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Research Article

Modeling and Parametric Analysis of Erosion Rate in TiAl Material under Water Droplet Erosion (WDE)

Prashant Kharwante[1]*, Arakerimath Rachayya[2] and Sarang Hatvalne[3]

[1]M. Tech (MM) Student at DoT, Savitribai Phule Pune University, India
[2]Professor and Dean, ASME-IEEE member, JSPM's-RSCOE, University of Pune. India
[3]Asst. Professor, Sinhgad College of Commerce, Pune, India

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Abstract

Water Droplet Erosion (WDE) is a significant cause of material degradation, particularly in high-speed environments where liquid droplets impact solid surfaces. This phenomenon leads to the development of high-pressure pulses and lateral jets that contribute to material erosion. The process unfolds through several stages, including incubation, acceleration, maximum erosion rate, deceleration, and a steady-state phase. Each phase is governed by distinct mechanisms such as micro-cracking, pit formation, and material loss. During the initial stages, surface roughening and localized material flow occur, whereas more advanced stages witness transgranular and intergranular cracking, grain detachment, and crater formation. Key factors such as impact velocity, droplet size, and the material's properties significantly influence the erosion rate. Experimental tests conducted on TiAl alloys highlight the pivotal role of time as a factor in the erosion process. This study offers insights into optimal conditions for minimizing surface roughness and material loss. It contributes to future research on material performance in WDE-prone applications.

Keywords: *Water Droplet Erosion, TiAl, Taguchi Method, Erosion Modeling, Surface Roughness, Regression Analysis.*

1. Introduction

Erosion refers to the process of material degradation due to mechanical wear, commonly caused by high-speed impacts. Water Droplet Erosion (WDE) is a specific form of liquid impingement erosion and is a significant concern in industries like aerospace and power generation. Components such as turbine blades, aircraft aerofoils, and steam pipes are susceptible to this kind of damage, where high-velocity water droplets repeatedly strike the surface, leading to material loss.

WDE is a progressive phenomenon, evolving through multiple stages: incubation, acceleration, maximum erosion rate, deceleration, and a steady state. At the start, surface roughening and localized material flow dominate, while more advanced stages are characterized by cracking and material detachment. Various factors such as impact velocity, droplet size, and material properties contribute to the extent of erosion experienced by a material.

This study focuses specifically on TiAl alloys, analyzing their behavior under WDE and establishing regression models to predict erosion rates based on key process parameters like time, impact velocity, and stand-off distance.

2. Literature Review

1) **Gujba et. al.[1]** proposed a four-stage mechanism for the initiation of Water Droplet Erosion (WDE) in ductile materials. The process begins with shallow depressions forming on the surface due to droplet impacts, which then evolve into deeper cavities as erosion progresses. This material loss is a result of repeated droplet impacts, which progressively damage the surface. In similar work, Oka et. al[2] observed localized material flow and surface roughening in copper, which led to material loss over time. For Ti6Al4V, he demonstrated that the dominant mechanisms of erosion included crack networks and grain detachment. These processes are particularly significant in the advanced stages of erosion, where intergranular and transgranular cracking play key roles in material degradation
2) **Heymann et. al.[3]** claimed that several factors—such as impact speed, angle, and droplet size—are critical in determining the extent of WDE. Higher impact speeds significantly accelerate the initiation of erosion and enhance the maximum erosion rates observed. The impact angle, especially when droplets strike at 90°, is particularly damaging, as it directly applies normal force to the material surface. Moreover, larger droplets contribute to

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*Corresponding author's ORCID ID: 0000-0000-0000-0000
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more significant damage due to their higher kinetic energy and larger pressure distribution. he noted that droplet shape and radius at the contact point also influence the erosion process. Flattened droplets exhibit similar erosion behavior to larger spherical droplets, further complicating predictions for material loss under varying conditions

