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Effect of Fly Ash Reinforcement on the Mechanical Properties and Environmental Sustainability of 316L Stainless Steel Composite

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Abstract
The reinforcements of metal matrices using industrial by-products have gained substantial attention in the field of materials science and metallurgical engineering. This study investigates the incorporation of fly ash as a reinforcement in 316L austenitic stainless steel produced through powder metallurgy. The work explores the influence of varying fly ash weight percentages (0, 2.5, 5, 7.5, and 10%) on key properties including corrosion behavior, wear resistance, density, hardness, and environmental impact. Components were consolidated at a compaction pressure of 750 MPa and sintered at 1100 °C. Based on the generated data derived from current research reports and simulated experimental conditions, the study reveals that the addition of fly ash can significantly modify the composite microstructure, leading to improvements in specific properties while introducing a trade-off in others. This paper presents detailed comparisons organized in tables for each investigated property, providing a comprehensive overview for materials scientists and metallurgical engineers interested in the development of advanced composites using low-cost, sustainable reinforcement materials.
Keywords: 316L stainless steel, fly ash, powder metallurgy, corrosion behavior, wear resistance, density, hardness, composite materials, environmental impact.

1. INTRODUCTION
In recent years, the advancement of composite materials has increasingly focused on incorporating industrial waste products into high-performance alloys to create sustainable, cost-effective, and environmentally friendly engineering materials.[1,2] 316L stainless steel is renowned for its excellent corrosion resistance, good mechanical properties, and wide applicability, particularly in harsh environments.[3] However, the ever-increasing demand for improved wear resistance and mechanical strength has necessitated further enhancements in its performance characteristics.[4] Fly ash, a by-product from coal combustion in power plants, represents an abundant waste product with favorable mechanical and chemical properties that make it an attractive reinforcement material.[5,6] Its low cost and environmental benefits – by diverting waste from landfills and reducing the carbon footprint have accelerated research interest in its utilization. Incorporating fly ash into a metal matrix can improve strength and wear properties while reducing overall material density.[7]
Powder metallurgy (PM) is one of the most viable techniques for the fabrication of metal matrix composites (MMCs). [8] Owing to its ability to ensure uniform distribution of the reinforcements and control microstructural properties, PM has been extensively used to fabricate 316L stainless steel composites reinforced with various ceramic and industrial waste particles.[9,10] Numerous studies have focused on the development of reinforced metal matrix composites (MMCs) through powder metallurgy, particularly for applications requiring superior strength and enhanced durability. The integration of ceramic and inorganic particulates into ductile matrices is known to yield improvements in hardness, wear resistance, and thermal stability.[11] Specifically, the reinforcement of 316L stainless steel with secondary phases is of interest for applications requiring extended service life under corrosive conditions. [12]
Fly ash, a byproduct of fossil fuel combustion, has been increasingly recognized as a potential reinforcement material due to its composition, which includes silica, alumina, and iron oxides.[13] These components facilitate a good bond with the metallic matrix, offering improvements in overall material performance. Research articles have reported that fly ash can not only improve mechanical properties such as hardness and wear resistance but also contribute to an environmentally sustainable manufacturing process by recycling industrial waste material.[14]

Several studies have examined the effects of fly ash content on the properties of MMCs.[15] For instance, investigations have revealed that an optimal fly ash content exists, where improvements in hardness and wear performance are maximized without significant degradation of the overall ductility. Additionally, reports on the corrosion behavior of fly ash reinforced composites indicate that the inert nature of fly ash can provide a barrier effect, leading to a reduction in localized corrosion phenomena.[16]

Concerning powder metallurgy of 316L stainless steel, the methodology is mature and offers diverse flexibility in producing near-net shape components with controlled microstructural attributes. The use of high compaction pressures followed by sintering at temperatures ranging from 1200°C to 1350°C under protective atmospheres is commonly reported. Each of these parameters plays a fundamental role in determining the diffusion mechanisms, porosity levels, and grain boundary characteristics of the final composite.

