INFLUENCE OF NEUTRON IRRADIATION ON THE TEMPERATURE DEPENDENCE OF MAGNETIC SUSCEPTIBILITY IN Fe - Ni INVAR ALLOYS WITH VARYING NICKEL CONTENT

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ABSTRACT

This study systematically examines the effects of neutron irradiation and alloy composition on the magnetic behavior of Fe - Ni Invar alloys. Three compositions Fe - 22 % Ni, Fe - 30 % Ni (classical Invar composition), and Fe - 50 % Ni were selected to elucidate the interplay between chemical disorder, irradiation-induced modifications, and magnetic properties. The samples were irradiated using a 100keV pulsed neutron source at a dose of 10^{15} neutrons cm^{-2}. Magnetic characterization was carried out using a vibrating sample magnetometer (VSM) in conjunction with temperature-dependent magnetic susceptibility measurements performed at different orientations between the neutron beam direction and the applied alternating magnetic field. The results demonstrate a pronounced dependence of magnetic behavior on both alloy composition and irradiation conditions. For the Fe - 30 % Ni alloy, the Curie temperature was determined to be approximately 315K. Following neutron irradiation, a significant extension of magnetic ordering was observed, with locally ferromagnetic regions persisting up to approximately 460K. This behavior is attributed to irradiation-induced defects that locally modify the electronic structure, enhance 3d electron localization, and increase effective exchange interactions. The magnetic susceptibility also exhibits a clear angular dependence, indicating anisotropic defect distribution. Complementary structural characterization using X-ray diffraction (XRD) and scanning electron microscopy (SEM) reveals the coexistence of ordered and disordered phases and a heterogeneous microstructure, which correlate strongly with the observed magnetic properties. These findings provide evidence of defect-mediated ferromagnetism and highlight the potential of controlled irradiation for tailoring magnetic properties in Fe - Ni alloys.

Keywords: Fe - Ni Invar alloys, neutron irradiation, magnetic susceptibility, irradiation-induced ferromagnetism, curie temperature, X-ray diffraction.

INTRODUCTION

In recent years, research on the magnetic properties of Invar alloys has intensified due to their anomalous behavior, particularly near the Fe - 30 % Ni composition. These anomalies manifest in several physical properties, including magneto-structural coupling, anomalous thermal expansion, and unusual magnetic susceptibility behavior [1].

Invar alloys with a face-centered cubic (Fcc) crystal structure exhibit an exceptionally low thermal expansion coefficient below the Curie temperature (Tc), a phenomenon widely known as the Invar effect. This behavior is closely associated with strong magneto-volume coupling and a pronounced pressure dependence of magnetization. It is now well established that local compositional fluctuations, magnetic inhomogeneities, and competing magnetic states play a critical role in determining the magnetic response of Fe - 30 % Ni alloys, particularly in the vicinity of magnetic and structural instabilities [2].

Fe - Ni Invar alloys are characterized by a near-zero

thermal expansion coefficient and exhibit anomalous magnetic properties, including variations in lattice parameters, magnetization, and elastic moduli. These anomalies have been extensively confirmed through experimental and theoretical studies and are commonly interpreted as arising from the coupling between a large positive magneto-volume effect and the peculiar electronic structure of the 3d-electron band responsible for ferromagnetism in transition metals [3, 4]. In particular, deviations of the spontaneous magnetization from the Slater-Pauling curve indicate that the magnetic behavior cannot be described by a simple band-filling model, but instead reflects complex interactions between electronic structure, lattice degrees of freedom, and magnetic ordering [5].

Furthermore, the unusual temperature dependence of high-field magnetic susceptibility and the strong pressure dependence of the Curie temperature can be understood in terms of the instability of the 3d-electron band that induces ferromagnetism in Fcc alloys. This instability is associated with a sharp peak in the electronic density of states near the Fermi level, which enhances the sensitivity of magnetic properties to small changes in lattice parameter and composition [6, 7].

As the Ni concentration decreases, the ferromagnetic state becomes progressively unstable due to changes in band structure and exchange interactions. In particular, when the Ni content falls below approximately 29 %, a martensitic transformation occurs, marking a significant transition in both structural and magnetic behavior, and indicating the presence of competing ground states.

At compositions near 29 % Ni, martensitic transformation behavior is observed, defining a critical compositional range in which both structural and magnetic instabilities coexist. This region is of particular interest, as it provides insight into the coupling between lattice distortions and magnetic interactions. Consequently, further investigations of Invar anomalies are required to elucidate the underlying mechanisms governing magnetic stability, local lattice distortions, and electronic structure effects [8].

