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Precision Machining of an Aluminum Alloy Piston Reinforced with a Cast Iron Insert

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Bimetallic pistons consisting of aluminum alloy reinforced with a cast iron (CI) insert are used to reduce the weight and improve the wear resistance of pistons. A major problem with machining such bimetallic pistons is producing the desired shape with minimal cutting forces and without damaging the bonding registry. The objective of this paper is to determine the optimal cutting parameters (cutting speed, feed, and depth of cut) for turning bimetallic pistons. When machining, we wish to obtain optimal values of the cutting forces and a better surface integrity while maintaining the required surface finish. Experiments were conducted following Taguchi's parameter design approach using a cubic boron nitride tool for the machining. The results indicate that the process parameters affected the mean and variance of the cutting force at the Al-CI interface of the piston. The Al–CI interface was examined using an ultrasonic piston bond tester after machining to assure the bond quality. The surface roughness of the components was measured with a surface roughness tester. A mathematical model was developed using the Systat 12.0 software package to establish the relationship between the input quantities (speed, feed, and depth of cut) and the output data (cutting force). The output data of the mathematical model were compared with the experimental results. The results from the Taguchi robust design concept were compared with the results obtained from a nonconventional Genetic Algorithm optimization technique.

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NOMENCLATURE

D = depth of cut	E = error
F = feed	Fm = mean force
Fx = feed force	Fy = thrust force
Fz = main cutting force	n = number of trials
Ra = average surface roughness	S = speed
S/N or η = signal to noise ratio	T = total
y = response of quality characteristics	

1. Introduction

To meet weight savings and production cost requirements, many components for transport vehicles that were previously made of cast iron (CI) are now being fabricated from light aluminum alloys. These alloys are often reinforced with a strong metal-based insert, especially at high load bearing regions, to improve their performance. Different techniques can be used to produce bimetallic components from aluminum alloys with CI inserts. In conventional die casting, a liquid aluminum alloy is poured into a mold over the insert; the later is simply embedded in the light alloy after solidification. However, an iron and aluminum oxide layer prevents direct contact from being established between two metals so that no real interfacial bonding exists. Forming a metallurgical bond at the insert/alloy interface using a special casting technique derived from the Al-Fin process is possible,[1] and the strength of the metallurgical bond can be enhanced by a suitable heat treatment process.[2] This results in a bimetallic component with improved functionality. Al–CI bimetallic pistons are generally employed only in diesel engines of heavy-duty vehicles. An aluminum alloy piston with a CI insert is shown in Figure 1.

2. Literature Survey

Considerable interest exists in replacing the CI and steel in

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automotive components such as pistons with lightweight aluminum alloy castings to improve the performance and efficiency of the vehicle.[3] The low expansion group of aluminum-silicon alloy, referred to as piston alloy, provides the best overall balance of properties.[4] A metal-based insert reinforces the base alloy to improve the wear performance. Engineering components, such as pistons and the cylinder head, are first processed by die casting. They are than machined to achieve the desired dimensions and surface finish.[5,6]

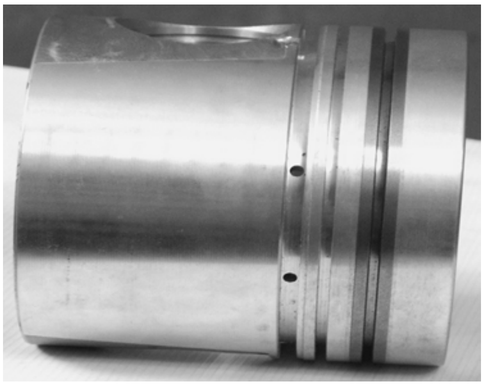


Fig. 1 Typical piston with insert

Metal cutting industries continue to suffer from not being able to run machine tools at their optimum operating conditions.[7] The functional behavior of machined parts is determined by their fine finish, which represents the last step in the process chain and can be performed by cutting.[8] Cubic Boron Nitride (CBN) is a sintered product that has excellent wear durability, high hardness, and good thermal resistance. It is unlikely to generate a chemical reaction with the workpiece under high thermal conditions, but the cost of CBN tools is extremely high, between 10 and 20 times greater than the cost of carbide tools.[9] The improved qualities of the machined surface and associated productivity improvement help alleviate their initial high cost.