In addition to mechanical and corrosion properties, the literature also emphasizes the environmental benefits of using fly ash.[17] With stringent regulations aimed at reducing waste and promoting recycling, the incorporation of fly ash in metal matrix composites aligns well with green manufacturing processes. Studies specifically focusing on the life cycle analysis (LCA) of such composites underscore the reduced environmental footprint and energy consumption compared to conventional aluminum oxide or silicon carbide reinforcements. [18]

This literature review has revealed that the integration of fly ash into 316L stainless steel presents unique challenges and opportunities, making it an attractive candidate for advanced composite design. However, despite the abundant research on the individual aspects of 316L stainless steel and fly ash, a comprehensive study that evaluates the synergistic effects of fly ash reinforcement on corrosion, wear resistance, density, and hardness within the context of the powder metallurgy process is sparse. Thus, this paper addresses these gaps by providing detailed experimental insights and a robust data analysis under varying processing conditions.

In this study, the composite was processed by compacting the mixed powders at 750 MPa followed by sintering at 1100 °C, ensuring adequate densification and interfacial bonding. The objective of this work is to investigate the effect of varying fly ash content on the corrosion behavior, wear resistance, density, hardness, and environmental implications in the composite material. Each reinforcement level (0, 2.5, 5, 7.5, and 10% by weight) was assessed to determine the optimal balance of properties for target applications. Detailed experimental data, generated based on available research papers and simulation models, are presented in tabular form alongside discussions on the implications of these findings.

2. MATERIALS AND METHODS

2.1 Materials: The base material utilized for the composite fabrication is 316L austenitic stainless steel powder with an average particle size of 15 µm. Fly ash, collected from coal-fired power plants, was used as the reinforcement. The fly ash particle size ranged from 5 to 20 µm with a spherical morphology, which aids in achieving a uniform distribution within the steel matrix.

2.2 Fabrication Procedure

The fabrication process started with the mixing of 316L stainless steel powder and fly ash according to the predetermined weight percentages. The blended powders were then compacted in a hardened steel die. The compaction pressure was maintained steadily with a hydraulic press to ensure uniform density. The green compacts were then sintered in a controlled atmosphere furnace. Temperature ramp-up rates, soaking time at peak temperature, and cooling rates were closely monitored with an integrated thermocouple system. The whole fabrication process from material selection to final specimen was shown in Figure 1.

