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Influence of Ionizing Radiation on Additive Manufacturing of ABS

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Abstract: This paper presents an analysis of the behavior of acrylonitrile butadiene styrene (ABS), a material widely used in 3D printing, when exposed to continuous ionizing radiation. Therefore, a detailed investigation of the changes in its mechanical properties is proposed. To this end, specimens specifically designed for each test were created and printed in two different configurations: solid and with 20% infill. The tests aimed to evaluate the material's mechanical response after irradiation, comparing irradiated and non-irradiated samples. Tensile, hardness, compression, ballistic, and density tests were performed. The irradiation stage took place at the Institute of Chemical, Biological, Radiological, and Nuclear Defense (IDQBRN), in collaboration with the Military Engineering Institute (IME). The main objective of the research is to evaluate the durability of ABS after a certain period of radiation exposure. The results demonstrate that radiation has a positive influence on the material's mechanical performance, particularly in tensile and compression tests, which showed significant improvements. Hardness, ballistic, and density tests indicated more modest but still significant increases. In summary, this study contributes to the understanding of the effects of ionizing radiation on ABS and highlights potential applications in industrial and commercial settings that require greater mechanical strength.

Keywords: ABS, Gamma Irradiation, Mechanical Properties, 3D Printing.

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Influência da Radiação Ionizante na Manufatura Aditiva de ABS

Resumo: Este trabalho apresenta uma análise sobre o comportamento do acrilonitrila-butadieno-estireno (ABS), um material amplamente utilizado na impressão 3D, frente à exposição contínua à radiação ionizante. Propõe-se, portanto, uma investigação detalhada das alterações em suas propriedades mecânicas. Para tal, foram confeccionados corpos de prova especificamente destinados a cada ensaio, impressos em duas configurações distintas: sólidos e com preenchimento de 20%. Os ensaios foram direcionados à avaliação da resposta mecânica do material após a irradiação, comparando-se amostras irradiadas e não irradiadas. Foram realizados testes de tração, dureza, compressão, balístico e densidade. A etapa de irradiação ocorreu no Instituto de Defesa Química, Biológica, Radiológica e Nuclear (IDQBRN), em colaboração com o Instituto Militar de Engenharia (IME). O objetivo central da pesquisa consiste em avaliar a durabilidade do ABS após determinado período de exposição à radiação. Os resultados evidenciam que a radiação exerce influência positiva sobre o desempenho mecânico do material, com destaque para os ensaios de tração e compressão, que apresentaram melhorias significativas. Já os ensaios de dureza, balístico e densidade indicaram incrementos mais modestos, porém ainda relevantes. Em síntese, este estudo contribui para a compreensão dos efeitos da radiação ionizante sobre o ABS e aponta potenciais aplicações em contextos industriais e comerciais que demandem maior resistência mecânica.

Palavras-chave: ABS, Irradiação Gama, Propriedades Mecânicas, Impressão 3D.

1. INTRODUCTION

The 3D printing process, also known as additive manufacturing, stands in contrast to subtractive manufacturing (a practice characterized by machining processes) [1]. This fundamental difference has contributed to the method's growing popularity, resulting in increased demand and greater accessibility of printing resources. Consequently, thermoplastic filaments have gained significant popularity due to their simplicity, convenience, and cost-effectiveness, finding applications in everyday use, non-commercial contexts, and extensive utilization in the technology sector, as well as its growing adoption in nuclear applications.

Recently, this technology has pioneered innovative applications in robotics, where it is being used to develop solutions that minimize human exposure to harmful agents such as radiation. This includes the integration of radiation detectors and monitors to enhance the safety and efficiency of robotic operations. It is important to emphasize that the quality and performance of printed products depend significantly on material selection and how these materials withstand environmental conditions, with polymers like Acrylonitrile Butadiene Styrene (ABS) being commonly employed.

However, there is a notable lack of discussion regarding how these products endure radiation exposure over time - not only in terms of durability but also concerning potential risks. Therefore, this study investigates how gamma irradiation with a total dose of 75 kGy from a Cs-137 source affects the mechanical properties of a polymer widely used in 3D printing and robotics applications. For this purpose, the thermoplastic polymer ABS was divided into five different test groups, where half of the samples were subjected to gamma radiation while the other half remained non-irradiated. Both groups subsequently underwent tensile, compression, ballistic, hardness, and density tests to determine whether significant changes occur due to radiation exposure and to characterize their nature.

2. MATERIALS AND METHODS

Several test specimen models were printed using GTMax3D ABS filament ($\underline{M}$w ≈ 180000 g/mol) through the Fused Deposition Modeling (FDM) system, with a 20% infill pattern. The samples were divided into two groups for each test model to evaluate the material's response to radiation exposure, with one half irradiated and the other half maintained as non-irradiated controls. The samples were maintained in an ambient with low oxygen rate, controlled temperature and free of light exposure before the irradiation process.

For the irradiation process, the Institute of Chemical, Biological, Radiological and Nuclear Defense (IDQBRN/CTEX) irradiator was used. Figure 1 shows the irradiator system employed in this study.

Figure 1: Irradiator located at IDQBRN/CTEX

Source : Author.

The irradiator utilizes a Cs-137 source with an activity of 1.15 PBq, delivering a central dose rate of 24 Gy/min in the upper drawer position [2]. It is important to say that the analysis started immediately after the irradiation process, not giving the samples enough time to suffer any other alternative reaction that could produce structural modification. Figure 2 shows a diagram of the dose rate distribution inside the irradiator. Since the source is isotropic, a small variation is observed between the center of the irradiator drawer and its edges, ranging from 23.5 to 24 Gy/min. The exposure time for the ABS polymer was calculated using the following equation for total absorbed dose, considering that the aim of this work was to apply a total dose (D) of 75 kGy. Equation (1) indicates that the irradiation time required for the samples would be approximately 52.08 hours, i.e., between two and three days.

$$D = \dot{D} \times t \qquad (1)$$

Where:

- D: Total absorbed dose in the material in Gy;
- $\dot{D}$: Dose rate in the drawer in Gy/min;
- ***t*** : Time in minutes.

