International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 10 Issue: 08 | Aug 2023 www.irjet.net p-ISSN: 2395-0072

Multi Response surface optimization and desirability Function Approach for grinding material removal rate in Alloy Steel

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Abstract - *The provided information includes essential grinding parameters alongside real-world grinding outcomes, material removal principles, and feasible strategies for performance improvement. The analysis of the presented Material Removal Rate (MRR) figures confirms previous conclusions, revealing that the most significant influence on MRR values is the depth of cut at 92.06%, followed by cutting speed at 4.65%, and feed rate at 0.94%, which has a relatively minor impact. The ideal combination of input control parameters is A2B3C1. Calculating the grey relational grade using equation (7) yields a value of 0.4413. The results of the confirmation experiment for the response parameters are displayed in Table 5.9. Notably, Grey Relational Analysis (GRA) substantially enhances the experimental values of cutting speed (VC) in rpm, depth of cut in mm, and feed rate in mm/rev. The optimum material removal rate is 2.816 Gm./Min, achieved at (a) Cutting Speed in rpm (VC) A2 1900 rpm, (b) B3 0.06 mm cut depth, and (c) C1 0.04 mm/rev feed rate. The mixed desirability, represented by C1 D, is 0.93650. It's important to note that increasing the grinding contact width results in proportional increases in grinding forces and power. , Grey Relational Analysis (GRA)*

Key Words *Material Removal Rate (MRR), cutting speed (VC) in rpm, depth of cut in mm, and feed rate in mm/rev,*

1. INTRODUCTION

Grinding is a machining process used to achieve precise and smooth surface finishes or to remove material from a workpiece to create the desired shape and dimension. It involves using abrasive particles to gradually wear away the material through friction and cutting action. Grinding is commonly used in various industries, such as manufacturing, automotive, aerospace, and electronics, to produce components with high precision and accuracy.

Here's how grinding works:

1. **Abrasive Material**: Abrasive materials, such as grinding wheels, belts, or stones, are used in the grinding process. These abrasives are made up of hard and tough particles that are capable of cutting and removing material.

2. **Workpiece and Grinding Wheel Interaction**: The workpiece is the object being ground, and it is held securely in place on a grinding machine. The grinding wheel or abrasive material is rotated at high speed, creating a cutting or shearing action when it comes into contact with the workpiece.

3. **Contact and Friction**: As the rotating abrasive contacts the workpiece, it creates friction and generates heat. The abrasive particles continuously remove small chips of material from the work piece's surface.

4. **Material Removal**: The combination of cutting action and abrasive wear results in material being removed from the workpiece. The grinding process gradually shapes the workpiece to the desired dimensions or provides the desired surface finish.

5. **Coolant or Lubrication**: To control the heat generated during grinding and prevent damage to the workpiece or grinding wheel, a coolant or lubricating fluid is often used. This fluid also helps to wash away the removed material and keep the grinding surface clean.

6. **Precision and Finish**: Grinding is capable of achieving extremely tight tolerances and smooth surface finishes that may not be achievable through other machining methods. This makes it suitable for applications where precision and aesthetics are crucial.

7. **Types of Grinding**: There are various types of grinding processes, each designed for specific applications. Some common types include surface grinding, cylindrical grinding, centerless grinding, and internal grinding. Each type uses specialized grinding machines and techniques to achieve the desired results.

Overall, grinding is a versatile and essential process used to produce parts with high accuracy, achieve smooth surfaces, remove material from tough materials, and refine the shapes of workpiece to meet specific requirements.

1.2 Basic Surface and Cylindrical Grinding Processes

Surface Grinding Process:

Surface grinding is a widely used abrasive machining process that involves grinding a flat or contoured surface of a workpiece using a rotating grinding wheel. The primary goal of surface grinding is to achieve a smooth and flat surface finish on the workpiece. Here's an overview of the basic steps involved in the surface grinding process:

1. Preparation: The workpiece is securely mounted on the grinding machine's worktable. The grinding wheel is chosen based on the material being worked on and the desired finish. The wheel is then dressed to ensure its proper shape and abrasive grain exposure.

2. Grinding Operation: The grinding wheel rotates at high speed, and the worktable holding the workpiece moves back and forth beneath the rotating wheel. As the wheel contacts the workpiece surface, abrasive particles on its surface cut into and remove small layers of material, creating a flat and smooth finish.