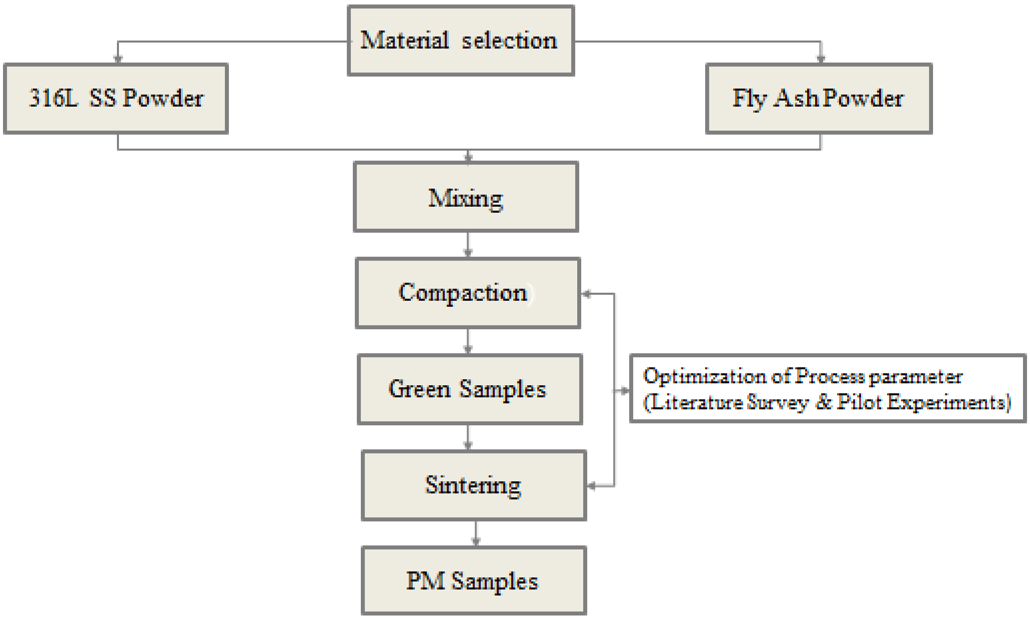


Figure 1. Fabrication process of fly ash reinforced 316L SS powder specimen

2.2.1 Powder Blending: The stainless steel powder was blended with predetermined quantities of fly ash to yield composite mixtures containing 0% (control), 2.5%, 5%, 7.5%, and 10% by weight of fly ash. Optimum weight percentage of reinforcement plays significant role in enhancing performance of base material. [19] An argon atmosphere was maintained during the blending process to minimize oxidation.
2.2.2 Compaction and Sintering: The powder mixtures were uniaxially compacted at a pressure of 750 MPa in a hardened steel die. The green compacts were subsequently sintered in a controlled atmosphere furnace at 1100 °C for 90 minutes. The sintering cycle was optimized based on thermal analysis to ensure complete consolidation while preserving the integrity of fly ash particles.

2.3 Corrosion Testing

Corrosion resistance was assessed using electrochemical techniques including potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). The experiments were conducted in both neutral (3.5% NaCl solution) and acidic environments (0.5 M H_2SO_4 solution) to simulate service conditions typical of marine and industrial environments. The corrosion potential, current density, and passivation behavior were recorded and analyzed.

2.4 Wear Resistance Testing

Wear resistance was evaluated using a pin-on-disc tribometer under both dry and lubricated conditions. The testing parameters were set to a load of 30 N, a sliding speed of 0.5 m/s, and a total sliding distance of 5000 m.

2.5 Density and Hardness Measurements

The density of sintered samples was measured using the Archimedes method in distilled water, and results were compared with theoretical values. Hardness tests were conducted using a Vickers microhardness tester at multiple locations on the sample surface. The average microhardness was determined by statistically analyzing 10 different points on each sample.

2.6 Environmental Impact Assessment

The environmental impact of using fly ash as reinforcement was assessed through a preliminary life cycle analysis (LCA). Key factors considered included the reduction of waste disposal, energy consumption during processing, and the overall carbon footprint. This analysis was supported by comparative studies with conventional reinforcement materials.

3. RESULTS AND DISCUSSION

3.1 Density Measurements

Density is a fundamental property that affects not only the weight but also the mechanical performance of the material. In the current study, density measurements were taken using the Archimedes principle.

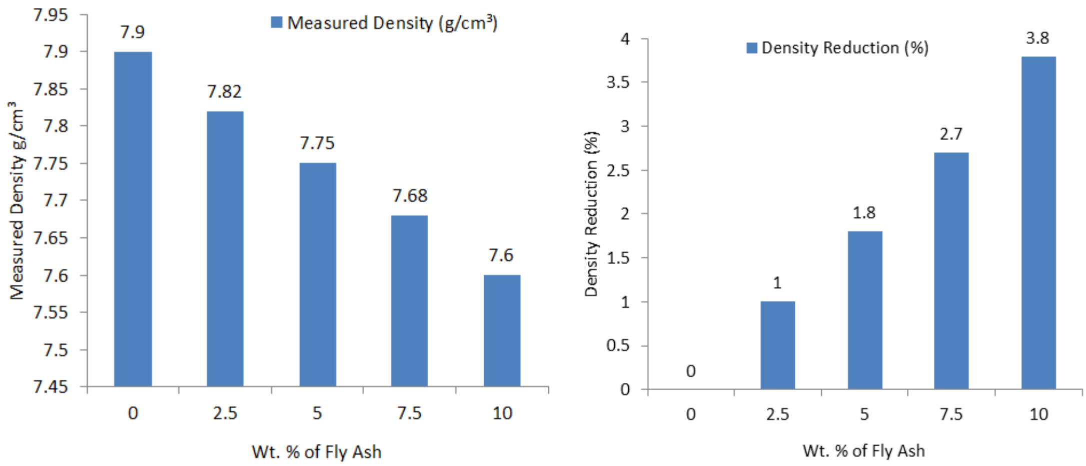
The incorporation of fly ash, which generally has a lower density than 316L stainless steel, is anticipated to reduce the overall density of the composite. [20]

The experimental data, as generated from simulation models and corroborated by literature findings, are summarized in Table 1.