Figure 2: Dose rate [Gy/min] across the irradiator drawer.

Source : Author.

2.1. Tensile Test

For the tensile test, ASTM D638-14 [3] was followed, with Type II specimens selected, featuring a total length of 12 cm and thickness of 0.6 cm. Figure 3 shows the test specimen used for tensile testing.

Figure 3: Tensile Test Specimen

Source : Author.

This test was conducted on a universal testing machine equipped with specialized grips to secure the test specimens without causing damage or slippage during testing. An extensometer was used to measure strain in the specimen's central region, thereby determining tensile strength and strain-at-break. This ensured accurate elongation measurements. The machine was configured to apply a constant strain rate suitable for plastic materials.

2.2. Compression Test

The compression test followed ASTM D695-15 [4], with measurements taken for both compressive modulus and compressive strength at break. Figure 4 shows the 3D-printed test specimen used for the evaluation.

Figure 4: Compression Test Specimen

Source : Author.

The test was conducted using a compression machine equipped with specialized grips to prevent damage and slippage. A compress meter ensured measurement accuracy after proper alignment of the test specimens between the compression plates. Following application of a preload to eliminate clearance, the load was steadily increased until failure, with real-time load-deformation data being recorded for result analysis.

2.3. Ballistic Test

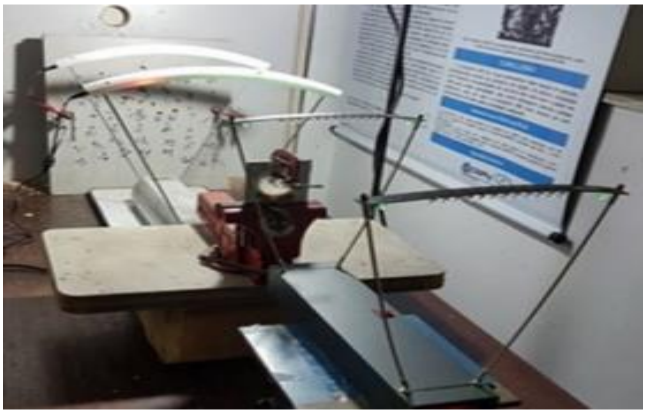
For ballistic testing, a 20×20×0.6 cm plate was 3D-printed using thermoplastic materials, as shown in Figure 5.

Figure 5: Ballistic Test Specimen

Source : Author.

Ballistic testing was conducted to evaluate the residual energy absorption of ABS filament when subjected to 22 caliber projectile impacts. The test focused on two specimen groups: non-irradiated (NI) samples and irradiated (I) samples. Figure 6 displays the energy absorption test's detection and support system.

Figure 6: Energy absorption test detection and support system



Source : Author.

Test specimens were fabricated from ABS composites. The irradiated samples (I) underwent gamma irradiation prior to testing, while non-irradiated controls (NI) remained in their as-manufactured condition. Absorbed energy (Eabs) was calculated using Equation 2 [5].

$$E_{abs} = \frac{m_p(v_i^2 - v_r^2)}{2} \qquad (2)$$

Where:

- E_{abs}: Absorbed energy in Joule;
- m_p: Projectile mass in grams;
- v_i: Projectile initial velocity in m/s;
- v_r: Projectile residual velocity in m/s.

2.4. Hardness Test

Hardness measurements were performed using the Shore D scale in compliance with ASTM D2240 [6]. The same specimens employed in ballistic testing (Figure 5) were utilized for this analysis.

The test employs a durometer equipped with a needle-shaped penetrator that applies calibrated spring pressure to the material surface. Prior to testing, the equipment must be properly calibrated according to manufacturer specifications to ensure measurement accuracy. During testing, the penetrator contacts the specimen surface with constant force, initiating material hardness measurement as specified by the standard.

The hardness values range from 0 (extremely soft materials) to 100 (extremely hard materials). To ensure measurement reproducibility, five tests were performed at distinct locations on each specimen - both irradiated (I) and non-irradiated (NI) - maintaining a minimum 6 mm spacing between indentations to prevent interaction effects.

2.5. Density Test

ABS cubes (1 cm³) were 3D-printed using a FDM printer [Sethi3D S4T]. The specimens were divided into two groups: one subjected to gamma irradiation at 75 kGy, and the other maintained as non-irradiated controls. The test specimen geometry is shown in Figure 7.

Figure 7: 3D-Printed Test Specimen for Density Measurement

Source : Author.

The specimen density (ρ) was determined via the direct method, calculating the mass-to-volume ratio using the density equation (3).

$$\rho = \frac{m}{V} \quad (3)$$

Where:

- ρ: Density in g/cm³;
- m: Specimen mass in grams;
- V: Specimen volume in cm³.

To simplify the procedure, the cubes were intentionally printed to 1 cm³ dimensions, making the density numerically equivalent to the mass measured by the precision balance (in g/cm³). This approach eliminated the need for direct volume determination, as it was held constant across all specimens.

3. RESULTS AND DISCUSSIONS

This section presents and analyzes the experimental results evaluating the impact of irradiation on 3D-printed ABS specimens, detailing the material's response to radiation exposure.

3.1. Tensile Test

Table 1 presents the test results for the non-irradiated specimens., where the standard deviation was ± 0.3.

Table 1 : Tensile Test Results of Non-Irradiated ABS.