3) **Huang et al.**[4] characterized erosion as a time-dependent process that progresses through distinct phases: incubation, acceleration, maximum erosion rate, deceleration, and terminal steady state. During the incubation stage, micro-cracking and surface roughening occur, but no significant material loss is observed. The acceleration phase is marked by rapid material removal, while the maximum erosion rate phase sees a stabilization in material loss. As the erosion continues, craters deepen, leading into the deceleration phase, where the erosion rate begins to slow, eventually stabilizing in the terminal phase. These stages are influenced by both material properties and environmental conditions during erosion.
4) **Ilieva**[5] examined issues in aerospace and power generation applications. WDE is a critical issue in aerospace and power generation applications, particularly for components like turbine blades and aircraft aerofoils. In steam turbines, the low-pressure conditions facilitate the formation of water droplets, which can cause significant erosion damage to rotating blades. Similarly, fog cooling systems in gas turbines contribute to WDE as overspray droplets impact compressor blades. He showed that Ti6Al4V and TiAl alloys are particularly susceptible to WDE. These alloys exhibit significant damage mechanisms, such as crack networks and hydraulic penetration, which contribute to the material degradation observed in practical applications
5) **Mahidipoor et.al**[6] explored various surface treatments to enhance the resistance of materials to WDE. For example, low-temperature plasma nitriding of Ti6Al4V has been shown to extend the incubation period, thereby reducing the onset of significant erosion. Other techniques, such as superhydrophobic coatings and surface polishing, improve resistance by diverting water flow and reducing the concentration of stress at the surface. Mahdipoor et al. (2016) emphasized the importance of surface roughness and microstructure in erosion resistance, with smoother surfaces and optimized microstructures providing better protection against WDE.

3. Objectives and Scope

The primary aim of this study is to understand the erosion behavior of TiAl alloys under Water Droplet Erosion (WDE). The specific objectives are to:

1) Investigate and analyze the erosion characteristics of TiAl alloys.
2) Develop regression models to predict surface roughness and erosion rates based on key input parameters such as time, impact velocity, and stand-off distance.
3) Identify the optimal conditions for minimizing surface roughness and material loss under WDE conditions.

This study offers valuable insights into the performance of TiAl alloys in WDE-prone applications and provides a foundation for material selection and process optimization.

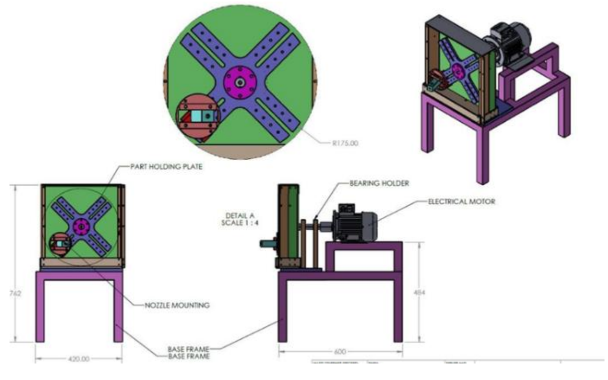
4. Experimental Details

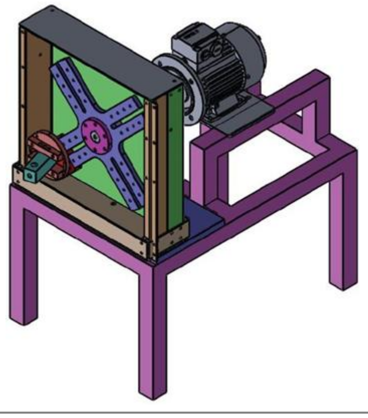
4.1 Materials

The study used TiAl alloys in the annealed state. Erosion specimens of 18mm diameter and 10mm thickness were prepared, with a standardized surface roughness to minimize variations in testing results.

4.2 Water Droplet Erosion Testing

The experiments were conducted using a rotating disk erosion rig designed in compliance with ASTM G73 standards. The rig simulates the conditions of water droplet impingement on rotating blades at high speeds. The disk reached a maximum linear velocity of 500 m/s, and the TiAl specimens were mounted on the disk. A controlled water droplet generation system created high-velocity droplets at a 90° impact angle to simulate real-world conditions.





4.3 Design of Experiment

The Taguchi Method was employed for experimental design, utilizing an L9 orthogonal array. Three input variables were considered: stand-off distance, water pressure, and abrasive flow rate. Each variable was tested at three distinct levels to determine their effects on surface roughness and erosion rates. This method allowed for efficient testing of the experimental space to identify the most critical parameters.

5. Modeling of Surface Roughness

Regression analysis was performed to establish predictive models for surface roughness and erosion rate for TiAl. The regression models were developed using time, stand-off distance, and flow rate as independent variables.