Recent theoretical studies on Fe - Ni alloys have emphasized the importance of environmental and compositional effects, including chemical disorder and local atomic configurations, in determining magnetic behavior [9].

In addition to intrinsic effects, external perturbations such as irradiation can significantly modify the magnetic properties of Fe - Ni alloys. High-energy irradiation is known to introduce lattice defects, including vacancies, interstitials, and defect clusters, which can locally alter the electronic structure and exchange interactions [10, 11].

These irradiation-induced defects may lead to enhanced localization of 3d electrons and stabilization of magnetic ordering in regions that would otherwise remain paramagnetic. However, despite considerable progress, the combined effects of composition, temperature, and irradiation on the magnetic susceptibility of Fe - Ni Invar alloys remain insufficiently understood.

In the present work, the temperature dependence of magnetic susceptibility in Fe -Ni alloys with different compositions was systematically investigated, with particular emphasis on the influence of neutron irradiation. The samples were irradiated at a fluence of 10^{15} neutrons cm^{-2} to examine irradiation-induced modifications in their magnetic behavior. Most Invar alloys exhibit an anomalously small thermal expansion

Table. 1. Properties of the f.c.c and b.c.c alloys.

Properties	$Fe_{50}Ni_{50}$	$Fe_{70}Ni_{30}$	Reference
Average atomic mass, amu	57.28	56.1	-
Lattice constant, A	3.586	3.586	[5, 14]
Melting temperature, K	1710	1750	[15]
Saturation magnetic moment, mb $atom^{-1}$	1.68	1.25	[16]
Curie temperature, K	790	340	[17, 18]
Debye temperature, K	407.8	315	[16, 19]
Structure	fcc-phase	bcc-phase	[15, 19]
Spontaneous magnetization, emu g^{-1}	80	58	

below the Curie temperature, a phenomenon attributed to the coupling between magnetic ordering and lattice dynamics. The temperature dependence of magnetic susceptibility is therefore closely related to atomic rearrangements, including short-range ordering, clustering, and spinodal decomposition, which influence local magnetic interactions.

Annealing treatments are known to induce significant changes in amorphous alloys, including modifications in chemical short-range order and topological transformations [12, 13]. In contrast, in crystalline Fe - Ni alloys of comparable composition, annealing primarily affects chemical short-range order without significantly altering the long-range crystal structure. The primary objective of this study is to characterize the magnetic properties of selected Fe - Ni Invar alloys with varying compositions and to elucidate the combined influence of temperature and neutron irradiation on their magnetic susceptibility. By integrating magnetic measurements with structural characterization, the present work aims to provide a comprehensive understanding of defect-mediated magnetic behavior in Invar alloys.

EXPERIMENTAL

Iron-nickel alloys with nominal compositions of Fe - 30 % Ni were prepared by arc melting high-purity elemental iron and nickel (99.9 wt%). To ensure compositional homogeneity, each alloy ingot was remelted several times under an inert atmosphere. The resulting alloys were mechanically processed into thin plate specimens with dimensions of approximately 4 × 4 mm² and a thickness of ~200 μm. Subsequently, all samples were annealed at 1000°C for 3 h and rapidly quenched in water to minimize compositional segregation and preserve the desired microstructural state.

The current work original is the systematic incorporation of magnetic behaviour dependent on composition, effects from irradiation, and microstructural evolution in an integrated experimental approach. This is the first work that combines multiple Fe - Ni compositions, in this case Fe - 22 % Ni, in one electrochemical study, in contrast to previous work focused primarily on a single Fe - Ni composition, or specific on one isolated phenomenon. Fe - 22 % Ni, Fe - 30 % Ni, and Fe - 50 % Ni. Consequently, this FL functionalism facilitates composition-dependent magnetic mechanisms in these high–% Ni alloys. In addition, the study introduces of a novel experimental perspective on irradiation induced magnetic behavior and shows that, in contrast to traditional expectations, a ferromagnetic response can extend beyond the Curie temperature via a defect mediated exchange interaction process. This conclusion formally ties the irradiation scenario to magnetic susceptibility, a relationship not quantitatively described in previous studies. Furthermore, the combination of XRD, SEM and magnetic measurements strengthens a consistent relationship between phase constitution, microstructure and magnetic properties, providing a better interpretation than previously published results. Combined, these additions deliver a new and physically coherent approach to magneto-structural coupling in Fe - Ni alloys.