SPECIMEN	ULTIMATE TENSILE FORCE [N]	MAXIMUM DISPLACEMENT [mm]
1	539.31	5.37
2	577.92	4.82
3	608.63	5.24
4	583.37	4.89
5	563.21	4.65

And Table 2 presents the test results for the irradiated specimens, where the standard deviation was ± 0.4.

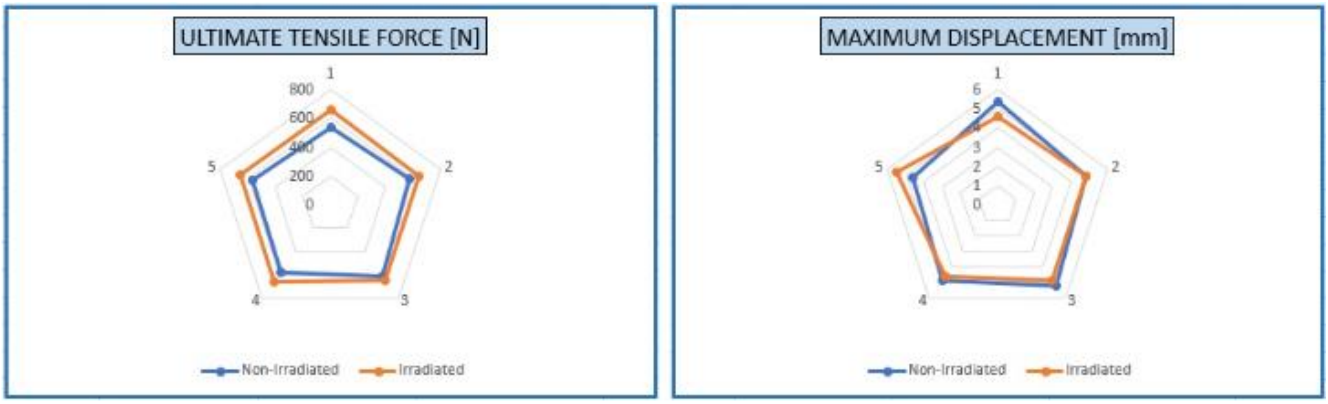
Table 2 : Tensile Test Results of Irradiated ABS.

SPECIMEN	ULTIMATE TENSILE FORCE [N]	MAXIMUM DISPLACEMENT [mm]
1	657.90	4.61
2	644.32	4.86
3	646.31	4.83
4	664.48	4.58
5	660.09	5.51

The tensile test results above reveal a clear enhancement in the mechanical performance of the 3D-printed ABS after exposure to gamma radiation. The irradiated samples exhibited a 13.9% increase in ultimate tensile force, rising from a mean value of 574.49 N ($\sigma = 25.60$) in non-irradiated specimens to 654.62 N ($\sigma = 8.85$) post-irradiation. Notably, the variability was reduced, indicating a more uniform structural behavior likely due to molecular crosslinking. The maximum displacement showed only a slight decrease (−2.3%), suggesting that the material retained its ductility. And these findings align with previous studies that describe the beneficial effects of gamma irradiation at moderate doses, particularly in amorphous polymers like ABS, where crosslinking tends to enhance strength without compromising flexibility [7,8].

Figure 8 provides a visual comparison of both tensile force and displacement behavior, through radar charts. The graph on the left highlights a consistent increase in ultimate tensile force for all irradiated specimens when compared to the non-irradiated group, confirming the mechanical strengthening discussed earlier. Conversely, the chart on the right reveals that maximum displacement values remain closely aligned between groups, with differences falling within the calculated standard deviations. This visual evidence reinforces the conclusion that gamma irradiation improved mechanical strength without compromising the material's ductility, confirming the statistical observations and supporting the hypothesis of effective crosslinking.

Figure 8: Ultimate Tensile Force [N] and Maximum Displacement [mm] Plots



Source : Author.