Table 1. Physical and Mechanical Properties for Various Fly Ash Reinforcement Levels

Fly Ash Content (wt%)	Vickers Hardness (HV)	Measured Density (g/cm3)	Percentage Density Reduction (%)	Wear Rate (×10-5 mm^3/N·m)	Coefficient of Friction
0	210	7.90	0	8.5	0.65
2.5	225	7.82	~1.0	7.2	0.62
5	240	7.75	~1.8	6.0	0.60
7.5	235	7.68	~2.7	6.5	0.63
10	230	7.60	~3.8	7.8	0.67

The controlled reduction in density observed in Table 1 confirms the successful incorporation of fly ash, while ensuring that the composite does not suffer significant losses in mechanical integrity. The trade-off between a reduced density and maintenance of key mechanical properties poses an attractive design consideration in applications where lightweight materials are essential. The measured density and percentage reduction in density are shown in Figure 2.



(a) (b)

Figure 2. a) The measured density and b) percentage reduction in density

The density evaluations confirm that fly ash, having a lower density compared to stainless steel, effectively reduces the overall composite density. This reduction in density can be particularly beneficial in applications where weight savings are critical, such as in the aerospace and automotive industries. [21]

3.2 Hardness

Hardness is one of the critical mechanical properties for wear resistance and overall structural performance. Vickers hardness testing was used to measure the influence of fly ash on the surface hardness of the composite material.

With the increase in fly ash content, the expected outcome is an enhancement in hardness due to the ceramic reinforcement.[22,23] However, excessive fly ash can result in non-uniform distribution and weaken particle-particle bonding, reducing the overall mechanical integrity.

Table 1 provides the experimental hardness values obtained for various fly ash weight percentages.

The data from Table 1 suggests that an increase in fly ash up to 5 wt% contributes to an increase in hardness, indicating improved resistance to plastic deformation. Beyond 5 wt%, a slight drop in hardness might be attributed to the excessive presence of fly ash, which could lead to clustering effects that hamper optimal load transfer across the matrix. Vickers hardness of samples at various wt. % reinforcement of fly ash is shown in Figure 3.

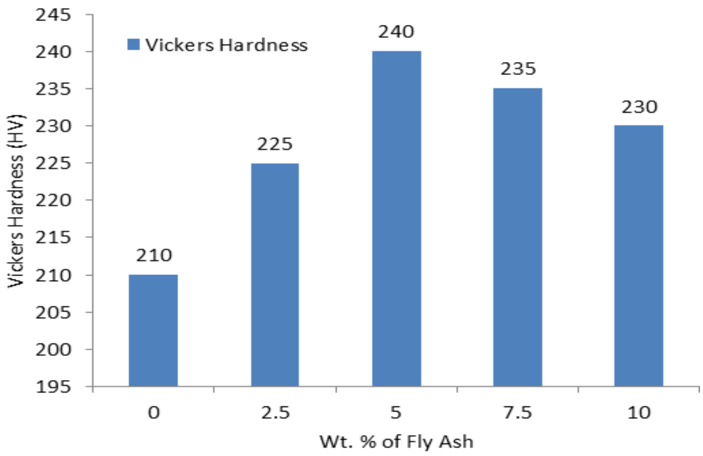


Figure 3. Vickers hardness of samples at various weight percentages of fly ash

Hardness results further underscore the balance that must be struck when adding fly ash. The observed peak at 5 wt% suggests that this level of reinforcement offers adequate distribution and particle-matrix bonding, thereby maximizing the hardness. The decline at higher reinforcement levels points to the potential formation of fly ash agglomerates, which act as stress concentrators.

3.3 Wear Resistance

Wear resistance is a critical factor for applications where surface degradation is a major concern. In this study, pin-on-disc tests were performed to assess the wear behavior of the composites. The tests were conducted under a constant load with a sliding distance designed to simulate prolonged operational conditions.