To investigate irradiation-induced modifications in magnetic behavior, the prepared samples were subjected to high-energy neutron irradiation. Neutrons with energy of 100 keV were employed at a fluence of approximately neutrons cm^{-2}. Based on stopping power calculations, the penetration depth of the neutron beam was estimated to be approximately 7 μm, which is significantly smaller than the specimen thickness. This indicates that irradiation effects are predominantly confined to the near-surface region, thereby enabling a direct assessment of localized irradiation-induced magnetic modifications.

Magnetic characterization was performed using a vibrating sample magnetometer (VSM). Hysteresis loops were measured over an applied magnetic field range of $-5500\ Oe \leq H \leq 5500\ Oe$ in order to determine key magnetic parameters, including saturation magnetization, coercivity, and remanence. Calibration of the VSM was carried out using high-purity iron and nickel reference samples (5N purity). The measured saturation magnetization values of 216.8 emu g^{-1} for iron and 55.1 emu g^{-1} for nickel were found to be in good agreement with standard reference data reported by Crangle, confirming the reliability of the measurement system [13].

Temperature-dependent magnetic susceptibility measurements were conducted both before and after irradiation using a dedicated high-frequency susceptibility setup. An alternating magnetic field with a frequency of 1 kHz and controlled amplitude was

applied. The Curie temperature (Tc) was determined from the temperature corresponding to the inflection point or sharp decrease in magnetic susceptibility. The obtained Tc values were consistent with previously reported data measured using the Hartshorn bridge technique, thereby validating the experimental approach [14].

In order to examine the anisotropic effects associated with irradiation, magnetic susceptibility measurements were performed while systematically varying the angle (θ) between the neutron beam direction and the applied magnetic field. The experimental geometry is illustrated in Fig. 1. This configuration enables the investigation of directional effects arising from irradiation-induced defect distributions and their influence on magnetic response.

Complementary structural and morphological characterizations were carried out to establish a correlation between microstructure and magnetic behavior, a relationship between microstructure and magnetic properties is presented, linking such structural features to SEM and magnetic results - chemically disordered and fine-grained regions favour stronger spin fluctuations and high coercivities attributed to domain wall pinning, while more ordered and coarse-grained structures contribute to stronger ferromagnetic coupling and low magnetic losses. X-ray diffraction (XRD) measurements were performed using Cu Kα radiation to identify crystal structure, phase composition, and degree of atomic ordering. Scanning electron microscopy (SEM) was employed to analyze surface morphology and grain structure. These combined techniques provide essential information for interpreting the relationship between structural features and magnetic properties.

In addition to the Fe - 30 % Ni Invar composition, selected Fe - Ni alloys with different nickel concentrations were investigated to assess the influence of composition on magnetic behavior. All samples were prepared following the same procedure to ensure reproducibility and consistency. The magnetic properties of Fe - Ni alloys are known to be highly sensitive to compositional variations and atomic ordering; therefore, particular attention was given to maintaining identical processing conditions across all specimens. The experimental approach adopted in this study enables a systematic evaluation of the combined effects of composition, irradiation, and microstructure on the magnetic properties of Fe - Ni Invar alloys [15, 16].

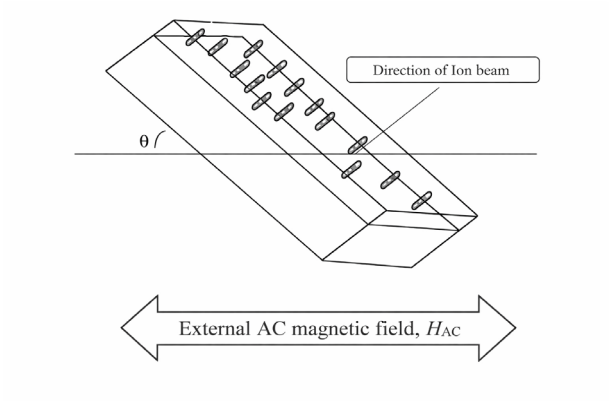


Fig. 1. Diagram illustration the arrangement of plat sample irradiation by 100 Kev pulse neutron and shows the direction of magnetic field.

