each section. This

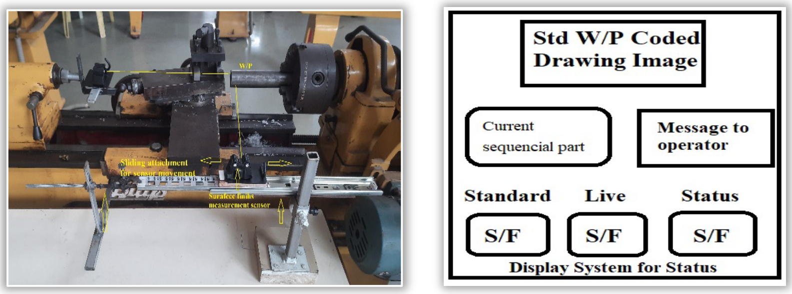


Figure 4. Surface finish Display system measurement

setup allows operators to easily reference the display, facilitating instant communication. The displayed image mirrors the workpiece to be manufactured, with color changes occurring upon completion of each section.

Correction reference Module

Based on the communication module, the operator confirms actions taken. Communicating the status of surface finish in phases facilitates smooth operation, allowing the operator to focus on different aspects of the work. This approach ensures that the operator can proceed confidently through rough operations while remaining vigilant during finishing. The experimental setup is designed with the following considerations:

- Measurement of surface finish value over specified length sections.[11]
- Conversion of sensor analog values of surface point distance into digital values.
- Calculation of the average distance between corresponding adjacent points over the length, known as Roughness value Ra, and input into the Algorithm.
- Completion of each section:
- At 25% completion of sequential section: The original diameter of 38 mm is to be reduced to 28 mm, requiring a depth of cut up to 30 mm to remove the maximum material. Surface finish value is displayed but not considered for quality achievement as the focus is on maximizing material removal with rough cuts.
- At 50% job completion: Displayed but not considered for high–diameter cutting. The aim remains to remove the maximum material through rough cuts.
- This phase becomes crucial for the quality of the workpiece section, particularly when the diameter needs to be reduced from the original 38 mm to 36 mm.
- At 75% job completion: Attention is focused on this phase.
- Up to 100% job completion: Complete attention is given during the cutting operation, with only finished cuts introduced by the operator. Rough cuts are permissible only up to 75% job completion, and only roughness values within specified limits are accepted.
- The status of the workpiece is continuously displayed phase–wise regarding surface finish. Any deviations trigger signals to the operator for corrective action.

3. WORKING OF SMART MODULE

Scanning and sequencing

Due to machine vibration, the workpiece may have an initial variance in surface reading before beginning manufacture. The sensor is then adjusted to zero in accordance with the vibrational variation. When there is a new piece or a modification in the work piece drawing, the operator just scans the standard drawing into the display system. The basic scanner is located beneath the standard W/P coded drawing picture portion. Once the image is scanned by the scanner, it will be shown on the screen. [12] The operator can then quickly assign component names based on the sequence of work piece drawings. Additionally, the typical surface finish required can be input into the algorithm..

Manufacturing and Measurement

Initially, the starting point is fixed. The tool point and the sensor incident point are in the same place. The operator begins constructing the sensor in the precise middle of the work piece, travels longitudinally, and provides the distance between surface points from the sensor along the given length of section. [13–15] The Ra is calculated by measuring the distance between distinct adjacent spots using a sensor. This Ra value is then supplied into the inbuilt flexible algorithm. The previously given standard requirement for surface finish to the algorithm assesses the operator's current remarks. The surface finish along the considered portion of the work item is specified with a remark.

Algorithm's processing

Encoded programming plays a critical role in verifying the accuracy of cutting parameters and surface finish. The algorithm continuously assesses the standard surface finish against real–time values. Pillow, an open CV library, is utilized for Python–based coding to compare and display messages. The Ra value, also known as the Roughness Average, is pivotal in measuring surface roughness. [16] It is determined by computing the average absolute values of surface height deviations from the mean line within a specified evaluation length. This Ra value represents the average of all individual measurements of a surface's peaks and valleys. The Ra formula is expressed as follows: Ra = 1/L ∫|y(x)| dx from 0 to L. Here, L represents the sampling length, while y(x) denotes the vertical deviation from the mean line at a distance x along the surface. This formula provides a comprehensive understanding of the Ra value and its significance in assessing surface roughness. [15] [17–18]

In this experimental context, the desired outcome is an AS–MACHINED FINISH type of surface finish, among several other types like Smooth Finish, Textured Finish, Mirror Finish, and Anodized Finish. As–machined finish refers to the surface finish obtained directly from the machining process without any post–processing. It may exhibit noticeable tool marks and is typically not exceedingly smooth.