3. Coolant Application: Coolant or lubricating fluid is typically applied during the grinding process to control heat buildup, wash away debris, and improve surface quality.

4. Finishing Passes: Depending on the desired surface finish and material removal requirements, multiple passes may be made over the workpiece. Each pass removes a thin layer of material until the desired specifications are met.

5. Inspection and Quality Check: After grinding, the workpiece is inspected for dimensional accuracy, surface finish, and other quality parameters to ensure it meets the required specifications.

Cylindrical Grinding Process:

Cylindrical grinding is another common abrasive machining process used to create cylindrical or tapered surfaces on a workpiece. It is often used to produce precise cylindrical parts, such as shafts, tubes, and rods. Here's an overview of the basic steps involved in the cylindrical grinding process:

1. Workpiece Setup: The cylindrical workpiece is mounted between centers on a cylindrical grinding machine. The workpiece may be rotated by the machine or driven by a separate motor.

2. Grinding Wheel Selection: A cylindrical grinding wheel is selected based on the workpiece material, size, and desired finish. The wheel is dressed to the required shape and abrasive grain exposure.

3. Grinding Operation: The grinding wheel rotates and moves axially along the length of the workpiece. As the wheel makes contact with the work piece's cylindrical surface, it removes material to achieve the desired diameter and finish.

4. Coolant and Lubrication: Coolant is applied to control heat and wash away debris generated during grinding, ensuring a smoother operation and better surface finish.

5. Final Dimensions and Surface Finish: The cylindrical grinding process is performed in multiple passes, gradually reducing the diameter of the workpiece to the specified dimensions. The final pass achieves the desired surface finish.

6. Measurement and Inspection: After grinding, the work piece's diameter and surface finish are measured and inspected to ensure they meet the required tolerances and quality standards.

Both surface grinding and cylindrical grinding are fundamental processes in the field of precision machining, allowing manufacturers to produce components with accurate dimensions, smooth surfaces, and tight tolerances. These processes are crucial in various industries, including automotive, aerospace, tool making, and more.

2. LI TRATURE REVIEW

Year	Author's Name	Material	Tool	Parameters	Quality Parameters	Most Significant
2010	KomsonJirapatarasilp, sittichaikaewkuekoolPeeranuklahan	AISI4140 Hardened 5+-3HR	38A-60K V35	Work Speed Feed rate depth of cut	Surface roughness Roundness	Depth of cut
2011	Kirankumar R.jagtap, S.B.Ubale Dr. M.S.Kadam	Hardened AISI1040	Al2O3	Depth of cut work speed number of passes wheel speed	Surface roughness MMR	Work Speed number of passes
2011	KirankumarR.jagtap, S.B.UbaleDr.M.S.Kadam	Hardened AISI5120 58HR	Al2O4	Depth of cut work speed number of passes wheel speed	Surface roughness MMR	Work Speed number of passes
2012	Kunadan Kumar S.ChattopadhyayaHari Singh	Mildsteel		Depth of cut cutting speed	MMR	Cutting Speed
2013	Lijohn P George, K Varughese job I M Chandran	EN24 EN31 EN353	AA46K5V40	depth of cut material hardness work speed	surface rughness	hardness
2013	Pawan Kumar Anish Kumar Balindar Singh	EN24	Al2O3	wheel speed table speed depth of cut	Surface roughness MMR	
2014	M.Melwin Sridhar M.ManickamV.KalaiyarasanM.AbdulGhani Khan Ttm.Kannan	AISI01	Al2O4	work speed depth of cut number of passes	MMR	number of passes
2014	K Mekala J Chandradas K Chandrasekaran TTM Kannan R Narasingbabu	AISI316 Hardened 55HRC	Al2O3	cutting speed feed rate depth of cut	MMR	Depth of cut
2014	Suresh P Thakor	EN8	Al2O4	work speed cutting fulidsdeepth of cut	surface rughness MMR	
2014	M.GanesanS.KarthikeyanN.Karthikayan	304 stainless steel		cutting speed feed rate depth of cut	surface rughness	Cutting Speed
2015	Sandeep Kumar Onkar Singh Bhatia	EN15AM (0.3 to 0.4)	AA46K5V40	wheel speed table speed depth of cut cutting fluid	MMR	work piece speed
2015	S.M.DeshmukhR.D.ShelkeC.V.Bhusare	OHNS (Hardened)	Al2O3	Spindle speed feed depth cut	surface rughness MMR	feed rate depth of cut
2015	Naresh Kumar HimanshuTripathi Sandeep Gandotra	C40E steel 0.4-0.45	Al2O3	speed feed depth cut	surface rughness	feed
2016	Prashant J Patil HimanshuTripathi Sandeep Gandotra	EN8 0.4-0.46	Al2O4	depth of cut feed depth of cut	G ratio surface rughness	Coolant
2016	Prashant J Patil C.R. Patil	EN8		depth of cut of lubricatnt wheel speed coolant flow rate nanoparticle size	G ratio Surface finish	Coolant
2016	CentinOzayBaikayaVedalSavas	AISI D3 tool steel	AA46K5V40	Depth of cut Wheel speed work piece speed	surface rughness	All