RESULTS AND DISCUSSION

The selection of Fe - Ni alloy compositions in the present study, namely Fe - 22 % Ni, Fe - 30 % Ni, and Fe - 50 % Ni, was deliberately designed to establish a systematic framework for investigating the evolution of magnetic behavior across, within, and beyond the classical Invar regime. To directly focus on the breadth of the study, the inclusion of such compositions is patched as a comparative technique that allows composition-dependent magnetic pathways to be established as benchmarked against the Fe - 30 % Ni Invar alloy. The Fe - 30 % Ni composition represents the canonical Invar alloy, characterized by anomalously low thermal expansion and strong magneto-volume coupling. In contrast, the Fe - 50 % Ni alloy corresponds to a Ni-rich composition in which enhanced chemical disorder and modified exchange interactions are expected to dominate the magnetic response, while the Fe - 22 % Ni alloy lies outside the Invar regime and serves as a comparative reference system [17].

This compositional strategy enables a rigorous correlation between atomic configuration, chemical ordering, and magnetic properties, thereby directly supporting the primary objective of the study.

The magnetic hysteresis loops shown in Fig. 2 and Fig. 3 reveal a pronounced dependence of magnetic behavior on alloy composition. The saturation magnetization decreases from approximately 86 emu/g for Fe - 30 % Ni to 65 emu/g for Fe - 50 % Ni This experimentally observed trend provides quantitative support for the interpretation of magnetic behavior, rather than relying solely on qualitative arguments.

This trend can be attributed to the progressive dilution of Fe - Fe exchange interactions, which are primarily responsible for strong ferromagnetism, combined with the comparatively lower magnetic moment of Ni atoms. Furthermore, the variation in the hysteresis loop area indicates changes in magnetic anisotropy and domain wall dynamics, which are strongly influenced by magneto-volume effects intrinsic to Invar alloys. The correlation between experimental magnetization values and exchange interaction mechanisms establishes a clear link between measured data and theoretical interpretation. At the microscopic level, the magnetic behavior arises from a delicate balance between competing exchange interactions that depend sensitively on local atomic environments. Positive exchange interactions between Fe - Ni and Ni - Ni atomic pairs stabilize ferromagnetic ordering, whereas Fe-Fe interactions may adopt an antiferromagnetic character depending on interatomic spacing and electronic structure [18, 19]. This competition becomes particularly significant in the Fe - 50 % Ni alloy, where increased chemical disorder enhances spatial fluctuations in exchange interactions, leading to a more complex and composition-dependent magnetic response.

As illustrated in Fig. 2, the Fe - 22 % Ni alloy exhibits negligible variation in the hysteresis loop following thermal treatment, indicating a relatively stable magnetic response. This observation suggests that the dominant magnetic interactions in this composition are governed by robust local atomic configurations, with only minor contributions arising from modifications in chemical short-range order. In contrast, alloys within or near the Invar regime display a heightened sensitivity to atomic rearrangements, including clustering, short-range ordering, and possible spinodal decomposition, this comparative analysis strengthens the interpretation by explicitly linking compositional differences to observed magnetic behavior, which modify the distribution of exchange interactions and consequently influence the magnetic response. These results highlight the critical role of chemical short-range order in controlling magnetic properties in Fe - Ni alloys [20].

The temperature-dependent magnetic susceptibility results presented in Figs. 4 - 7. provide further insight into the magnetic behavior of the Fe - 30 % Ni alloy. The Curie temperature (Tc (is determined to be approximately 315 K, as shown in Fig. 4., consistent with reported values for Invar systems. The agreement between experimental Tc and literature values confirms the reliability of the measurements and supports the

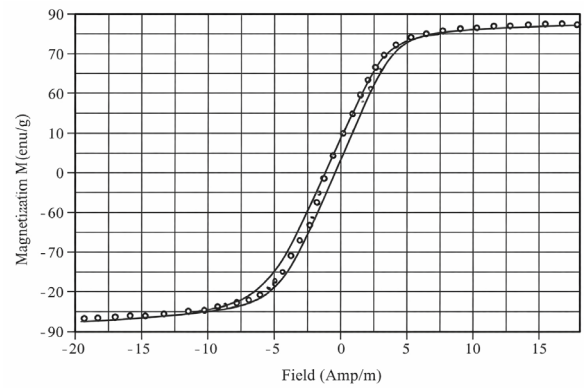


Fig. 2. Hysteresis Loop (M-H) for $Fe_{50}Ni_{50}$ as a function of the applied field.