CBN cutting tools are commonly used for single-point turning of hardened materials.[10] Due to recent cutting tool developments, as well as the improved machine tool structural rigidity and better CNC controllers, hard turning is emerging as an alternative process to grinding due to its reduced cost and cycle time.[11] The high CBN content of CBN tools (as much as 90%) gives a better surface finish, [12] but the geometry of the cut evolves considerably over the lifetime of a CBN tool.[13] In the past, two different tools and two different machining parameters were used to machine bimetallic components. The cycle time of these processes was unnecessarily long due to the frequent tool changes required. Hence, a single tool that can machine both metals is desirable. Coated cemented carbide cutting tool inserts have been used to machine bimetallic engine blocks such as aluminum alloys and CI.[14] However, literature on the machining and surface integrity of such bimetallic components is scarce. The present study addresses current problems encountered when machining bimetallic components.

3. Taguchi Method

The Taguchi method has produced a unique and powerful quality improvement discipline that differs from the traditional process. Since the product and process design has a great impact on the life cycle, cost, and quality of a component, the Taguchi design of experiment (DOE) approach provides a design engineer with a systematic method for determining the optimum design parameters to obtain the best performance at the lowest cost.[15,16] The quality characteristics to be optimized are identified for any engineering or nonengineering optimization problem. Quality characteristics are classified as maximation, minimization, or normal criterion. Then the factors (parameters) likely to affect the quality characteristics are identified and segregated under control (signal) and noise factors. An orthogonal array is selected based on the number of parameters and levels of variations, and a loss function is then defined to calculate the deviation between the experimental and desired values. The selection of the loss function is based on the quality characteristics. The value of the overall loss function is further transferred into a signal to noise ratio (S/N) that is identified by η with units of decibels (dB). The best value of the identified parameter is predicted from the S/N curves. A statistical analysis of variance (ANOVA) is performed to find the percentage effect on the output response. The ANOVA separates the variation in an experiment into categories related to the cause of the variation. Finally, a confirmation test is conducted using the best set of selected values of the identified parameters; this last step is of the utmost important in the DOE approach.[17] The best set of values will yield a product of superior quality compared to other possible combinations of values.

4. Experimental Plan

The identified parameters that affect the characteristics of turned parts are the cutting tool parameters (tool geometry and tool material), workpiece-related parameters (microstructure and hardness), cutting parameters (speed, feed, and depth of cut), and environmental parameters (dry cutting and wet cutting). The ranges of the selected turning process parameters (cutting speed, feed, and depth of cut) were ascertained by conducting preliminary experiments. The details of work material, machine tool, cutting tool, and cutting conditions are as follows.

Work material:	Aluminum alloy piston reinforced with a CI insert
Machine tool:	Leadwell (T5) turning center
Cutting tool:	CBN with a top rake angle of 0°, aclearance angle of 15°, and a nose of 0.6 mm
Cutting condition:	Dry
Dynamometer:	Kistler Quartz 3 component

An orthogonal array gives a more reliable estimate of the factor effects with fewer tests compared to traditional methods. The process parameters along with their values at three levels are given in Table 1.

Table 1 Factors and their levels

Factors	Units	Level 1	Level 2	Level 3
Cutting speed	m/min	452	482	512
Feed	mm/rev	0.15	0.20	0.25
Depth of cut	mm	0.15	0.20	0.25

Three major control factors (cutting speed, feed, and depth of cut) were selected to conduct the tests. All three factors are multilevel variables and their outcome effects have nonlinear relationships; hence, we used three-level tests for each factor. Figure 2 shows the piston machining arrangement with a dynamometer.

The number of degrees of freedom was calculated from the number of parameters identified and their number of levels of variation. Using the full factorial design (3×3×3×3) reduced a total of 81 sets of experiments down to 9, thereby decreasing the cost, time, and effort.[18] The array along with the factor assigned to the columns is presented in Table 2, where L9 indicates the 9 trials considered for the test.