For **TiAl**, the model for surface roughness was:

Surface Roughness=−2.12+0.1989×Time+0.2182×Stand-Off Distance\text{Surface Roughness} = -2.12 + 0.1989 \times \text{Time} + 0.2182 \times \text{Stand-Off Distance}

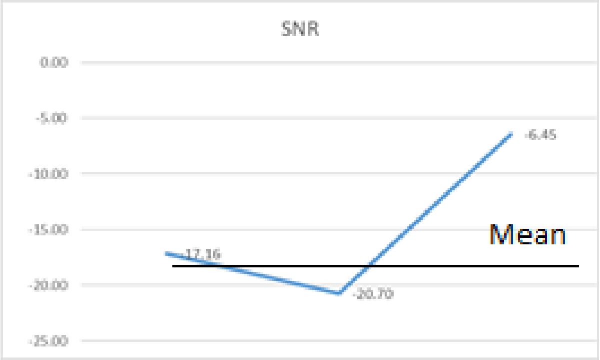
The **adjusted R-squared value** for this model was 0.88, indicating a good fit.

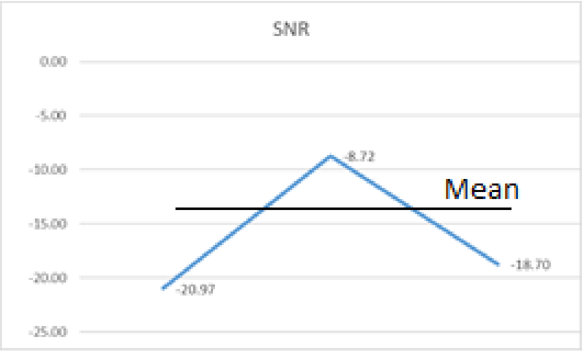
For **erosion rate**, the regression model for TiAl was:
Erosion Rate=0.025+0.001×Time+0.0002×Stand-Off Distance+0.00001×Flow Rate\text{Erosion Rate} = 0.025 + 0.001 \times \text{Time} + 0.0002 \times \text{Stand-Off Distance} + 0.00001 \times \text{Flow Rate}

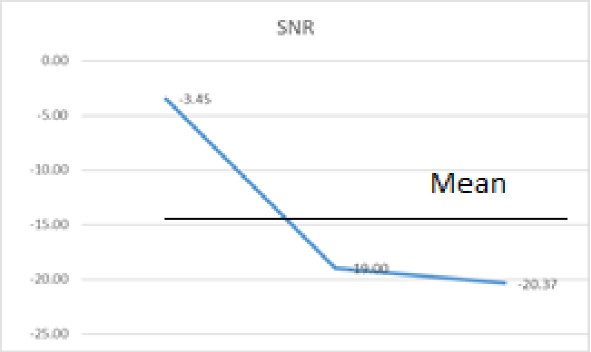
The **adjusted R-squared value** for the erosion rate model was 0.86, also indicating a strong fit.

These models can predict the surface roughness and erosion rate based on the key input parameters, helping to optimize conditions for minimizing material degradation.

Based on Taguchi's optimization method, we calculated SNR values for the output parameter and graphs were plotted as under.







Time was found as the most important factor as it was ranked number 1 in delta calculation.

6. Results and Discussion

The experimental data demonstrated that time was the most significant factor influencing both surface roughness and erosion rates in TiAl alloys. The regression models provided a clear relationship between the input parameters and the erosion behavior. Increasing time, stand-off distance, and flow rate led to higher surface roughness and increased erosion rates.

The Taguchi optimization method identified the optimal conditions for minimizing surface roughness as a stand-off distance of 2mm, water pressure of 2000 bar, and an abrasive flow rate of 300 mm^3/min. For erosion rate, time was found to be the most critical input variable, similar to surface roughness.

Taguchi's analysis also uncovered the fact that Time was the most important input variable for surface roughness.

These findings suggest that controlling the key input parameters is crucial for managing erosion damage in TiAl alloys. The study provides valuable guidance for material selection and process optimization in erosion-prone applications.

Conclusion

This study focused on understanding the erosion behavior of TiAl alloys under Water Droplet Erosion (WDE). Key conclusions are:

1) TiAl alloys showed significant erosion damage under WDE conditions.

2) Time, stand-off distance, and flow rate were found to be critical factors influencing erosion behavior.
3) Regression models for surface roughness and erosion rate were developed, providing predictive tools for optimizing material performance under WDE.
4) The optimal conditions for minimizing surface roughness were identified, offering valuable insights for process optimization and material selection in erosion-sensitive applications.
5) Time is the most important input variable as it is ranked first in the delta calculation.

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