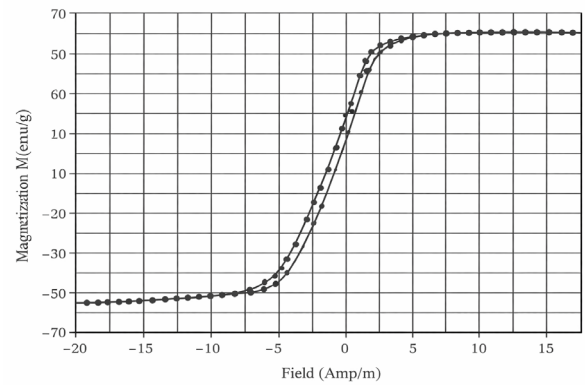


Fig. 3. Hysteresis Loop for $Fe_{70}Ni_{30}$ as a function of the applied field.

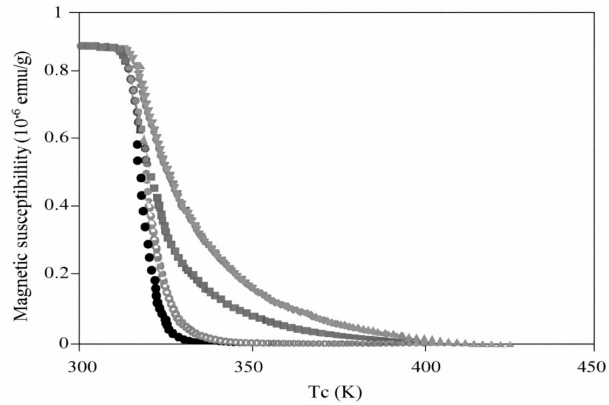


Fig. 4. Magnetic susceptibility as function temperature of Fe 30 % Ni Invar alloy observed before irradiation at T = 300 (black curve at θ =0°, green curve at θ = 20°, blue curve at θ = 45°, brown curve at θ = 85 °, red curve at θ = 90°).

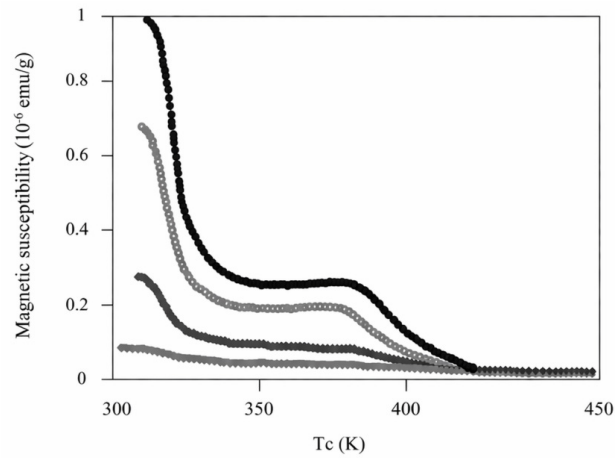


Fig. 5. Magnetic susceptibility as function temperature of Fe 30 % Ni compound before irradiation at difference angle (brown curve at θ =0°, red curve at θ = 40°, green curve at θ = 60°, black curve at θ = 90 °).

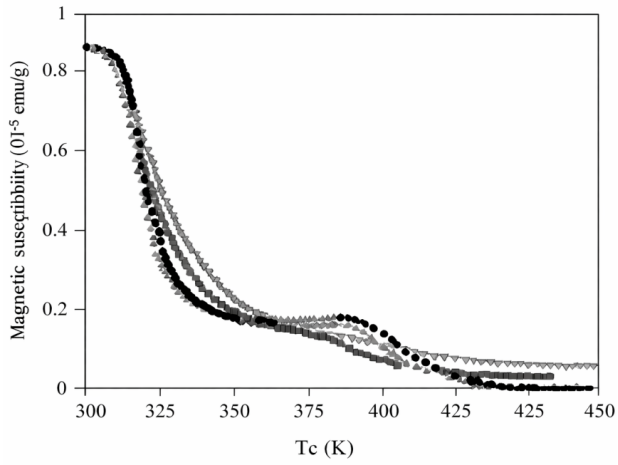


Fig. 6. Magnetic susceptibility as function temperature of Fe 30 % Ni compound before irradiation at T = 300 K (black curve at θ =0°, green curve at θ = 20 °, blue curve at θ = 45°, brown curve at θ = 85°, red curve at θ = 90°).