3. METHODOLOGY

3.1 DESIGN OF EXPERIMENT:

Design of Experiments (DOE) is a systematic and structured approach used in research and experimentation to optimize processes, improve products, or investigate the effects of variables on an outcome. It involves carefully planning and conducting experiments to efficiently gather relevant data, analyze it, and draw meaningful conclusions. The primary goal of DOE is to achieve the most information with the fewest experimental runs, thereby saving time, resources, and reducing the potential for error.

Here are the key steps and concepts involved in the design of experiments:

1. **Define Objectives and Factors**: Clearly state the goals of the experiment and identify the factors (independent variables) that may influence the outcome of interest. Factors can be qualitative (categories or levels) or quantitative (continuous values).

2. **Select Response Variables**: Determine the response variable (dependent variable) that you want to measure or observe. This could be a physical measurement, a performance metric, or any other observable outcome.

3. **Choose Experimental Design**: Select an appropriate experimental design based on the nature of the factors and the objectives of the experiment. Common designs include:

    - **Full Factorial Design**: All possible combinations of factor levels are tested.

    - **Fractional Factorial Design**: A subset of factor combinations is tested to reduce the number of experimental runs.

    - **Response Surface Design**: Used to model the relationship between factors and responses to find optimal conditions.

    - **Randomized Complete Block Design**: Used when experimental units can be grouped into blocks, reducing variability.

    - **Taguchi Method**: Focuses on robust parameter design to minimize variability in the presence of noise.

4. **Determine Experimental Runs**: Based on the chosen design, decide how many experimental runs are needed and allocate them across the different factor combinations.

5. **Randomization and Replication**: Randomly assign experimental runs to different factor combinations to account for potential bias and variability. Replicate some runs to assess experimental error and improve reliability.

6. **Conduct Experiments**: Perform the planned experimental runs while carefully controlling the factors and recording the corresponding responses.

7. **Data Analysis**: Analyze the collected data using statistical techniques such as analysis of variance (ANOVA), regression analysis, and graphical methods. Identify significant factors and their interactions.

8. **Draw Conclusions**: Interpret the results to answer the research questions or achieve the objectives of the experiment. Understand how factors influence the response variable and whether there are optimal settings.

9. **Optimization**: If the goal is to optimize a process or system, use the information from the experiment to determine the best factor levels for achieving desired outcomes.

10. **Validation and Verification**: Validate the conclusions by conducting additional experiments or applying the findings in real-world scenarios. Verify that the recommended settings indeed lead to the desired improvements.

DOE is widely used in various fields such as manufacturing, engineering, pharmaceuticals, agriculture, and social sciences to make informed decisions, improve processes, and optimize outcomes. Properly designed experiments help researchers efficiently explore relationships between variables and make reliable conclusions.

4. Result and discussion

Alloy steel EN6 is chosen as the work piece material in the study presented in [1] Table 3.1 L27 orthogonal array and results.

Parameter	Factor	Level1	Level2	Level3
Cutting Speed(V_C) in rpm	A	1700	1900	2200
Depth of cut mm	B	0.02	0.04	0.06
Feed Rate mm/rev	C	0.04	0.06	0.08

Table 3.2 Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	
Cutting Speed	2	0.29614	4.65%	0.29614	0.14807	19.75	0.000	Significant
DOC	2	5.86121	92.06%	5.86121	2.93060	390.81	0.000	Significant
Feed Rate	2	0.05958	0.94%	0.05958	0.02979	3.97	0.035	
Error	20	0.14997	2.36%	0.14997	0.00750			
Lack-of-Fit	2	0.00736	0.12%	0.00736	0.00368	0.46	0.636	
Pure Error	18	0.14261	2.24%	0.14261	0.00792			
Total	26	6.36690	100.00%					

Model Summary: Finally the regression equation is shown give the exact model equation or it will show the relationship between the input and the output variables.