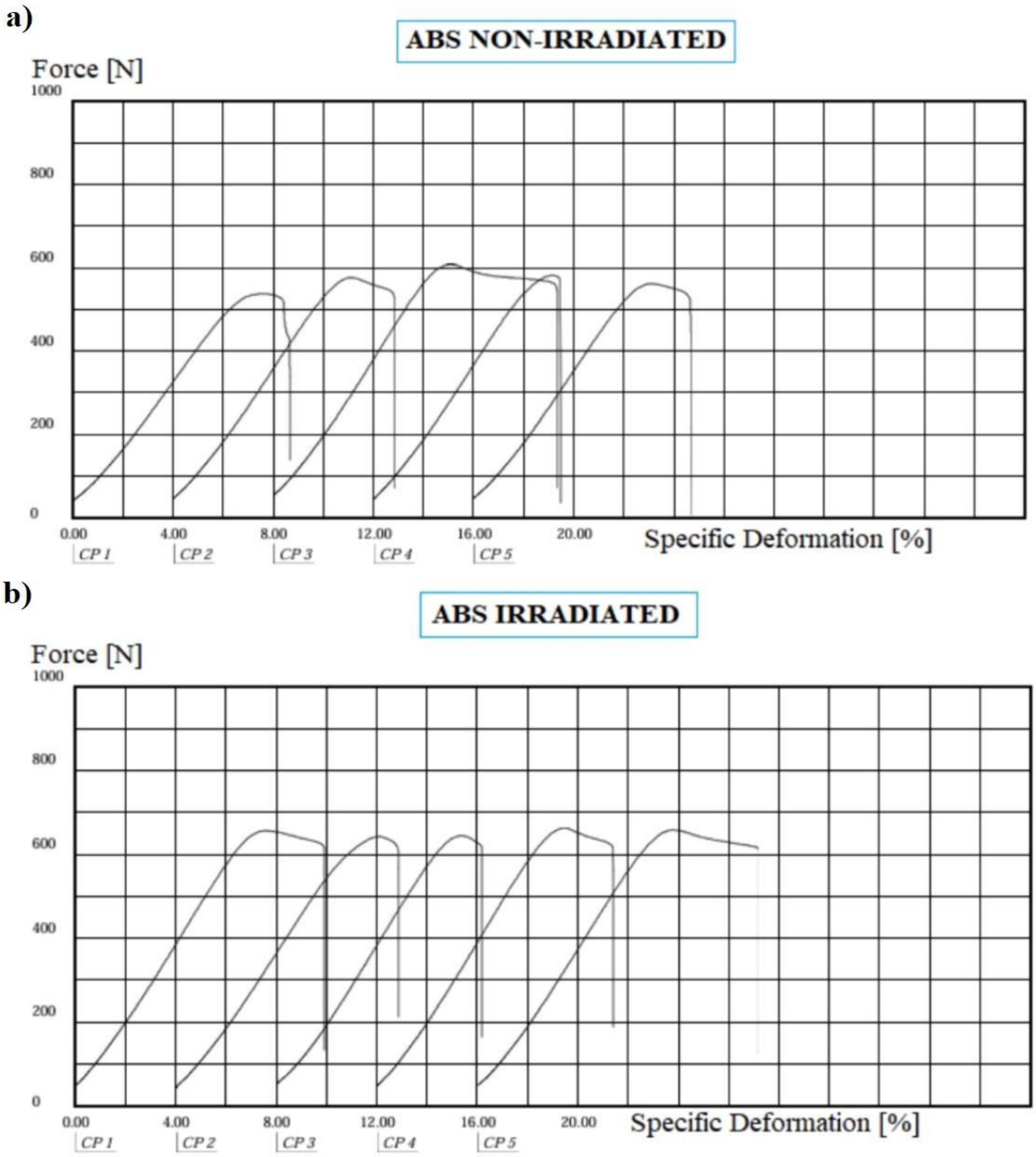
Figures 9 present the individual force versus specific deformation curves for the non-irradiated and irradiated ABS specimens, respectively. These plots serve as a critical complement to the tabulated values and radar charts previously discussed, providing a more complete understanding of the tensile behavior of the material.

As recommended by ASTM D638 [3], stress–strain curves (or force-deformation plots) are essential not only for determining ultimate values (e.g., tensile strength, elongation at break) but also for observing the overall mechanical behavior, including yield, strain hardening, and failure mode. In the present study, the curves for the irradiated specimens (Figure 9) show a more consistent pattern with slightly higher force levels sustained across the deformation range, when compared to the non-irradiated samples (Figure 9). This homogeneity reflects the mechanical stabilization effect induced by gamma irradiation.

The shape and reproducibility of the curves also allow the identification of structural changes such as increased molecular crosslinking, as theorized in polymer materials science [9]. Despite the increase in maximum tensile force observed in the irradiated group, the final deformation values remain close to those of the control group, suggesting that ductility was preserved. This supports the hypothesis of controlled crosslinking without significant chain scission, a phenomenon also described in studies focused on radiation-modified polymers [7,8].

The use of these force-deformation plots further strengthens the reliability of the experimental results and aligns with previous publications that highlight their value in detecting changes in mechanical response due to irradiation treatments [7], [10].

Figure 9: Tensile Force vs. Specific Deformation for (a) Non-Irradiated and (b) Irradiated ABS Specimens



Source : Author.

3.2. Compression Test

Tables 3 and 4 summarize the compressive behavior of non-irradiated and irradiated ABS specimens, respectively.

Table 3 : Compression Test Results of Non-Irradiated ABS.

SPECIMEN	ULTIMATE TENSILE FORCE [N]	SPECIFIC DEFORMATION [%]
1	1461.41	2.62
2	1667.61	2.50
3	1489.31	2.80
4	1737.70	2.58
5	1529.80	2.46

Table 4 : Compression Test Results of Irradiated ABS.

SPECIMEN	ULTIMATE TENSILE FORCE [N]	SPECIFIC DEFORMATION [%]
1	1525.38	2.53
2	1475.02	2.60
3	1497.14	2.77
4	1522.66	2.55
5	1547.16	3.11

The standard deviation was ± 0.1 in compressive behavior of non-irradiated specimens and ± 0.2 in the irradiated specimens.

The results in Tables 3 and 4 summarize the compressive behavior of non-irradiated and irradiated ABS specimens, respectively. The analysis reveals a modest decrease in the average maximum compressive force after irradiation, from 1577.17 N ($\sigma = 119.70$ N) in the control group to 1513.47 N ($\sigma = 27.87$ N) in the irradiated group, corresponding to a reduction of approximately 4.0%. This decline, though minor, indicates that gamma irradiation did not enhance the compressive strength of the material, a result consistent with previous findings that highlight how radiation-induced crosslinking typically favors tensile rather than compressive performance in amorphous polymers like ABS [7].