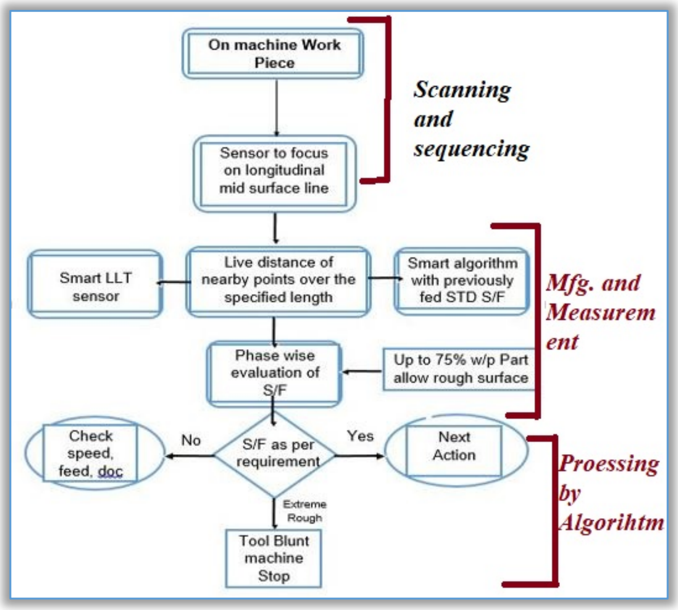


Figure 5. Flow of surface finish measurement and decision-making

Ra is the integer average of all absolute roughness profile departures along the measurement length from the centerline. On the other hand, Rz represents the absolute peak–to–valley average of five successive sample lengths within the measurement length. While Ra analyzes all dimensions, it lacks differentiation for selecting rejects from appropriate cylinders.

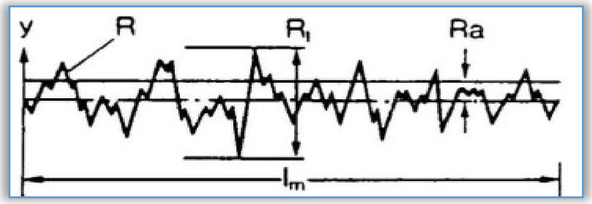


Figure 6. Roughness value Ra

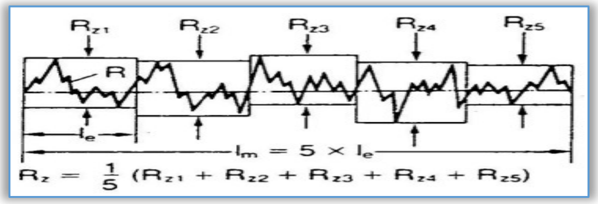


Figure 7. Mean roughness depth Rz.

The mean roughness value, Ra, represents the arithmetic mean of all roughness profile R values within the measurement distance lm. It signifies the average deviation of the surface profile from the mean line.

Algorithm part

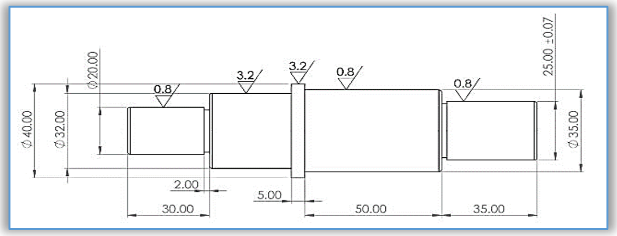


Figure 8. Holding stepped Shaft, Workpiece type No. 02 manufactured

Raspberry pi setup code, gpio.setmode(gpio.bcm), # define gpio to use on pi, # measurement function, defmeasuredistance():,class and function definitions , handling the GUI for the data_widget, variable initializations, variables for pixel values in bgr format, tkinter and image variables, GUI navigation logic were used in developing algorithm part.[19] [20]

4. OBSERVATION AND DATA COLLECTION

The work piece as holding stepped shaft of four types with different features are considered for experimentation. A batch size of 10 each sample is machined by smart set up to validate the results of smart set up by ease of surface finish measure and to adopt method for change work piece features. The operator is empowered to incorporate the sequential parts of the W/P into the algorithm, which is then visually represented on a scanned image of the workpiece. When turning the first sequential part of the workpiece, with an initial length (L) of 68.5 mm and a diameter (D) of 40.0 mm, it's segmented into phases or strokes of manufacturing, as executing it in a single phase isn't feasible. Each phase progresses at a depth of cut of 1 mm, aiming for a target standard diameter of 38.50 mm.