Table 3.3 Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)
0.0865951	97.64%	96.94%	0.273328	95.71%

P-Value: In ANOVA analysis, the p-value assumes a crucial role by indicating the significance of individual variables on the output. Following the American standard of mechanical engineering, a p-value below 0.05 is required to meet the criterion of statistical significance. When a factor's p-value is below 0.05, it signifies a noteworthy impact on the output. In essence, this factor becomes the primary influencer, accounting for variations or distinctions in product quality or response values. Maintaining a p-value below 0.05 is pivotal for achieving enhanced product quality or improved responses.

F Value: The F value stands as a pivotal term in data analysis, particularly when multiple variables exhibit p-values below 0.05, indicating a confidence interval of 95%. This prompts the question of identifying the most influential factor among those with p-values below 0.05 that impact the response. The relationship between the p-value and the F value comes into play here: as the p-value decreases, the F value correspondingly increases. Among all variables with p-values below 0.05, the factor possessing the lowest p-value and the highest F value emerges as the key driver influencing the response.

R-Squared (R-sq): As per research methodology, an R-sq value exceeding 40% signifies a strong prediction agreement between input and output values. The presented table shows an R-sq value of 97.64%, indicative of a robust connection between input and output variables. Thus, a robust and meaningful relationship is evident between the input and output variables.

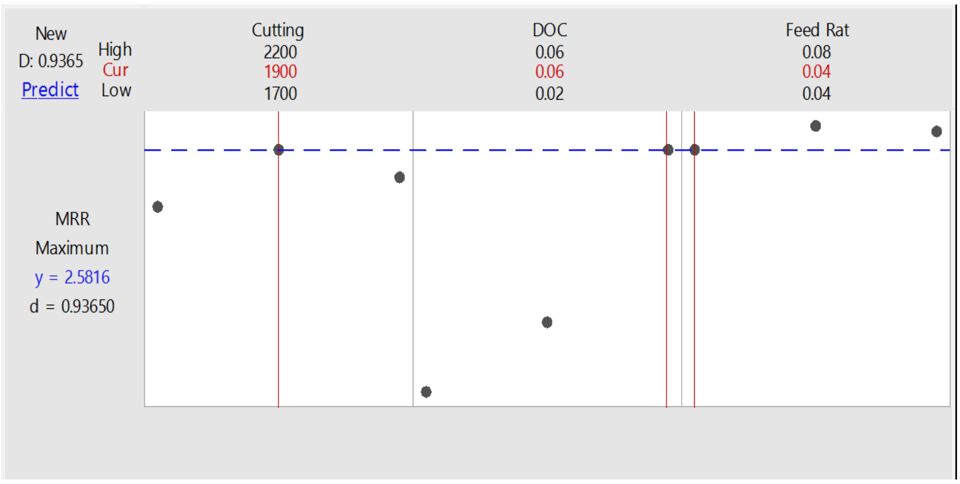
4.1 Response Surface Methodology (RSM):

Is a suite of statistical and mathematical tools that prove invaluable in modeling and enhancing the interplay between a response variable and a set of input factors? It holds particular significance within the industry due to its unparalleled efficacy in aligning with welding requisites. This study delves into the realm of cost-effective product preparation and the enhancement of welding integrity to ensure seamless functionality. This technique is widely employed to curtail expenses while concurrently bolstering product excellence, encapsulating these gains as functions of desired performance. By meticulously orchestrating experiments, this approach meticulously mitigates variance in processes, fostering a streamlined avenue for data comprehension and the anticipation of optimal outcomes.

The subsequent objectives and gauges of RSM in the parameter design phase encapsulate its essence: proficiently sculpting and forecasting the intricate fabric of relationships between factors and responses. This methodology comes into its own when grappling with intricate interactions and curvature that characterize the nexus between factors and responses.

Numerical Optimization: The focal point of this study is to discern the paramount parametric configurations that yield an utmost Material Removal Rate (MRR) within the grinding process while concurrently ensuring optimal grinding efficiency. To accomplish this, desirability analysis is harnessed, guiding the identification of parameter settings that foster the highest MRR achievement in the grinding process. The optimization endeavors within the realm of grinding are carried out through the utilization of the Minitab18 software, meticulously adhering to the procedural guidelines and steps elucidated in comprehensive detail herein.

