ISSN: 2710-0588

Effect of Filling Ratio on Mechanical, Density and Surface Wetting Properties of Si6.5Fe/HDPE Composites

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Abstract

To meet the demands of corrosion resistance, light weight, certain load-bearing capacity and ballast for PE-boat applications, high-density polyethylene (HDPE, Formosa 9001, extrusion grade) was used as the continuous phase and Si6.5Fe Fe-Si alloy powder as the functional filler. Under a fixed baseline hot-pressing process (200 °C, holding pressure for 15 min, 10–15 MPa, staged venting), five composites with powder-to-HDPE mass ratios of 2:8, 3:7, 4:6, 5:5 and 6:4 were prepared, and their tensile yield and fracture performance, density, water contact angle and Izod notched impact strength were tested. Results show that as the filling ratio increases, the mean yield strength decreases from 23.38 MPa to 18.68 MPa, the actual fracture force from 789.76 N to 694.96 N, density rises monotonically from 1.13 g/cm^3 to 1.95 g/cm^3, the contact angle rises from 67.21° to a peak of 75.57° at 5:5 and then falls back to 74.54°, and the Izod notched impact strength decreases from 10.98 kJ/m^2 to 7.20 kJ/m^2. All five ratios exceed the 17 MPa yield-strength threshold, and the measured density agrees closely with the rule-of-mixtures value, indicating good compactness. The study provides an experimental basis for selecting the optimal filling ratio and for subsequent hot-pressing process optimization.

Keywords

Si6.5Fe Fe-Si alloy powder; HDPE; filling ratio; yield strength; density; contact angle; Izod notched impact.

1. Introduction

Structural materials for ships and marine engineering are required to resist seawater corrosion, be light and easy to form, and possess sufficient strength, rigidity and toughness at load-bearing positions. Traditional wooden fishing boats are prone to rot and mildew, costly to maintain and short-lived; fiber-reinforced resin (FRP) boats are light and strong but difficult to recycle after disposal, creating environmental pressure. High-density polyethylene (HDPE), owing to its good chemical stability, resistance to acids, alkalis and seawater, low density, ease of extrusion molding, low cost and recyclability, has been applied to marine interiors, small craft and fixtures.

Pure HDPE, however, still has three shortcomings as a load-bearing marine material: first, its rigidity and yield capacity are limited and can hardly meet the load-bearing demands of equipment bases and backing blocks; second, its low density (about 0.95 g/cm^3) offers no advantage where a certain ballast or anti-floating weight is needed; third, as an insulating non-magnetic material it has no electromagnetic shielding capability. Therefore, on the basis of retaining the corrosion resistance and formability of HDPE, filling functional particles to simultaneously improve load-bearing capacity, density and electromagnetic shielding performance is of clear engineering significance.

Particle-filled modification is a common low-cost route to upgrading thermoplastics. When hard functional particles are dispersed in HDPE, under external loading the load is transferred

ISSN: 2710-0588

from the continuous matrix to the particles, which constrain matrix deformation and hinder crack propagation, thereby raising yield and flexural capacity within an acceptable toughness range; meanwhile, high-density particles markedly increase composite density and serve as ballast; magnetic particles produce absorption attenuation through permeability and magnetic loss, and together with multiple internal reflections at interfaces contribute to shielding effectiveness. Filler type, particle size, filling ratio, as well as particle dispersion and interfacial bonding, are the key factors controlling the modification effect. Too low a filling ratio gives insufficient densification and functional contribution, whereas too high a ratio worsens mechanical properties and toughness through agglomeration, interfacial defects and weakening of the continuous phase; a systematic gradient study is therefore needed to locate the reasonable interval where performance turns.

Si6.5Fe Fe-Si alloy powder was selected as the functional filler. Regarding silicon content, 6.5%Si is the preferred high-silicon composition of Fe-Si soft magnetic alloys: at this silicon level the magnetostriction coefficient is near zero, resistivity is relatively high, high-frequency eddy-current loss is low and soft-magnetic performance is excellent; this understanding is drawn from studies of high-silicon electrical steel, including review work at University of Science and Technology Beijing, JFE JNEX soft-magnetic material data, and the early work of Ninomiya. It should be noted that these properties mainly concern bulk high-silicon electrical steel and are used here only as a basis for material selection; the actual shielding performance of the composite shall be determined by measurement according to GB/T 30142. Silicon content is not a variable in this study, which examines only the effect of filling ratio and lays a foundation for later hot-pressing optimization.