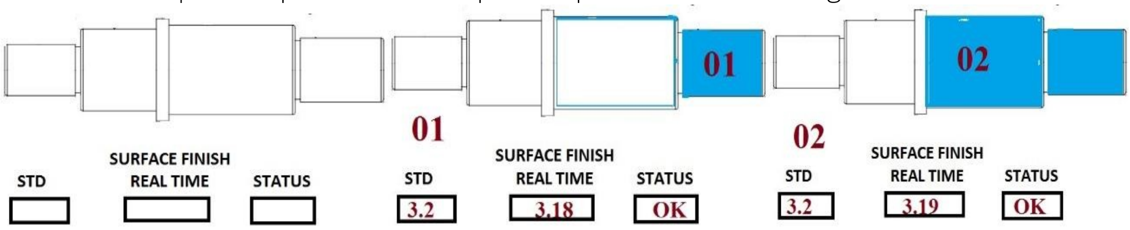
Table 1. Showing phase wise surface finish detection of each section of holding stepped shaft workpiece type No. 01 section wise sequentially

Sr No	Component Part Sequence	Phase wise Surface Finish Detection in µm										
		Initial Length Diameter	Phase	Doc mm	Standard Diameter	% Phase completion	Standard Ra Value	Display Ra Value by Smart Set up	Display By S/F Tester	Error Difference µm	% Error	Remark /Action to be taken
1	Sequence Part 01 Over length	L 115.0 mm D 44.0 mm	I	@ 1 mm 3 cuts	– 0.05 40.00 – 0.02	D 41.00 % 75	NA for first two cut Third Cut –	NA for first two cut 3.41	NA for first two cut 3.45	0.04	4	NA for 2 cut Take next Cut smoothly
			II	@ 0.5 mm 2 cuts	– 0.05 40.00 – 0.02	75 to 100	Ra= 3.2 µm	Ra= 3.18 µm	Ra= 3.26 µm	0.08	8	SP1 Complete Ok
2	Sequence Part 02	L 60.0 mm D 40.0 mm	III	@ 1.5 mm 4 cuts	32.00	D 34.00 % 75	NA or any Ra Value	NA or any Ra Value	NA	–	–	NA
			IV	@ 1 mm 1 cut	32.00	D 33.00 Up to 95	3.2	3.191	3.25	0.06	6	Take next Cut smoothly
			V	@ 0.5 mm 2 cuts	32.00	D 32.00 95 to 100	3.2	3.180	3.26	0.08	8	Ok, Next Dia
3	Sequence Part 03	L 30.0 mm D 32.0 mm	VI	@ 1.5 mm 6 cuts	20.00	D 23.00 % 75	NA	NA	NA	–	–	
			VII	@ 1.5 mm 1 cuts	20.00	D 21.50 Up to 87	NA	NA	NA	–	–	Take next Cut smoothly
			VIII	@ 0.5 mm 3 cuts	20.00	D 20.00 87 to 100	0.8	0.796	0.810	0.14	14	Ok, Next Dia
4	Reverse Side Sequence Part 04	L 90.0 mm D 40.0 mm	IX	@ 1.5 mm 2 cuts	D 35.00 L 85.00	D 37.00 % 75	NA for first two cut Third Cut – 0.80	NA for first two cut 0.82	NA for first two cut 0.792	0.10	10	NA for first two cut Take next Cut smoothly
			X	@ 1 mm 2 cuts	D 35.00 L 85.00	D 30.00 Up to 100	NA for first two cut Third Cut –	NA for first two cut	NA for first two cut	–	–	
5	Reverse Side Sequence Part 05	L 35.0 mm D 35.00 mm	IX	@ 1.5 mm 6 cuts	D 25.0 ± 0.07	D 26.00 % 75	NA for first two cut Five Cuts –0.8	NA for first Five cuts 0.82	NA for first two cut 0.793	0.10	10	
			X	@ 0.5 2 cuts	D 25.0 ± 0.07	D 25.0 ± 0.07 Up to 100	0.8	0.794	0.808	0.12	12	Ok, Next Operation

Upon achieving a diameter of 39.00 mm, indicating 75% completion of the initial operation, no attention is given to surface finish, as it's deemed a rough operation. For the remaining 25% phase, with a depth of cut of 0.25 mm, two cuts are made to attain a surface finish of 0.8 µm, displayed on a smart display guided by the algorithm. This value is then compared with the standard roughness value over the 68.5 mm length.