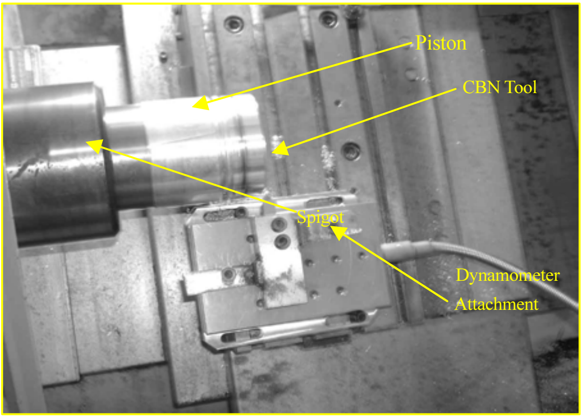


Fig. 2 Typical arrangement for machining

Table 2 L9 orthogonal array

Test number	Column		
	Speed (*S*)	Feed (*F*)	Depth of cut (*D*)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Pistons that were 96 mm in diameter and 30 mm in length (with bonding zones from one end) were machined on a turning center with a CBN tool. The cutting forces were measured using a dynamometer while each specimen was turned. Dynamometers have been developed that are capable of measuring tool forces with an increasing degree of accuracy.[19] The component forces were also taken into account and the mean force was calculated from the formula

$$Fm = \sqrt{Fx^2 + Fy^2 + Fz^2} \tag{1}$$

The optimal cutting conditions were identified from the experimental results by applying the ANOVA. The surface integrity of the machined piston was evaluated through bond checking and surface roughness measurements. A mathematical model was then developed to estimate the mean cutting force. The results obtained through the Taguchi method were compared with those obtained using the nontraditional Genetic Algorithm (GA) method.

5. Results and Discussion

5.1 Cutting force

The machining tests were conducted as per the orthogonal array. The forces were observed and the mean forces were calculated. The experimental results are listed in Table 3.

Table 3 Experimental results

Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Mean cutting force at bonding region (N)
452	0.15	0.15	42
452	0.20	0.20	55
452	0.25	0.25	82
482	0.15	0.20	60
482	0.20	0.25	85
482	0.25	0.15	58
512	0.15	0.25	53
512	0.20	0.15	39
512	0.25	0.20	76

The cutting forces present during machining were measured using a dynamometer. A typical graphical representation of the cutting force (Fz) while machining the bimetallic piston is shown in Figure 3. The observed cutting force while machining the aluminum alloy portion of the bimetallic piston was low, around 30 N. The cutting force increased to around 55 N when the tool started to machine the harder CI material. The subsequent reduction in the cutting force profile was due to a groove in the CI.

To find the optimal cutting conditions, the selected quality characteristic (cutting force at bonding zone) should be of lower order; hence, the S/N for the "lower the better" type of response was used:

$$\text{S/N ratio (in dB)} = -10\log\left[\frac{1}{n}\sum\left(y_1^2 + y_2^2 + \ldots\ldots\ldots y_n^2\right)\right], \tag{2}$$

where y is the response of the quality characteristic for the trial condition and n is the number of trials. The S/N was computed for all trials; the results are listed in Table 4.

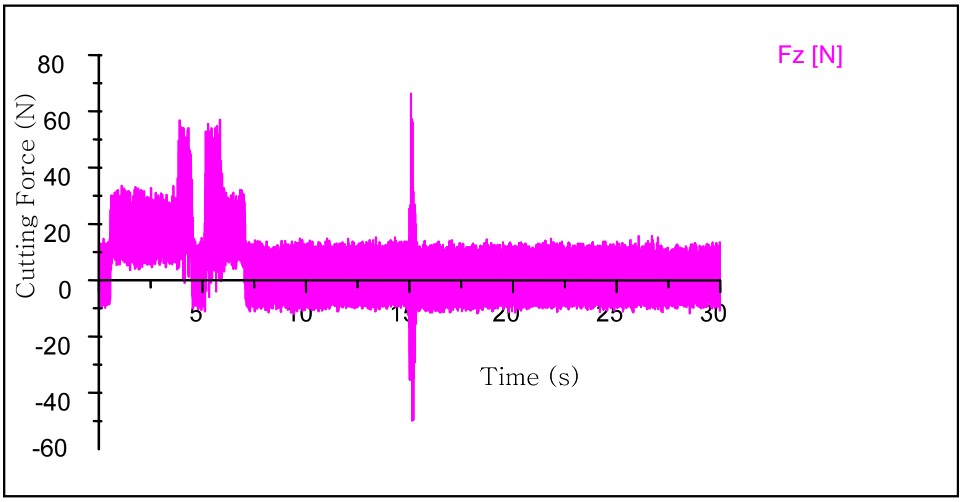


Fig. 3 Typical cutting force variation

Table 4 Computing the cutting force variation

Factors		Speed (m/min)	Feed (mm/rev)	Depth of cut (mm)	Error	Total
Sum at factors levels	1	14.82	15.73	16.82	13.78	43.82
	2	13.43	14.93	13.91	15.14	
	3	15.57	12.94	12.88	14.68	
Sum of the square of the difference(s)		7.07	12.38	25.05	2.87	47.37
Contribution ratio (%)		14.93	26.13	52.88	6.06	100