On this basis, using HDPE as the continuous phase and Si6.5Fe powder as the functional filler, five mass ratios were scanned under a fixed baseline hot-pressing process; tensile yield and fracture performance, density, water contact angle and Izod notched impact strength were tested, and the influence of filling ratio and its microscopic cause were analyzed, so as to provide an experimental basis for selecting the optimal filling ratio and to prepare for flexural, wear, shielding, SEM and response-surface optimization work.

2. Experimental

2.1. Raw Materials

Two main raw materials were used. The matrix was high-density polyethylene (HDPE, Formosa 9001, extrusion grade), density about 0.95 g/cm^3, which provides good chemical stability, seawater and general acid/alkali resistance, a wide molding window and recyclability, acting as the continuous phase for formability, corrosion resistance and impact toughness. The functional filler was Si6.5Fe Fe-Si alloy powder with about 6.5 wt% Si, particle size about 45 μm (325 mesh), density about 7.20 g/cm^3, providing reinforcement through hard-particle constraint, densification/ballast, and soft-magnetic loss. Main parameters are listed in Table 1.

Table 1. Raw materials

Material	Grade/specification	Main parameters	Role
HDPE	Formosa 9001 (extrusion)	density ≈0.95 g/cm^3	Matrix (continuous phase)
Si6.5Fe Fe-Si powder	Si ≈6.5 wt%	particle ≈45 μm (325 mesh); density ≈7.20 g/cm^3	Functional filler

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2.2. Design of Five Filling Ratios

Keeping the baseline process fixed, five mass ratios of powder to HDPE, namely 2:8, 3:7, 4:6, 5:5 and 6:4, were arranged from low to high filling, corresponding to about 20%, 30%, 40%, 50% and 60% powder mass fraction (Table 2). Sufficient parallel specimens were prepared: six parallels for tensile, density and contact angle tests and five parallels for Izod impact; results are expressed as means, with coefficient of variation (CV = standard deviation/mean ×100%) characterizing dispersion.

Table 2. Five mass-ratio designs (powder:HDPE)

No.	Powder:HDPE (mass)	Powder mass fraction (≈)
1	2:8	20%
2	3:7	30%
3	4:6	40%
4	5:5	50%
5	6:4	60%

2.3. Baseline Process and Fabrication

All five ratios were pressed under the same baseline process for cross-comparison: hot-pressing temperature 200 °C, holding time 15 min, pressure 10–15 MPa, staged venting. The sequence was: weighing → high-speed pre-dispersion → mixing → single-screw extrusion granulation → re-feeding and repeated extrusion/mixing twice → forming the final batch into a block in the mold → hot pressing → demolding.

After accurate weighing, high-speed pre-dispersion reduced particle agglomeration; the mixture was granulated by single-screw extrusion and then re-extruded twice to disperse the powder uniformly in HDPE. The final batch was not re-granulated but formed directly into a block, loaded into the standard mold, held at 200 °C for 15 min under pressure with staged venting to remove gas and reduce porosity, then demolded into standard specimens. All specimens were tested under the same environmental condition to exclude process/environment interference.

2.4. Test Methods and Standards

Tensile yield performance was tested according to GB/T 1040 (Plastics — Determination of tensile properties) on a universal testing machine at the specified rate; yield strength $\sigma s = Fs/A0$, where σs (MPa) is yield strength, Fs (N) yield load and A0 (mm^2) original cross-sectional area; the actual fracture force was also recorded.

Izod notched impact strength was tested according to GB/T 1843-2008 (Plastics — Determination of Izod impact strength); the notched specimen was clamped as a cantilever and broken by a pendulum, with impact energy divided by the section below the notch to characterize toughness. Density was measured by the immersion (water-displacement) method per GB/T 1033.1-2008, converted from masses in air and in the immersion liquid, and compared with the rule-of-mixtures theoretical density; relative density (measured/theoretical) evaluated compactness.

The water contact angle was measured by the sessile-drop method following GB/T 30693-2014; a fixed volume of deionized water was placed on a flat specimen and the solid–liquid–gas tangent angle θ was read to characterize wetting. Flexural properties (GB/T 9341-2008), sliding friction and wear (GB/T 3960-2016), electromagnetic shielding effectiveness (GB/T 30142-2013) and SEM fracture analysis will be completed in a later stage and are not reported as results here.

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3. Results and Analysis

Under the baseline process (200 °C, 15 min holding, 10–15 MPa), tensile yield/fracture, density, water contact angle and Izod notched impact were tested; values are means of parallels, with CV as a reliability measure.