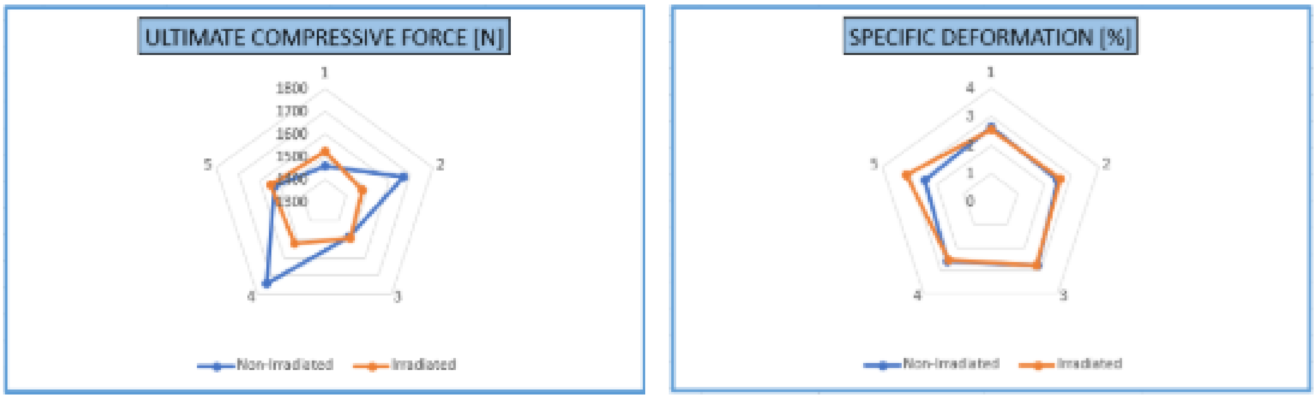
On the other hand, the irradiated group exhibited a slightly higher mean specific deformation (2.712%) compared to the non-irradiated group (2.592%), suggesting a greater ability to accommodate deformation before reaching peak load. While this difference is small, it may reflect a subtle microstructural reorganization within the polymer matrix, allowing for strain redistribution under compressive loading [8].

An important observation from the compression test results is the significant reduction in the standard deviation of the maximum compressive force in the irradiated group (σ = 27.87 N), compared to the non-irradiated group (σ = 119.70 N). While the mean strength showed a modest decrease, the marked drop in variability suggests that gamma irradiation acted as a stabilizing agent, leading to greater consistency in mechanical response among specimens.

This homogenization effect is particularly valuable in the context of additive manufacturing, where intrinsic anisotropies and microstructural imperfections are common due to layer-by-layer deposition processes. Ionizing radiation has been reported to reduce residual stress, eliminate microvoids, and promote partial healing of interlayer defects through localized chain mobility and crosslinking, especially in amorphous polymers such as ABS [3], [11] e [12]. These mechanisms may explain the improved repeatability of mechanical performance seen here.

The lower deviation indicates that the irradiated material responded more predictably under compressive loading, which could be advantageous in applications requiring reliable and reproducible mechanical behavior, even if peak strength is slightly compromised. This reinforces the role of controlled irradiation as a post-processing method to enhance dimensional and structural reliability in 3D-printed thermoplastics.

Figure 10: Ultimate Tensile Force [N] and Specific Deformation [%] Plots



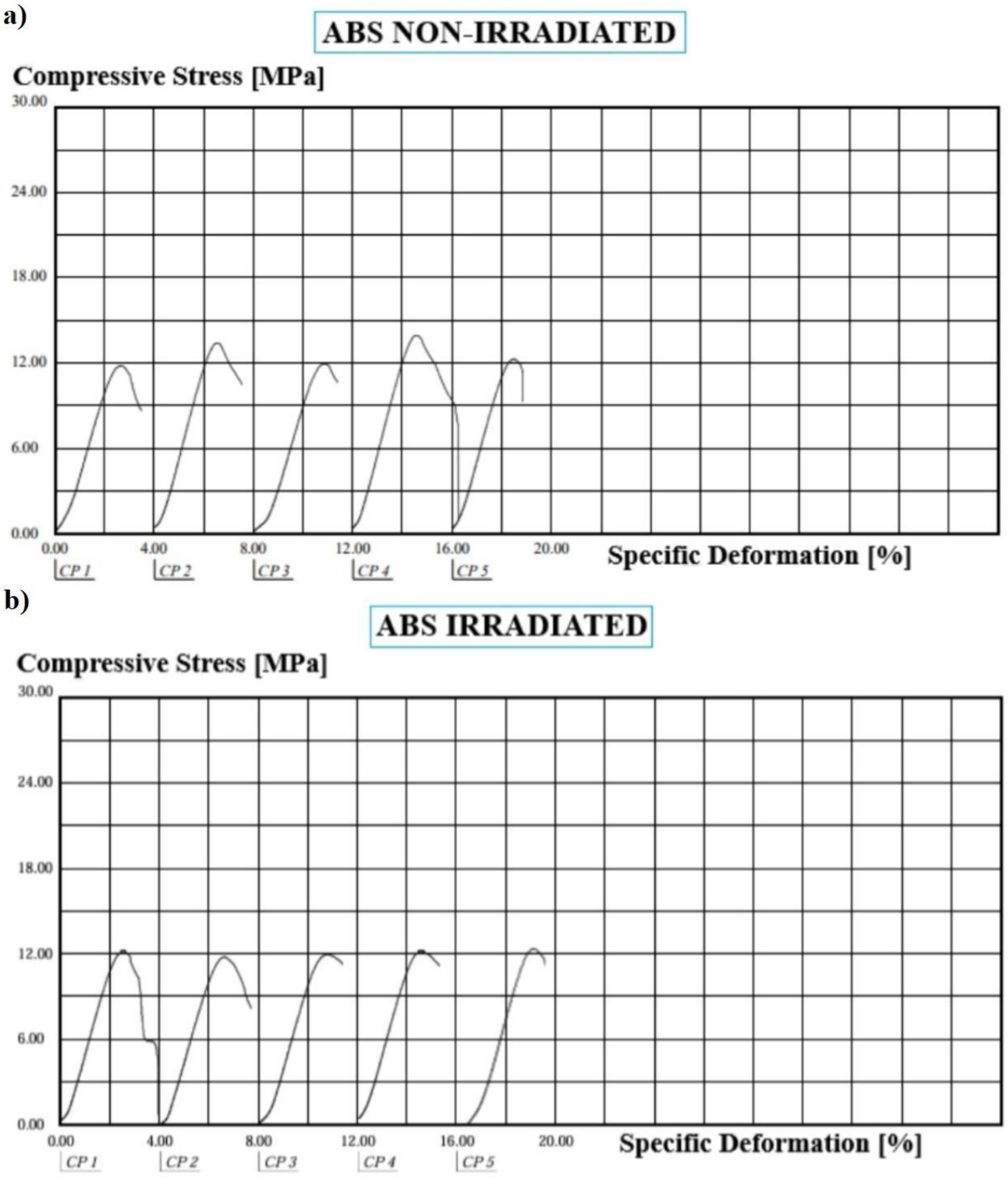
Source : Author.