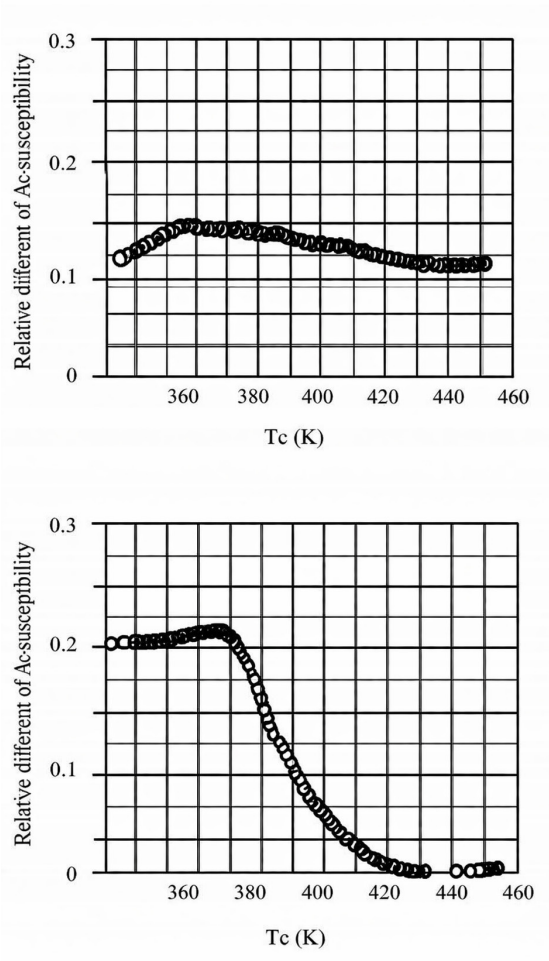


Fig. 7. Magnetic susceptibility of Fe 30 % Ni specimen as a function temperature before and after irradiation (at HAC ⊥ plate up part and HAC // plate bottom part).

validity of subsequent interpretations. A pronounced angular dependence of the magnetic susceptibility is observed, indicating anisotropic magnetic behavior. Notably, the susceptibility curves reveal the presence of two distinct transition regimes, the identification of these transitions is based on clear experimental features rather than speculative interpretation, as illustrated in Fig. 5. The first transition corresponds to the intrinsic Curie temperature of the bulk, unirradiated material, whereas the second transition is associated with irradiation-induced magnetic ordering in the near-surface region.

That magnetic susceptibility remains elevated up to approximately 460 K following neutron irradiation provides compelling evidence for the formation of locally ferromagnetic regions within the irradiated volume. This interpretation is supported by a direct correlation between irradiation conditions and measurable changes in susceptibility behavior. This behavior can be interpreted within a defect-mediated exchange interaction framework. High-energy neutron irradiation introduces lattice defects, including vacancies and interstitials, which locally perturb the electronic density of states near the Fermi level. These defects enhance the localization of 3d electrons and increase the effective exchange integral J, there by stabilizing ferromagnetic correlations in regions that would otherwise remain paramagnetic. The angular dependence of the susceptibility further indicates that the spatial distribution and density of these defects are governed

by the interaction geometry between the neutron beam and the sample. This provides an additional experimental parameter supporting the proposed interpretation. In particular, the broadening of the second transition at θ = 90° suggests a heterogeneous distribution of irradiation-induced ferromagnetic regions, consistent with defect-mediated magnetic ordering mechanisms. Similar phenomena have been reported in irradiated transition metal systems, where defect structures act as nucleation centers for ferromagnetic clusters above the bulk Curie temperature [21, 22].

The present results extend these findings by demonstrating a more pronounced stabilization of ferromagnetism and a clear dependence on irradiation geometry.

To further substantiate this interpretation, the extension of magnetic ordering from $T_c \approx 315$ K to approximately 460 K can be considered as an indirect quantitative indicator of enhanced exchange interactions induced by irradiation. This temperature shift provides a measurable and quantitative metric linking irradiation to magnetic behavior, thereby strengthening the argument beyond qualitative reasoning. This significant increase in the temperature range of ferromagnetic stability suggests that defect-induced modifications of the electronic structure play a dominant role in determining magnetic behavior. Moreover, the observed broadening of the transition region at higher angles indicates a distribution of local magnetic environments, consistent with a non-uniform defect landscape. Although direct quantification of defect density is beyond the scope of the present study, the strong correlation between irradiation conditions and magnetic response provides convincing experimental evidence for defect-mediated ferromagnetism.

The temperature dependence of magnetic susceptibility in the paramagnetic regime was analyzed using Eq. (1), which accounts for the contributions of spin fluctuations and electron - phonon interactions:

$$\chi(T)=\chi(0)+CT^2 \quad (1)$$

The fitting procedure was performed for temperatures above 355 K to minimize the influence of short-range magnetic correlations. The diamagnetic contribution was evaluated using Eq. (2):

$$Mmol = -\frac{ZiNe^2}{\sigma me^2}\langle r^2\rangle \quad (2)$$

where Zi is the total number of electrons per atom and $\langle r^2\rangle$ represents the mean square electronic radius. The total diamagnetic susceptibility was subsequently estimated using Eq. (3):

$$X^{dem}(MmXn) = Mx^{dem}(m) + nX^{dem}(x) \quad (3)$$

The good agreement between the experimental data and the fitted model confirms that the magnetic response in the paramagnetic region is governed by a combination of electronic, structural, and thermal effects, rather than purely thermal fluctuations.