Moving to sequential part 2, with an initial length of 41.5 mm and diameter of 38.5 mm, the target diameter is set at 18 mm. Initially, a depth of cut of 1.5 mm is considered, with ten continuous cuts, achieving a diameter of 23.55 mm, signifying 75% completion of the phase. No significant emphasis is placed on roughness value until this point, as it's primarily a rough operation. Subsequently, a 1 mm depth of cut is utilized for the next 20% operation, resulting in three cuts to achieve a 19 mm diameter. Surface finish is continuously monitored and displayed on the smart display system. For the final phase, depths of cut at a rate of 0.5 mm, with two cuts, yield an 18 mm diameter, with priority given to attaining a roughness value of 0.8 µm over the length of 41.5 mm.

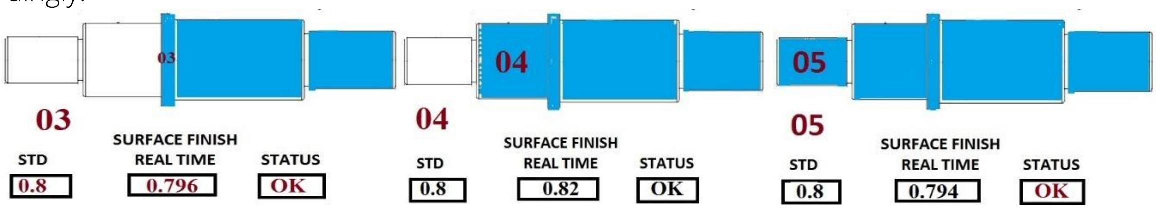
In sequential part 3, with a length of 18 mm and diameter of 16.5 mm, the target diameter remains at 16.5 mm. Three cuts, each at a depth of 0.5 mm, are executed to achieve a roughness value of 0.8 µm. Once attained, the operator proceeds to sequential part 4 manufacturing.



(a) W/P yet to start (b) 01 Section completed (c) 02 Section completed

Figure 9. Sequential parts

In sequential part 4, with a length of 23.5 mm and diameter of 38.5 mm, the target diameter is set at 18 mm. Initially, a depth of cut of 1.5 mm, with three cuts, accomplishes 80% of the sequential part 4. Subsequently, the remaining 20% operation prioritizes achieving a roughness value of 0.8 µm, utilizing a depth of cut at a rate of 0.5 mm and two cuts. If this criterion is met, it indicates successful completion of the workpiece with the specified surface finish. The real–time value obtained from the smart setup is then compared with the standard surface finish value, and an evaluation is performed and displayed accordingly.



(d) 03 Section completed (e) 04 Section completed (f) 05 Section completed

Figure 10. Indicates section wise status of Work piece with help of SMART system

The blank or white image section indicates the section under the consideration of manufacturing currently or yet to start for operating. Section number indicates the sequence of operation section. The converted blue section indicates the completion of work piece with respect to surface finish.

5. VALIDATION OF RESULT

Upon completing each sequential part of the workpiece, the manufactured component undergoes surface finish testing utilizing a modern surface roughness tester. The measured value is subsequently juxtaposed with the value obtained from the smart module. This process is iterated for every sequential section of the workpiece, and the values are juxtaposed with those acquired through physical inspection methods. Following this, the disparity between the values is computed in terms of millimeters and as a percentage.

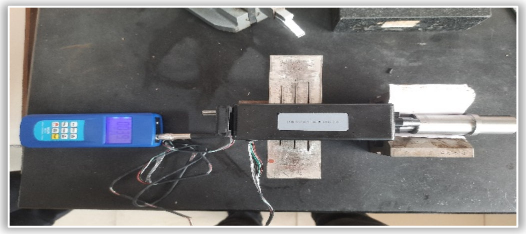


Figure 9. Physical inspection of Work piece manufactured using SMART system

Table 2. The comparison of manufacturing factors improved by both methods

Sr No	Workpiece Type A	Time for Job General Method appx	Time for Job SMART Set–Up Appx min	Saving of Time	% Time saving	Average % error of Surface finish	No of Job rejected General Method appx	No of Job rejected General Method appx
1	Type 1 W/P No 01	28	18	10	36	8	0	0
2	Type 1 W/P No 02	30	19	11	37	7	01	0
3	Type 1 W/P No 03	32	17	15	47	9.5	0	About to reject but recovered
4	Type 1 W/P No 04	27	18	09	33	9	0	0
5	Type 1 W/P No 05	29	19	10	34	7	0	0
6	Type 1 W/P No 06	26	18	08	31	8	01	About to reject but recovered
7	Type 1 W/P No 07	31	20	11	35	6	0	0
8	Type 1 W/P No 08	33	21	12	36	8.5	0	0
9	Type 1 W/P No 09	27	18	09	33	9	0	0
10	Type 1 W/P No 10	28	17	11	39	8	0	0