Table 5 Variation of cutting force

Source of variations	Sum of the squares	Degrees of freedom	Mean sum of the squares	Variance
Speed	7.07^	2	3.54	2.46
Feed	12.38**	2	6.19	4.30
Depth of cut	25.05*	2	12.53	8.70
Error	2.87	2	1.44	
Total		8		

If the variance value is greater than 2, it is considered a significant term.
* indicates very high significance.
** indicates significance.
^ indicates the least significance.

Table 6 Cutting force contribution

Factor	Depth of cut	Feed	Speed	Error
Contribution rate (%)	52.88	26.13	14.93	6.06
Cumulative contribution rate (%)	52.88	79.01	93.94	100

The data analysis procedure using the Taguchi experimental framework involves an analysis of means and variances. The analysis of means helps to identify the factor contributions whereas the ANOVAs establish the relative significance of the factors in terms of their percentage contribution to the response.

5.2 ANOVA scheme for an orthogonal array experiment

The ANOVA scheme was used to study the significance of the parameters affecting the quality characteristics of interest. The scheme subdivides the total variation in the data into useful and meaningful components of variation. The total variation contribution is shown in Table 5.

The ANOVA results in Table 6 clearly identify that the depth of cut and feed severely affected the cutting force by 52.88% and 26.13%, respectively, while the speed only affected the cutting force by 14.93%. A Pareto chart generated based on the contribution ratio is presented in Figure 4. This chart shows the importance of the significant parameters.

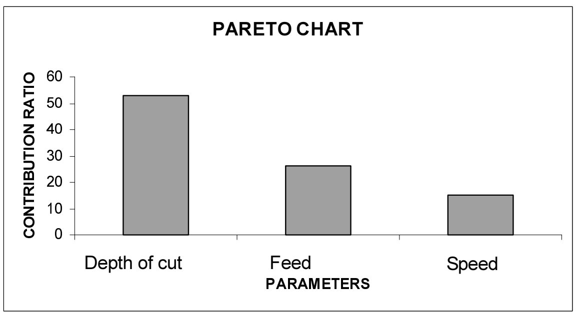


Fig. 4 Pareto chart

The mean responses refer to the average value of the performance characteristics for each parameter at different levels. The average values of the cutting force for each parameter at levels 1, 2 and 3 were calculated and plotted in Figure 5. The effect of the factor level was defined as the deviation it caused from the overall mean expressed in decibels. This process of estimating the main effects of each factor is known as an analysis of the mean. The minimum cutting force occurred at the 3rd speed level, 1st feed level, and 1st depth of cut level, giving [3 1 1] as the best level to obtain the minimum cutting force for the piston.

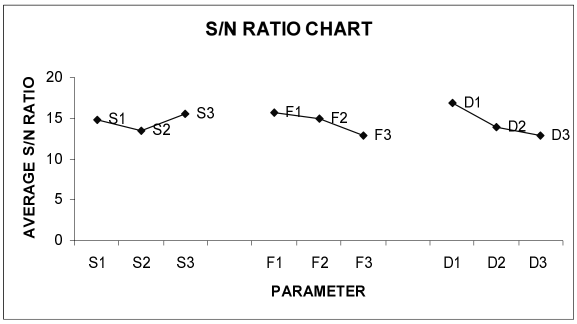


Fig. 5 Effects of the factor level on the cutting force

Conducting a verification experiment is a crucial and the last step of the robust design procedure. Its aim is to verify the optimum conditions identified by the matrix tests and it estimates how close the predictions are to actual conditions. Hence, a confirmation test was conducted with the optimum parameters, with good results.

5.3 Mathematical model

The design optimization method makes extensive use of functional or empirically developed mathematical models that explicitly link a quantitative dependent variable to certain independent variables.[20] The time-tested approach to building such models from observed quantitative data is a regression analysis. In the present study, empirical models were developed to approximate the cutting force using the Systat 12.0 software package based on a regression analysis of the experimental results. The cutting forces predicted using the developed model compared are compared to experimental values in Figure 6. Little variation was observed between the modeled and experimental values, confirming the applicability of the mathematical model.