3.1. Tensile Yield and Fracture Performance

Mean yield strength, fracture force and strength retention are in Table 3. As the ratio rises from 2:8 to 6:4, mean yield strength falls slowly from 23.38 MPa to 18.68 MPa, fracture force from 789.76 N to 694.96 N, and strength retention from 90.31% to 73.26%. In the low-filling interval (2:8–4:6) yield strength and fracture force decline gently (23.38 MPa to only 22.10 MPa), indicating that moderate particles hardly affect tensile load-bearing; beyond 5:5 and at 6:4, agglomeration and interfacial defects increase and yield/fracture drop markedly, reaching 18.68 MPa at 6:4.

Table 3. Mean yield strength, fracture force and strength retention

Ratio (powder:HDPE)	Yield strength /MPa	Fracture force /N	Strength retention
2:8	23.38	789.76	90.31%
3:7	22.39	770.26	87.82%
4:6	22.10	761.72	86.68%
5:5	20.86	754.75	81.82%
6:4	18.68	694.96	73.26%

Yield CV of the five ratios is about 2.70%, 3.31%, 2.33%, 4.61% and 5.06%, all small, showing good consistency and reliable data. Against the 17 MPa load-bearing threshold, all five ratios pass. Mechanistically, the HDPE continuous phase carries the main load; well-dispersed moderate particles share load and constrain deformation, whereas excessive filler enlarges specific surface area, makes full interfacial wetting difficult, and turns agglomerates into stress-concentration and crack-initiation sites that weaken load transfer; low and medium filling give better tensile performance.

Notably, 3:7 (22.39 MPa) and 4:6 (22.10 MPa) are very close, so within 30%–40% filling the marginal contribution of more particles to yield has become negative and the decline flattens; this interval can be viewed as the transition from "slow decline" to "rapid decline", while 5:5 and 6:4 fall in step with worsening agglomeration. This rhythm provides direct mechanical evidence for later comprehensive-score screening.

3.2. Density

Mean density, rule-of-mixtures theoretical density and relative density are in Table 4. Density rises monotonically from 1.13 to 1.95 g/cm^3, an inevitable result of replacing low-density HDPE (≈0.95) with high-density Fe-Si powder (≈7.20), consistent with the rule of mixtures. Measured density is close to theoretical; compactness (measured/theoretical) lies between 0.970 and 0.992, near unity, indicating agreement with theory, little residual gas/porosity and good forming quality.

Density is recorded as an objective ballast attribute and is not included in the comprehensive selection score, so that the high-density ratios are not unduly favored merely for monotonic increase. Densification has practical value for ballast and anti-floating, but also raises unit-volume cost and weight, and must be balanced against load-bearing and toughness.

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Table 4. Mean density, theoretical density and compactness

Ratio (powder:HDPE)	Measured /(g·cm^{-3})	Theoretical /(g·cm^{-3})	Compactness (measured/theoretical)
2:8	1.13	1.15	0.983
3:7	1.27	1.28	0.992
4:6	1.43	1.46	0.980
5:5	1.63	1.68	0.970
6:4	1.95	1.98	0.985

3.3. Surface Contact Angle

Mean water contact angle (Table 5) rises from 67.21° at 2:8 to a peak of 75.57° at 5:5 and falls back to 74.54° at 6:4, staying within 67°–76°. In the sessile-drop method θ<90° means water spreads (hydrophilic) and θ>90° means water beads up (hydrophobic). All five ratios are below 90°, i.e. weakly hydrophilic, moderately wettable surfaces, not yet hydrophobic.

Table 5. Mean water contact angle

Ratio (powder:HDPE)	Contact angle /°	Parallel CV
2:8	67.21	5.85%
3:7	72.92	3.19%
4:6	74.56	3.54%
5:5	75.57	2.74%
6:4	74.54	1.88%

HDPE is a non-polar, low-surface-energy material on which water does not spread fully. With increasing powder, exposed hard particles and particle–matrix boundaries create micro-scale roughness; per the Wenzel model the matrix's inherent beading tendency is amplified by roughness, raising the angle to the 5:5 peak. At 6:4 excessive powder worsens dispersion and causes local agglomeration and micro-pores, making surface energy and roughness uneven and lowering the angle slightly: moderate filling weakens wetting most, while over-filling complicates the surface through agglomeration and porosity. Contact-angle CVs are 5.85%, 3.19%, 3.54%, 2.74% and 1.88%, indicating good consistency.

For the sailing hull, long exposed to immersion, spray and wet–dry alternation, a larger angle prevents a continuous water film, reduces actual contact area, and in theory limits wetting adhesion, water retention and biofouling/absorbed weight; 5:5 is the least wettable here. These are room-temperature static values characterizing wetting tendency only, not dynamic drag reduction, anti-fouling or corrosion resistance, which require hydrodynamic and seawater hanging tests. Surface polish, temperature and drop volume affect the angle; identical surface state, deionized water and drop volume were used for cross-comparison.