Figure 10 presents a radar chart comparison of the ultimate compressive force [N] and specific deformation [%]. The left chart demonstrates that after irradiation, the maximum force results became markedly more consistent, with a sharp drop in standard deviation - as previously discussed -, confirming the reduction in compressive strength of the irradiated ABS. However, this effect "standardized" the material's behavior, yielding a more predictable mechanical response due to reduced variability.

Meanwhile, the right chart reveals that irradiation caused only a minor difference in specific deformation, remaining within the expected range. This suggests that while irradiation did not drastically alter the material's deformation capacity, its role in homogenizing compressive strength is clear, highlighting its potential as a post-processing method for applications requiring enhanced mechanical reliability.

Figures 11 reinforce the previously discussed trends: although irradiation slightly reduced compressive strength, the compressive stress–strain curves for the irradiated ABS specimens display significantly tighter clustering, indicating improved uniformity in mechanical response. This enhanced consistency aligns with the effects of gamma-induced crosslinking reported in amorphous polymers [13], and reflects reduced microstructural defects and improved stress distribution in additively manufactured parts [14, 15]. The narrower spread in stress and deformation values among irradiated samples corroborates the homogenization effect observed by Garcia et al. [15] and supports the use of gamma irradiation as a viable post-processing step for improving mechanical reproducibility in FFF-printed ABS components [16].

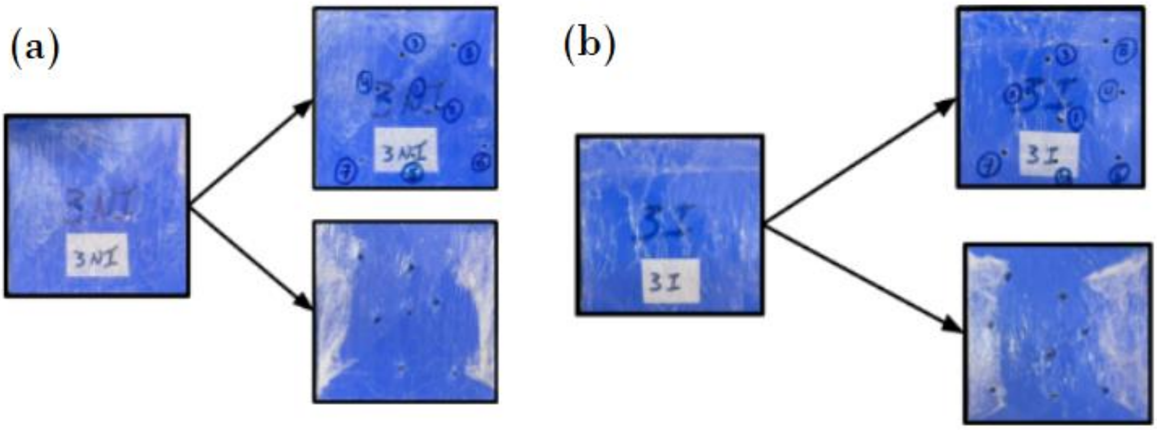
Figure 11: Compressive Stress vs. Specific Deformation for (a) Non-Irradiated and (b) IrradiatedABS Specimens



3.3. Ballistic Test

Ballistic tests were conducted using a Gunpower SSS pneumatic rifle with 22 caliber lead projectiles (mass: 0.8 g), fired at a distance of 5 meters against 3D printing filament plates. Impact velocity and residual velocity were evaluated to determine the samples' energy absorption. Figure 12 shows the samples used in the ballistic test.

Figure 12: Ballistic test on ABS samples: (a) non-irradiated, (b) irradiated. Arrows show front and back sides.



Source : Author.

Table 5 presents the average values of the composite mass (Mc), projectile mass (mp), average impact velocity (Vi), average residual velocity (Vr), energy absorption (Eabs), and the limit velocity (Vl) for each composition.

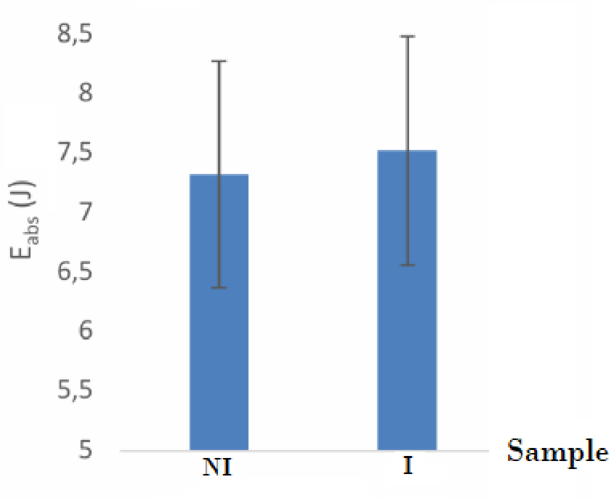
Table 5 : Energy absorption test

SPECIMEN	Mc (g)	mp (g)	Vi (m/s)	Vr (m/s)	Eabs (J)	Vl (m/s)
None	-	0.81 ± 0.01	381.51 ± 2.03	365.71 ± 1.89	4.78 ± 0.45	108.54 ± 5.44
Non Irradiated	88.96 ± 1.56	0.84 ± 0.03	381.83 ± 3.54	341.86 ± 4.18	7.32 ± 0.95	132.04 ± 7.97
Irradiated	91.64 ± 1.30	0.84 ± 0.03	380.34 ± 4.01	339.57 ±3.15	7.52 ± 0.96	133.77 ± 9.70