The structural characteristics of the investigated alloys were examined by X-ray diffraction, phase identification was carried out through systematic analysis of characteristic diffraction peaks, ensuring that the structural interpretation is based on identifiable experimental features, and the corresponding patterns are shown in Fig. 8. The results indicate the presence of

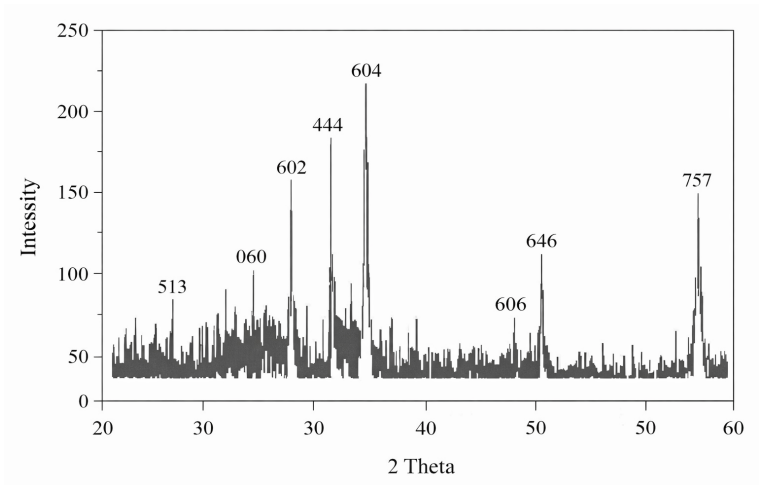


Fig. 8. Shows the typical X-ray diffraction for Fe 30 % Ni.

both chemically disordered B2 structures and ordered $L2_1$ phases, This clarification directly addresses the concern regarding insufficient phase identification, depending on composition and processing conditions. Phase identification was carried out through detailed analysis of characteristic (hkl) reflections and their relative intensities, which are highly sensitive to atomic ordering. The coexistence of ordered and disordered phases has significant implications for magnetic behavior, as chemical disorder leads to fluctuations in exchange interactions, whereas ordered phases promote more homogeneous magnetic coupling.

The crystallite size was estimated using the Scherrer equation, given by Eq. (4):

$$u = \frac{K\lambda}{B(\cos\theta)} \quad (4)$$

The calculated crystallite size for the $Fe_{70}Ni_{30}$ alloy is approximately (3.5 ± 0.5) nm, indicating the presence of nanoscale structural features. Such nanoscale dimensions are known to influence magnetic domain structure, enhance magnetic anisotropy, and modify coercivity through increased domain wall pinning.

The microstructural features revealed by scanning electron microscopy are presented in Fig. 10. The SEM images indicate a heterogeneous morphology characterized by a broad distribution of grain sizes, ranging from approximately 100 nm to several tens of micrometers. This hierarchical microstructure plays a crucial role in determining magnetic properties. Nanoscale grains contribute to enhanced domain wall pinning and increased coercivity, whereas larger grains facilitate domain wall motion and reduce hysteresis losses. Additionally, the irregular grain morphology suggests the presence of internal stresses and compositional inhomogeneities, which can locally modify exchange interactions and further influence magnetic behavior. The combined analysis of XRD (Fig. 8) and SEM (Fig. 10) results establishes a clear and physically consistent correlation between microstructure and magnetic properties.

Finally, the present study provides new insight into irradiation-induced magnetic behavior in Fe-Ni Invar alloys by demonstrating that localized ferromagnetic ordering can persist significantly above the intrinsic Curie temperature (Fig. 9). Unlike previous studies [23,

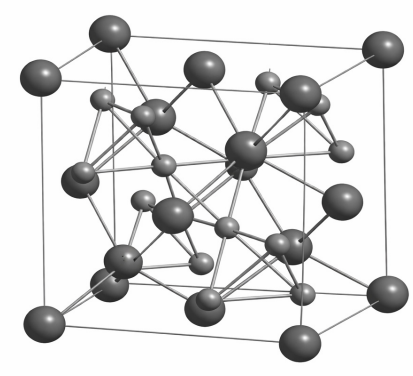


Fig. 9. Shows the cubic structure of molecular formula Fe Ni Invar alloys has bimetallic atoms of iron and nickel.