Table 3. Overall manufacturing factors improved by the SMART Module for gear Shaft Workpiece

Sr No	Workpiece Type	Manufacturing Time saved In min /Piece	Phase–wise Automatic Measuring facility	Average % error of Surface finish	No of Job rejected General	In process Inspection	Free from Fatigue of in–process	Increased production No of pieces/hr	In the process, Consistent display Guidance
1	Workpiece No 01	10	100 %	8	0	NA	100 %	1.5	100 %
2	Workpiece No 02	11	100 %	7	0	NA	100 %	1.5	100 %
3	Workpiece No 03	15	100 %	9.5	0	NA	100 %	1	100 %
4	Workpiece No 04	09	100 %	9	0	NA	100 %	1.5	100 %
5	Workpiece No 05	10	100 %	7	0	NA	100 %	1	100 %
6	Workpiece No 01	08	100 %	8	0	NA	100 %	1.5	100 %
7	Workpiece No 02	11	100 %	6	0	NA	100 %	1	100 %
8	Workpiece No 03	12	100 %	8.5	0	NA	100 %	1.5	100 %
9	Workpiece No 04	09	100 %	9	0	NA	100 %	1	100 %
10	Workpiece No 05	11	100 %	8	0	NA	100 %	1	100 %

Table 4 . Performance of manufacturing factors improved by the SMART Module for all workpieces.

Sr No	Workpiece Type	Avg. Manufacturing Time saved In min /Piece	Avg. Phase–wise Automatic Measuring facility	Average No of Jobs Rejected General by Module	Average % error of Surface finish	In process Inspection	Free from Fatigue of in–process	Average Increased production No of pieces/hr	In the process, Consistent display Guidance
1	Type A Workpiece	10	100 %	0	9 % / 0.09 µm	NA	100 %	1.5	100 %
2	Type B Workpiece	12	100 %	0	8 % / 0.08 µm	NA	100 %	1.5	100 %
3	Type C Workpiece	15	100 %	0	8.5 % / .85 µm	NA	100 %	1	100 %
4	Type D Workpiece	10	100 %	0	9 % / 0.09 µm	NA	100 %	1.5	100 %

Table 5. The average performance of manufacturing factors improved by the SMART Module.

Sr No	All Workpiece Type	Manufacturing Time saved In min /Piece	Phase–wise Automatic Measuring facility	No jobs rejected by the module	In process Inspection	Free from Fatigue of in–process	Increased production No of pieces/hr	Avg. Error In S/F measurement
Average factors		11.75	100%	0	NA	100%	1.37	8 – 9 % / 0.09µm

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The physical setup of the surface finish tester entails the use of a V block to secure the turned workpiece part. For each sequential workpiece part, 2–3 surface finish readings are taken, and the repetitive readings are tallied for comparison with the readings obtained through the smart setup and physical inspection. This identical procedure is replicated for other types of holding shaft workpieces with differing standard surface finish specifications. Given our primary emphasis on surface finish, it is imperative to consider the operator's reduction in diameter–wise cutting over the specified length. Here, an error of 1.00 μm is deemed equivalent to a 100% discrepancy. Table 2 shows the comparison of manufacturing factors improved by the SMART Module. Alog with surface finish following factors are also verified

6. CONCLUSION

This modern module simplifies the manufacturing process, regardless of changes in the workpiece profile. Feed rate, spindle speed, and depth of cut (DOC) play pivotal roles in determining surface finish. With the Smart Module setup, operators receive continuous support through a feedback system that presents real–time surface finish conditions. A distinctive feature of phase–wise surface finish feedback enhances operators' proficiency and confidence when dealing with profile changes. Distinguishing between rough and finished operations becomes effortless and straightforward.

Uncertainties regarding cutting parameters can be swiftly identified. A sequential chart instills operators with confidence to proceed with operations, eliminating the need for in–process workpiece inspections entirely. This eliminates the necessity for operators to frequently halt and resume operations for inspections, thereby reducing operator fatigue by 100% for that phase. Workpiece manufacturing efficiency has increased to an average of 1.5 pieces per hour. The streamlined manufacturing process and reduced fatigue contribute to an average time savings of 10 minutes per component. Consequently, even in the event of an error, it can be promptly identified and rectified before rework is required.

The average error in inspection by the Smart Module is within the range of 8–9%, corresponding to up to 0.09 μm, which is an acceptable value. There is potential for further reduction by employing high–quality sensors, thus enhancing accuracy and minimizing errors.

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