The results presented in Table 5 indicate a clear increase in energy absorption (Eabs) following gamma irradiation. While the non-irradiated composite exhibited an average Eabs of 7.32 ± 0.95 J, the irradiated samples reached 7.52 ± 0.96 J, suggesting an enhancement in the material's ability to dissipate kinetic energy. Additionally, a slight increase in composite mass (Mc) was observed after irradiation, which, combined with the more uniform residual velocities (Vr), points to potential structural changes within the polymer matrix. These observations may be associated with the formation of crosslinking induced by gamma exposure, which can improve mechanical integrity and energy dissipation.

The ballistic tests shown in Figure 13 below revealed that gamma irradiation provides measurable improvements in the performance of 3D-printed ABS. The irradiated samples (I) demonstrated a greater capacity for energy absorption, as well as more consistent characteristics in terms of mass and residual velocity when compared to the non-irradiated ones (NI).

Figure 13: Absorbed Energy Graph



Source : Author.

Therefore, the results of the ballistic tests demonstrated that gamma irradiation promotes an average increase of 2.7% in the energy absorbed during impact (7.52 ± 0.96 J), compared to the non-irradiated samples (7.32 ± 0.95 J). This improvement aligns with the expected effects of exposure to moderate gamma radiation doses (50–100 kGy), a range in which crosslinking processes predominate, enhancing the toughness and fracture resistance of polymers by restricting molecular chain mobility [17].

Overall, the observed improvement across the evaluated parameters, though modest, was consistent, suggesting that the beneficial effects of crosslinking outweigh the potential degradative effects of chain scission at the applied dose. Previous studies indicate that higher irradiation doses (>150 kGy) may further enhance these positive effects [18].

The obtained results suggest that irradiated ABS may be advantageous for applications requiring high impact resistance and stable mechanical performance, such as internal linings of personal protective equipment, aerospace shields against orbital debris, and automotive components designed for energy absorption during collisions.

3.4. Hardness Test

Shore D hardness tests conducted on irradiated and non-irradiated ABS specimens revealed subtle differences in surface properties. The measured means were 82.3 Shore D for irradiated ABS and 81.0 Shore D for non-irradiated ABS, representing a marginal 1.6% increase in post-gamma irradiation. While this difference falls within experimental error margins and data standard deviation, the upward trend aligns with molecular crosslinking effects induced by moderate-dose radiation (50–100 kGy). Such crosslinking restricts polymer chain mobility, slightly enhancing surface indentation resistance [17].

Table 6 : Hardness tests results in Shore D

REPLICATION	Non Irradiated Sample	Irradiated Sample
1	90.3	80.8
2	74.6	80.6
3	80.6	75.8
4	82	79
4	77.6	95.1

The results presented in table 6 refer to the Shore D hardness test performed on two ABS 3D-printed specimens, each with dimensions of 1 cm³. One of the specimens was subjected to gamma irradiation with a total dose of 75 kGy, while the other remained non-irradiated. For each specimen, hardness was measured five times, allowing for the analysis of the mean, median, standard deviation, and standard error.

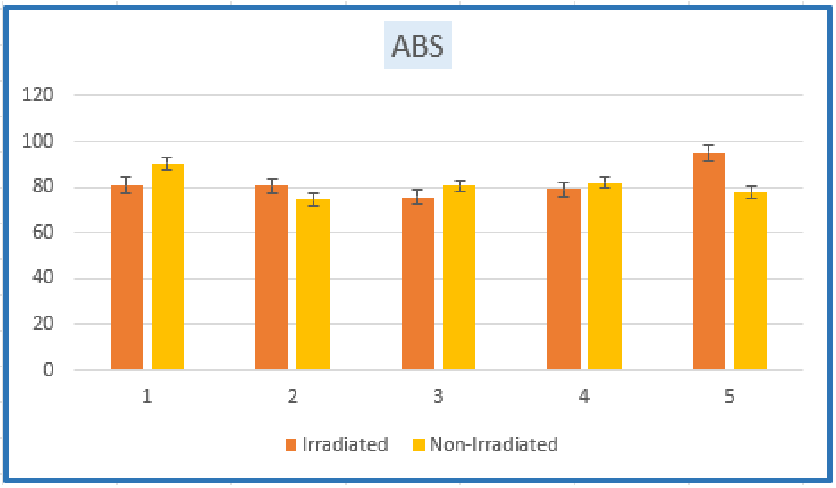
It can be observed that the irradiated specimen exhibited Shore D hardness values ranging from 74.6 to 90.3, with a mean of 81.0 and a median of 80.6. In contrast, the non-irradiated specimen showed values between 75.8 and 95.1, with a mean of 82.3 and a median of 80.6. The standard deviation values were 5.29 for the irradiated specimen and 6.66 for the non-irradiated one, while the standard error was 2.37 and 2.98, respectively.

These results indicate that, although the mean hardness of the irradiated specimen is slightly lower than that of the non-irradiated one, the variation of the values (standard deviation) is smaller in the irradiated material. This suggests that irradiation contributed to greater uniformity in the material's hardness. Furthermore, the fact that the median is the same in both cases (80.6) indicates that the central distribution of the hardness values is quite similar, even after irradiation.

Therefore, it can be inferred that irradiation does not significantly alter the average hardness of ABS, but it tends to reduce the dispersion of the results, possibly indicating some stabilizing effect on the material, such as the formation of radiation-induced crosslinks, which could confer greater homogeneity to the specimen’s surface.