3.4. Izod Notched Impact Strength

Mean impact strength (Table 6) decreases monotonically from 10.98 kJ/m^2 at 2:8 to 7.20 kJ/m^2 at 6:4, with only a small drop from 9.10 to 8.95 kJ/m^2 between 3:7 and 4:6. Impact strength reflects toughness: more hard particles become stress-concentration points and crack paths, while the continuous matrix is weakened, so toughness declines and high filling becomes more brittle; low filling retains the best toughness.

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Table 6. Mean Izod notched impact strength

Ratio (powder:HDPE)	Impact strength /(kJ·m^{-2})	Parallel CV
2:8	10.98	4.38%
3:7	9.10	3.98%
4:6	8.95	5.03%
5:5	7.65	6.49%
6:4	7.20	6.20%

Impact CVs are 4.38%, 3.98%, 5.03%, 6.49% and 6.20%, generally small and reliable. Impact strength falls while density rises, an inverse relation: high filling trades toughness for high density and ballast, suggesting the ratio must not be maximized blindly but balanced across load-bearing, ballast, wetting and toughness.

3.5. Comprehensive Discussion

Three regularities emerge. First, raising the ratio has a bidirectional effect: density rises monotonically and contact angle peaks at moderate filling, whereas yield, fracture and impact generally decline. Second, low and medium ratios (2:8–4:6), while keeping every yield value above 17 MPa, retain better tensile load-bearing and toughness with appreciable densification and are the more robust interval; at 5:5 and 6:4 tensile and toughness drop faster, and 6:4 falls to 73.26% retention and 7.20 kJ/m^2, with clearly lower value-for-performance. Third, parallel CVs generally lie in 2%–7%, so dispersion is controllable, the two-pass re-extrusion dispersion and baseline hot pressing are stable, and differences mainly arise from filling ratio itself, supporting later single-factor selection and process optimization.

This study completes only a single-factor scan under a fixed baseline process; flexural strength, sliding wear, shielding effectiveness and SEM dispersion/interface analysis are unfinished, and temperature/holding-time effects are unquantified. For marine backing blocks and bases, a part must carry yield load under compression, resist brittle fracture on impact, and gain ballast while improving wetting; selection therefore cannot rely on a single index. The high-density ratios have maximum density but clear losses in retention and toughness and may be unsuitable as load-bearing parts, whereas low filling has ample toughness and tensile margin but limited densification. Future comprehensive scoring should put yield strength, impact strength, compactness and contact angle on a common scale, together with the pending flexural, wear and shielding data, instead of judging by density or one property alone.

4. Conclusions and Outlook

4.1. Main Conclusions

Using HDPE (Formosa 9001) as continuous phase and Si6.5Fe powder as filler, five ratios were prepared under the baseline process (200 °C, 15 min, 10–15 MPa, staged venting), and tensile, density, contact angle and Izod impact were tested. Conclusions:

(1) From 2:8 to 6:4, mean yield strength falls from 23.38 to 18.68 MPa, fracture force from 789.76 to 694.96 N, retention from 90.31% to 73.26%; all exceed the 17 MPa threshold, with low/medium filling better in tensile load-bearing and high filling weakened by agglomeration and interfacial defects.

(2) Density rises monotonically from 1.13 to 1.95 g/cm^3 following the rule of mixtures; compactness 0.970–0.992 near unity indicates good forming quality and few internal pores.

(3) Contact angle rises from 67.21° to a 75.57° peak at 5:5 then back to 74.54°; all below 90° (weakly hydrophilic); moderate filling weakens wetting most, over-filling complicates the surface.

ISSN: 2710-0588

(4) Izod impact drops from 10.98 to 7.20 kJ/m^2, as high filling trades toughness for density; CVs in 2%–7% confirm reliable, stable data. Low/medium ratios are the more balanced candidate interval among qualified load-bearing, retained toughness and densification.

4.2. Limitations and Outlook

Only a fixed-process single-factor scan was completed; flexural, wear, shielding and SEM are untested, dispersion/interface lacks microscopic evidence, and temperature/holding-time are unquantified. Next, flexural, wear and shielding will be tested per GB/T 9341-2008, GB/T 3960-2016 and GB/T 30142-2013, the particle–matrix interface observed by SEM, and on the candidate optimal ratio a response-surface central-composite design will optimize hot-pressing temperature and holding time, fit a quadratic model and verify the optimum by confirmation tests.

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