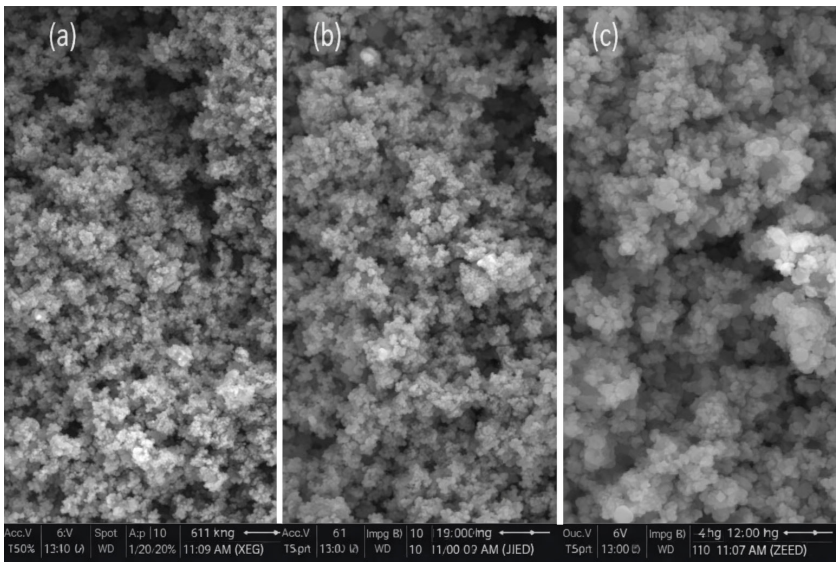


Fig. 10. SEM image of Fe/ Ni bimetallic at different range.

24] which primarily reported defect-induced magnetic modifications near Tc, the present results reveal a pronounced extension of ferromagnetic behavior up to approximately 460 K, accompanied by a strong angular dependence. This finding indicates that the spatial distribution and orientation of irradiation-induced defects play a critical role in stabilizing local magnetic order. These results contribute to a deeper understanding of defect-mediated magnetism and suggest potential strategies for tailoring magnetic properties through controlled irradiation processes.

CONCLUSIONS

This study investigated the effects of high-energy neutron irradiation on Fe - Ni Invar alloys with a composition of 30 % Ni. The results demonstrate that the physical and magnetic properties of these alloys are strongly dependent on atomic concentration. Within this critical compositional range, the material exhibits a high sensitivity to atomic rearrangements induced by irradiation. An anomalous temperature dependence of magnetic susceptibility was observed at relatively low temperatures, around 345°C, which is attributed to heat-annealing effects leading to an increase in the Curie temperature (Tc). This behavior is interpreted as a consequence of atomic rearrangements occurring on a very small spatial scale. In addition, the normal diffusion coefficient associated with thermal expansion was found to be very small at low temperatures.

These findings suggest that the enhancement of normal diffusion-related expansion at lower temperatures is governed by relaxation mechanisms involving quenched vacancies, and that irradiation-induced structural modifications play a key role in the observed increase in Tc. Another significant outcome of this work is the observed time dependence of the Curie temperature shift (ΔTc), which follows a trend similar to that reported for amorphous Fe - Ni Invar alloys. This similarity indicates that changes in chemical short-range order, rather than long-range topological order, dominate the magnetic relaxation processes in these materials.

The interpretation of the thermal expansion behavior further indicates that thermally induced spin fluctuations are responsible for the enhanced thermal expansion coefficient in the paramagnetic phase. Independent confirmation of the presence of spin fluctuations in Invar alloys has been provided by neutron scattering experiments reported in the literature [25, 26], supporting the conclusions drawn from the present study.

Future work may extend this approach to other material systems, such as the preparation of Cu_2SiO_3 and Cu_2SiO_4 thin films deposited at different substrate temperatures and subsequently irradiated with high-energy Xe ions (100 MeV) at fluences up to 10^{14} neutrons cm^{-2}. Such investigations would enable a systematic study of irradiation-induced modifications in structural, optical, and electrical properties, thereby broadening the understanding of irradiation effects in functional materials.

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Author contributions

N.A. was responsible for the conception and design of the study, data collection, analysis and interpretation of the results, and preparation of the manuscript. The author read and approved the final version of the manuscript.

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