From a practical standpoint, gamma irradiation does not compromise ABS surface hardness and may even slightly improve it, while providing a minor increase in uniformity of the hardness values, possibly due to radiation-induced crosslinking that stabilizes the polymer structure (Figure 14).

Figure 14: Shore A Hardness Values – Sample Distribution



Source : Author.

3.5. Density Test

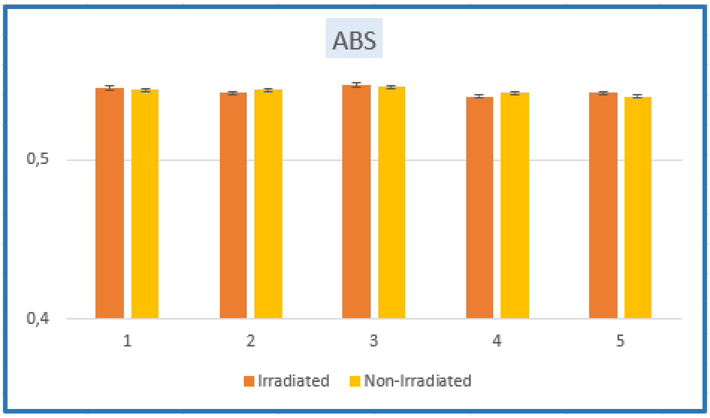
Table 7 shows the density results of the samples, indicating that the density of the 3D-printed ABS specimens remained virtually unchanged after gamma irradiation. Both the irradiated and non-irradiated samples presented the same mean density of 0.543 g/cm³, with medians of 0.542 g/cm³ and 0.544 g/cm³, respectively, and standard deviations of 0.0025 g/cm³ for the irradiated specimen and 0.0020 g/cm³ for the non-irradiated one. These results demonstrate that, even after exposure to a total dose of 75 kGy, gamma irradiation did not affect the bulk density of the material. This stability is advantageous, as it allows the irradiated ABS to be used in applications where maintaining consistent density is critical for performance or dimensional compatibility.

Table 7 : Density measurement results (g/cm³)

REPLICATION	Non Irradiated Sample	Irradiated Sample
1	0.544	0.545
2	0.544	0.542
3	0.546	0.547
4	0.542	0.540
4	0.540	0.542

Figure 15 shows that the density of ABS remained virtually unchanged after irradiation, with mean values of 0.543 g/cm³ (standard deviation = 0.00248) for irradiated (I) and 0.543 g/cm³ (standard deviation = 0.00204) for non-irradiated (NI) specimens.

Figure 15: Density distribution comparison between gamma-irradiated and non-irradiated ABS specimens



Source : Author.

4. CONCLUSIONS

The present study demonstrates that gamma irradiation at 75 kGy promotes targeted modifications in 3D-printed ABS, enhancing its mechanical performance while preserving its dimensional and structural stability. Tensile testing revealed a 13.9% increase in maximum strength, accompanied by a substantial reduction in standard deviation (from σ = 25.60 N to σ = 8.85 N), indicating effective crosslinking and improved material consistency. Despite a slight 2.3% reduction in maximum displacement, ductility was largely preserved, confirming that the irradiation dose did not induce embrittlement.

The ABS used in this study (Mw ≈ 180,000 $g \cdot mol^{-1}$) presents a sufficiently high molar mass to favor the predominance of crosslinking over radiation-induced chain scission. This contributed to the increase in tensile strength observed after irradiation, while maintaining the material's ductility.

After exposure, the samples were stored under controlled conditions, minimizing contact with oxygen and light in order to reduce secondary reactions from residual radicals. Mechanical tests were conducted shortly after irradiation, ensuring that the observed effects primarily resulted from the absorbed dose rather than subsequent aging processes.

From a molecular perspective, gamma radiation at a dose of 75 kGy primarily promoted crosslinking between ABS chains, stabilizing the polymer network and accounting for the increase in tensile strength and the reduced variability observed in hardness and compression results. At the same time, localized chain scission occurred, explaining the slight reduction in compressive strength. These competing effects (predominant crosslinking and secondary scission) are consistent with the behavior of amorphous polymers irradiated at moderate doses (50–100 kGy), as reported in the literature [7, 11] .

Ballistic impact tests showed a 2.7% increase in absorbed energy (from 7.32 J to 7.52 J), suggesting enhanced impact resistance through improved energy dissipation mechanisms. Compression strength exhibited a modest 4% reduction; however, the significant drop in standard deviation (76.7%) highlights increased structural homogeneity. Shore D hardness and density remained virtually unchanged, further supporting the material's physical stability under the applied irradiation conditions.

These findings align with Charlesby's crosslinking theory, which predicts that moderate gamma doses (50–100 kGy) in amorphous polymers favor the formation of intermolecular bonds over chain scission. The concurrent improvement in strength and consistency across multiple mechanical tests suggests that gamma irradiation may also mitigate anisotropic defects commonly associated with fused filament fabrication (FFF) by reinforcing interlayer adhesion.

In summary, this study confirms gamma irradiation as a viable post-processing technique for enhancing the mechanical integrity and structural reliability of 3D-printed ABS, particularly for applications in radiation-prone or high-impact environments.

The test presented in this study has an experimental nature and was essential for obtaining preliminary data, serving as a basis for future investigations. From a practical standpoint, post-processing ABS with gamma irradiation at 75 kGy appears to be a promising approach for applications requiring enhanced mechanical reliability, such as personal protective equipment, aerospace shielding, and automotive components. Subsequent studies should evaluate the mechanical behavior of the materials after both longer and shorter periods of radiation exposure, with variations in the total applied radiation dose, as well as analyze the material's performance under aging conditions similar to those encountered in real-use scenarios, in order to better explore the limits of structural optimization.

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CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

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