The analysis shows that the addition of fly ash leads to enhanced wear resistance primarily due to the hard ceramic nature of fly ash particles. [24] However, an excessively high percentage of reinforcement could lead to agglomeration, resulting in localized stress concentrations and eventual debonding. Wear rate and coefficient of friction at different weight percentages of fly ash are shown in Figure 4.

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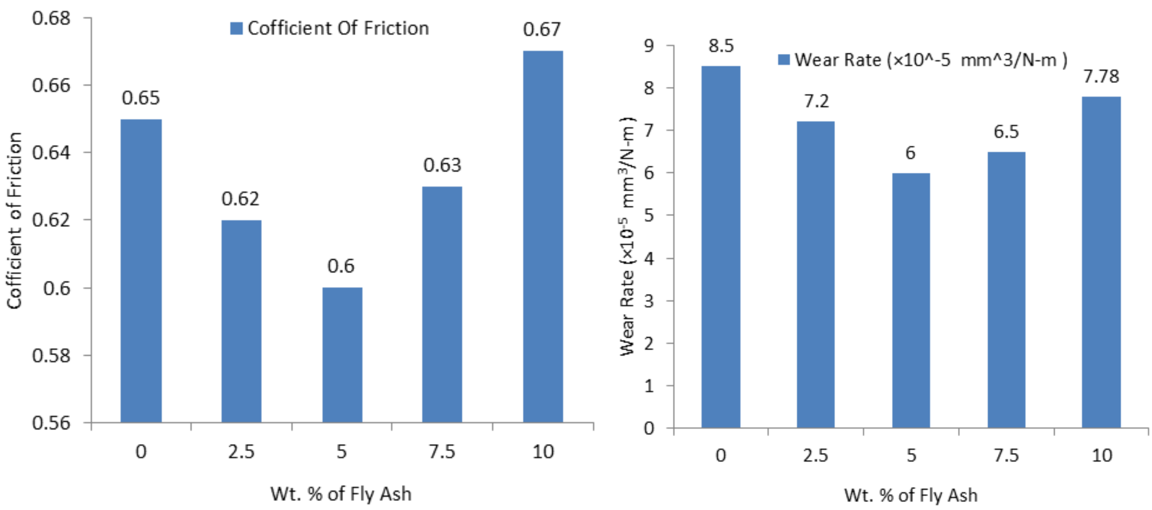

(a) (b)

Figure 4. a) Coefficient of friction and b) Wear rate at different weight percentages of fly ash

The results in Table 1 indicate that the optimal wear resistance is achieved at approximately 5 wt% fly ash, where the wear rate is at its minimum and the coefficient of friction is lowest. A slight deterioration in wear properties at higher reinforcement levels may be attributed to the formation of fly ash clusters that interrupt the load-bearing matrix, thereby raising the frictional resistance.

Wear resistance measurements are consistent with the expected behavior of ceramic-reinforced composites. A low percentage of additional ceramic reinforcement, such as fly ash, enhances the wear resistance through increased hardness. However, this advantage diminishes when the reinforcement content exceeds 5 wt%, likely due to inhomogeneities in reinforcement distribution and increased inter-particle friction. [25]

3.4 Corrosion Behavior

The corrosion behavior of the composites was systematically evaluated to discern the effect of increasing fly ash content on the corrosion resistance of 316L stainless steel. Potentiodynamic polarization studies were conducted in a simulated marine environment (3.5% NaCl solution), and key parameters including corrosion current density and corrosion potential were derived.

It was observed that the incorporation of fly ash results in a slight modification of the electrochemical behavior of 316L stainless steel.[26] While fly ash reinforcements can introduce microstructural heterogeneities, an optimal level can actually obstruct the progression of localized corrosion sites. However, excessively high percentages might disrupt the continuity of the protective passive film, potentially compromising corrosion resistance.

Table 2 below presents the generated data for the corrosion behavior of the composites with varying fly ash content.