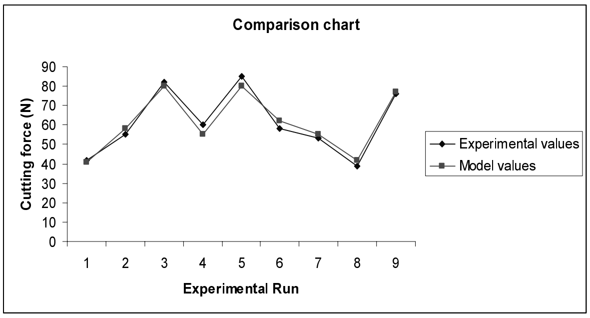


Fig. 6 Comparison between model and experimental results

5.4 Genetic algorithm

The GA is a search strategy that is able to search a large solution space efficiently by providing a concise computational cost because it uses probabilistic transaction rules instead of deterministic ones.[21] It is easy to implement and is increasingly being used to solve inherently intractable problems quickly. A GA is a computerized search and optimization algorithm based on the mechanics of neural genetics and natural selection.[22] The quality is the fitness function, which evaluates a chromosome[23] with respect to the objective function of the optimization problem. Using genetic operators (crossover and mutation), the algorithm creates a subsequent generation from a string of the current population. The generation cycle is repeated until a desired termination criterion is reached. A simple genetic algorithm that yields good results for many practical problems has three main operations:

- reproduction,
- crossover, and
- mutation.

Reproduction is a process in which individual strings are copied according to their objective function values. Crossover is the process of exchanging of information between or among the mating string. In most crossover operators, two strings are picked from the mating pool at random, and some portions of the strings are exchanged between the strings. Mutation is the occasional random alteration of the values in a string, and serves to create a point in the neighborhood of the current point, thereby achieving a local search and the current solution. The GA can be used for general optimization problems. A typical flowchart for a GA is presented in Figure 7.

The mathematical model created using the Systat 12.0 software package to relate the cutting force and process parameters was encoded for the Matlab software package in M-file format. Then the GA Toolbox was used to input the fitness function, given as *@filename.* The number of variables was 3, and other GA functionalities were chosen accordingly to obtain the best fitness value in a random process. The best fitness value obtained from the GA is compared with Taguchi's optimum parameters in Table 7.

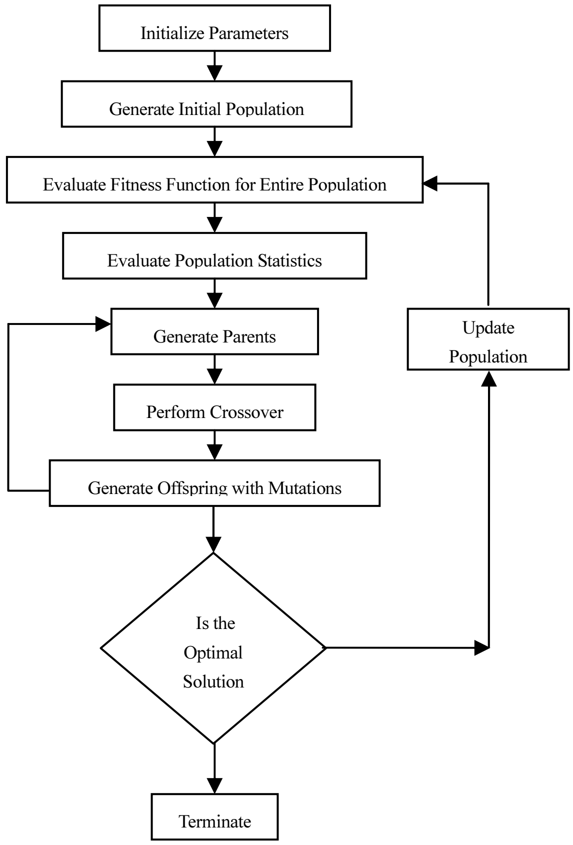


Fig. 7 GA flowchart

Table 7 Comparison between Taguchi results and GA output

Optimum parameters	Taguchi method	GA output
Speed (m/min)	512	506
Feed (mm/rev)	0.15	0.1517
Depth of cut (mm)	0.15	0.15329