The outcomes of the multi-objective optimization for Material Removal Rate are elegantly illustrated in Figure 4.1. An optimum Material Removal Rate of 2.816 (Gm./Min) is effectively realized through the strategic adjustment of parameters, namely: (a) Cutting Speed (VC) set at 1900 rpm for A2, (b) Depth of cut at 0.06 mm for B3, and (c) Feed Rate at 0.04 (mm/rev) for C1. The amalgamated desirability factor (D) attains a remarkable value of 0.93650, thereby underlining the substantial success achieved through this optimization endeavor.



4.2 Validation Testing: To establish the reliability of the attained optimization methodologies, validation studies were meticulously executed. The outcomes of these confirmatory tests are succinctly presented in Table 4.1, showcasing results obtained under optimal circumstances. A cursory examination of the table reveals that the percentage disparity between projected and empirical outcomes is exceedingly minute, well within the 1% threshold. This underscores the substantial efficacy of single optimization in significantly enhancing the experimental alloy steel EN9 parameters within cylindrical grinding.

To affirm the robustness of the developed models outlined in Equations (3) and (4), three additional trials were performed, incorporating the Material Removal Rate's optimal values. Notably, the average measurements align to an Optimal Material Removal Rate of 2.816 (Gm./Min), which ensues from meticulous parameter adjustments: (a) Cutting Speed (VC) at 1900 rpm for A2, (b) Depth of cut at 0.06 mm for B3, and (c) Feed Rate at 0.04 (mm/rev) for C1.

An incisive evaluation of model precision was carried out, gauging the percentage error. Remarkably, the error falls below the 10% threshold, substantiating the unequivocal alignment between predicted and experimental values [38]. Lastly, operating within the confines of experimental limitations, a conscientious endeavor was undertaken to pinpoint the optimal cylindrical machining position, thus ensuring the attainment of the most desirable outcomes.

Table 4.1 Multi-objective optimization results

Optimal Control Parameters	Level	Optimal Level	Experimental	Predicted (RSM)	Error (%)
Cutting Speed(V_C) in rpm	A	$A_2\ B_3\ C_1$	2.675	2.5816	1.3
Depth of cut mm	B				
Feed Rate mm/rev	C				

6. CONCLUSION

Summary and Prospects for the Future:

A comprehensive series of experiments were meticulously conducted, exploring a diverse array of tool rotational speeds and welding velocities across three distinct levels using Taguchi's orthogonal array. The joint strength was meticulously evaluated through rigorous hardness testing.

Key observations gleaned from this study are as follows:

1. Taguchi's orthogonal array proved to be an effective tool for pinpointing optimal process parameter configurations.

2. In the context of the larger-the-better quality characteristic, namely Material Removal Rate (MRR), a thorough examination of the main effect plot (Figure 3.1) revealed that the second level of cutting speed (A2), the first level of depth of cut (B1), and the third level of feed rate (C3) collectively yield the highest MRR value.

3. Single optimization analysis through analysis of variance (ANOVA) (as shown in Table 3.3) validates the significance of depth of cut, contributing 92.06%, followed by cutting speed (4.65%), and feed rate (0.94%) in determining MRR values, affirming the earlier conclusions.

4. Adhering to research methodology, an R-squared (R-sq) value exceeding 40% signifies robust alignment between input and output values. The recorded R-sq value of 97.64% underscores a robust interconnection between input and output variables.

5. To further solidify the established relationship between inputs and outputs, the adjusted R-sq (R-sq (adj)) should similarly surpass 40%. In this instance, the R-sq (adj) value stands at 96.94%, further cementing the substantial relationship between inputs and outputs.

6. The pinnacle achievement materialized as an optimal Material Removal Rate of 2.816 Gm./Min. This was attained by harmonizing the following parameters: (a) Cutting Speed (VC) set at 1900 rpm (A2), (b) Depth of cut at 0.06 mm (B3), and (c) Feed Rate at 0.04 mm/rev (C1). The composite desirability factor, D, culminated at 0.93650. The zenith configuration of input control parameters materialized as A2B3C1, culminating in a calculated grey relational grade of 0.4413, as outlined through the equation.

As this research paves the way for enhanced material removal in welding applications, future investigations could delve into broader parameters, expanded levels, and diverse materials, further enriching the realm of optimized manufacturing processes.

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