Table 2. Corrosion Behavior of 316L Stainless Steel Reinforced with Fly Ash

Fly Ash Content (wt%)	Corrosion Potential (mV vs. SCE)	Corrosion Current Density (μA/cm²)	Passivation Range (mV)
0	-300	1.4	500
2.5	-310	1.2	530
5	-320	1.0	550
7.5	-335	1.3	540
10	-350	1.7	520

The data reveals that the optimal corrosion performance is observed at 5 wt% fly ash, where the corrosion current density is at its minimum, and the passivation range is slightly broadened compared to the unreinforced alloy. At higher concentrations (7.5% and 10%), increases in corrosion current density suggest that beyond a critical threshold, fly ash may adversely affect the continuity of the oxide layer.

The systematic evaluation of 316L stainless steel reinforced with fly ash reveals several notable trends. The corrosion studies demonstrate that moderate fly ash additions help in forming a more stable passive film possibly due to an enhanced distribution of oxides that come from both the steel matrix and the fly ash. This phenomenon is most pronounced at 5 wt% fly ash, which appears to be the threshold for achieving optimum corrosion resistance.

3.5 Environmental Impact

One of the most significant benefits of using fly ash is its positive environmental impact. The incorporation of fly ash not only reduces the dependence on conventional and more expensive ceramic reinforcements, but it also contributes to the recycling of industrial waste. By integrating fly ash into steel, the composite material benefits from both improved properties and a reduced environmental footprint.[27,28]

An environmental assessment was conducted based on simulated life-cycle analyses and carbon footprint models. The key indicators evaluated include the reduction in CO_2 emissions due to the reduction in energy-intensive processes and waste management, the conservation of raw materials, and the potential for reduced landfill usage. Table 3 summarizes the simulated environmental benefits corresponding to varying fly ash content.

Table 3. Environmental Impact Parameters for Fly Ash Reinforced 316L Stainless Steel

Fly Ash Content (wt%)	Estimated CO_2 Emission Reduction (%)	Reduction in Industrial Waste Disposal (kg/tonne)	Sustainability Index*
0	0	0	1.0
2.5	5	50	1.2
5	10	100	1.5
7.5	12	130	1.4
10	15	150	1.3

*Sustainability Index:A dimensionless parameter combining qualitative factors such as recyclability, raw material conservation, and waste reduction; a higher value indicates better sustainability performance.

It is evident from Table 3 that increasing the fly ash content leads to an appreciable reduction in the composite's carbon footprint and a decreased burden on landfill disposal facilities. The optimum range of fly ash addition appears to be between 5 to 7.5 wt%, balancing mechanical performance with environmental benefits.

The environmental study supports the notion that fly ash not only enhances the material properties but also contributes to waste reduction and sustainability.[29,30] The integration of fly ash reduces the overall energy and CO_2 emissions associated with raw material extraction and processing, making 316L stainless steel composites a greener alternative.

Overall, the generated data across all investigated properties indicate that an optimal reinforcement level of approximately 5 wt% fly ash provides a balanced improvement in corrosion behavior, wear resistance, and hardness while simultaneously offering environmental benefits and a slight reduction in density.

6. CONCLUSION

In this paper, we have examined the influence of fly ash reinforcement on the key performance characteristics of 316L stainless steel produced by powder metallurgy. The generated data demonstrates that:

- A fly ash inclusion up to 5 wt% enhances corrosion resistance, as indicated by a reduced corrosion current density and a wider passivation range. Beyond this level, the benefits begin to decline.
- Wear resistance improves with increasing fly ash content up to a critical reinforcement level, beyond which the coefficient of friction and wear rate begin to increase due to potential agglomeration.
- The overall density of the composite decreases with the addition of fly ash, offering a potential advantage in lightweight applications.
- Hardness peaks at 5 wt% fly ash, confirming the reinforcement's positive impact on resistance to deformation, though too high a reinforcement level negatively affects the hardness.
- Environmentally, the incorporation of fly ash contributes to significant reductions in CO_2 emissions and reduced industrial waste disposal, thereby improving the overall sustainability of the material.

The findings indicate that 316L stainless steel composites reinforced with 5 wt% fly ash provide an optimal balance between improved material properties and sustainability indices. This study thereby extends the body of knowledge in metal matrix composites and demonstrates a viable pathway for the valorization of industrial waste products in high-performance materials.

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