6. Surface Integrity

6.1 Bond checking

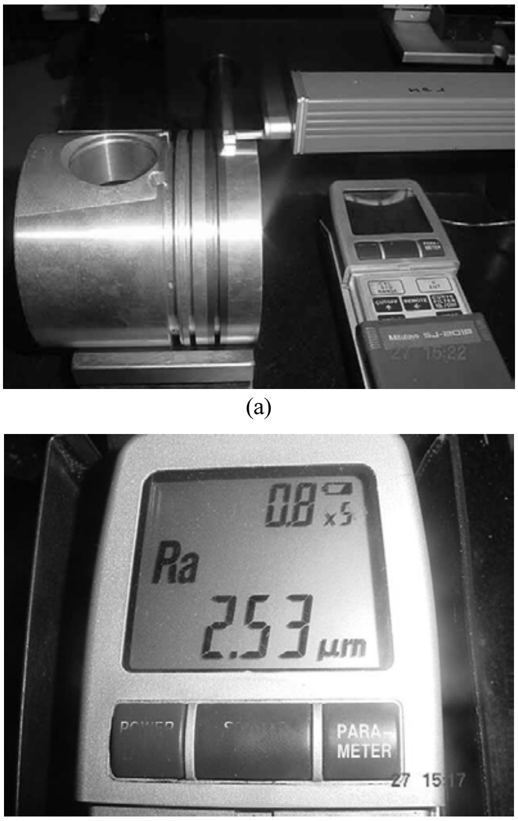
The integrity of all the machined surfaces of the pistons at the bond zone between the aluminum and CI was checked using an ultrasonic bond-checking machine (EPST II). The pistons were placed in such a way that the two probes were touching the top and bottom portions of the bonding region. The piston was rotated and the probe sensed if a debonding zone was present on the circumference of the Al–CI interface. Observations were made from the display graph and from the instantaneous signal from the controller. The bond-checking facility is shown in Figure 8.

Fig. 8 Ultrasonic bond-checking facility

6.2 Surface roughness

The surface quality of a machined component is one of the most specified customer requirements. A major indication of the surface quality on a machined part is the surface roughness, which is mainly a result of the process parameters such as the tool geometry and cutting conditions. A typical surface roughness measuring facility, the Mitutoyo CV2000, is shown in Figure 9(a), and typical results given by the display screen are presented in Figure 9(b). The piston was placed over the surface plate and the probe was moved on the machined surface at predetermined intervals (30 mm) to obtain the average surface roughness. These measurements were performed on all the machined surfaces.

The average surface roughness (*Ra*) value of all the machined pistons is shown in Figure 10. Normally, the maximum allowable surface roughness for a piston is 4 μm. All the tested pistons had satisfactory roughness values, and the empirical trials indicated that a lower surface roughness resulted when the feed rate was low.



(a)

(b)

Fig. 9 (a) Surface roughness measurement facility and (b) typical displayed results

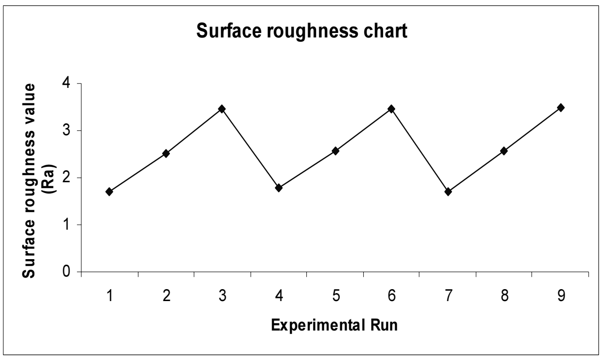


Fig. 10 Surface roughness measurements

7. Summary and Conclusions

The following summary and conclusions can be drawn from our experiment.

1. A CBN tool was used to machine bimetallic pistons.
2. The optimal cutting conditions for bimetallic pistons were obtained using the Taguchi method.
3. An ANOVA analysis indicated that the depth of cut and feed rate were the most important parameters that affected the cutting force.
4. The developed mathematical model accurately predicted the cutting force at the bonding zone.
5. The optimal results obtained using the Taguchi method were comparable with the results obtained using a GA.
6. The surface integrity of the machined pistons was evaluated using surface roughness and bond-checking tests. The machined pistons exhibited good surface integrity for the chosen level of parameters.

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