Development of SQUID Based System for Non-Destructive Evaluation

EXECUTIVE SUMMARY

Superconducting Quantum Interference Devices (SQUID), which are the most sensitive detectors of magnetic flux signals, have been developed at IGCAR using advanced micro-fabrication techniques. A novel SQUID based set-up for non-destructive evaluation based on a precision X-Y-θ scanner has been designed and developed. The set-up has been used for the characterization of subsurface defects using low frequency eddy current technique and for monitoring the progressive transformation of magnetic δ ferrite into nonmagnetic phases in a SS316 L(N) weldment specimen subjected to low cycle fatigue loading at 600°C. The results highlight the potential of SQUID based non-destructive evaluation as an emerging new technique.

OUTLINE

SQUID sensors, which are the most sensitive detectors of magnetic flux available today with a sensitivity of ~10fT/√Hz, have been developed at IGCAR through a sustained research and development program which is unique in the national context. To harness the high sensitivity of the SQUID sensors for nondestructive evaluation (NDE), a SQUID based set-up for NDE has been designed and developed with a capability to perform characterization of samples in both the low frequency eddy current testing mode and the remnant magnetization measurement mode. Fig. 1 shows a photograph of the SQUID based set-up for NDE, which is currently operational at IGCAR. The set-up incorporates an in-house developed thin film Nb SQUID, Flux Locked Loop electronics, a liquid helium cryostat with a low stand-off distance and a precision X-Y-θ scanner.

In the conventional eddy current testing, the depth of defect detection is limited by the skin depth of the material under investigation. In a SQUID based set-up, low frequency sensitivity of the SQUID sensor and the use of superconducting pick-up loop make it possible to detect even subsurface defects. A double-D excitation coil is used to excite eddy currents in the specimen at room temperature at relatively low frequencies ~200Hz, while a first order gradiometer made of superconducting wire is used as a pick-up loop inductively coupled to the SQUID. Changes in the induced eddy current flow associated with the presence of a defect manifest as magnetic anomalies detected by the SQUID. The X-Y-θ scanner used for scanning the specimen under a stationary liquid helium cryostat has a positional resolution of 25μm, a stroke length of 300 mm along both X and Y axes, a scanning speed of 1-50 mm/sec and is equipped with a specially designed nonmagnetic and nonmetallic sample stage. Fig.2(a) shows the magnetic anomalies associated with the defects representing a localized loss of thickness present on the bottom surface of a 10 mm thick aluminum plate. Potential of the system for the detection of subsurface defects is evident from the data.

Fatigue damage limits the life of a high temperature component, especially in the welded region. Presence of an optimum amount of magnetic δ-ferrite in the austenitic weld-metal is desirable to prevent hot cracking in the weldment. However, the magnetic δ ferrite structure is highly unstable during high temperature service and transforms to nonmagnetic carbides and brittle inter-metallic phases (ex. δ-phase). To investigate the potential of the SQUID based NDE set-up in tracking such transformations in a stainless steel 316L(N) weldment, low cycle fatigue tests were conducted at a strain amplitude of ±0.6% using an Instron servo hydraulic fatigue testing machine under total axial strain control mode at 600°C. As the sample was scanned under the cryostat, SQUID output revealed a characteristic magnetic anomaly when the center of the gauge length of the sample passed under the pick-up loop indicating the presence of a magnetic phase at the location of the weld. As shown in Fig.2(b), the amplitude of the magnetic anomaly was only 0.05Φ, for the fatigue fractured sample as compared to 1.78 Φ, for the virgin sample. Fig.2(c) and 2(d) show the results of a more detailed study indicating the decrease of δ-ferrite content as a function of number of fatigue cycles. Capability of the system in capturing such phase transformation augurs well for further development of the technique.
Nondestructive evaluation refers to techniques that allow characterization of functionality of a material or component without compromising its continued usability. Common techniques for nondestructive evaluation are ultrasonics, eddy currents, magnetic flux leakage, acoustic emission etc. SQUID based NDE is a new emerging technique, which harnesses the high sensitivity of the SQUID for detection of magnetic signals in the context of non-destructive evaluation.

Eddy currents are induced in conducting specimens when subjected to alternating magnetic fields. The amplitude of the induced eddy currents decays exponentially from the top surface and the decay is characterized by a skin depth. At high frequencies, induced eddy currents are confined to the surface regions and do not sample the deep subsurface defects. If the frequency is lowered to increase the depth of penetration, the signal-to-noise ratio suffers since the voltage induced in the pick-up loop is proportional to the rate of change of magnetic flux. SQUID based NDE overcomes these limitations imposed by the skin depth (1) by use of superconducting pick-up loops, which sense the magnetic field $B$ directly rather than its time derivative $dB/dt$ and (2) by use of SQUID sensors whose sensitivity is independent of frequency down to ~1Hz.

Ferromagnetic phases exhibit a remnant magnetization even after the magnetizing field is removed. High sensitivity of the SQUID allows one to detect the presence of even a small volume fraction of a ferromagnetic phase dispersed in a matrix and study the transformation of such magnetic phases to nonmagnetic ones.

Numerical computations were performed to investigate the eddy current distribution excited by the double-D coil in the 10mm thick Al plate carrying a defect on its bottom surface representing a localized loss of thickness. Computations were performed for a set of 20 different locations of the defect relative to the common axis of the pick-up loop and the excitation coil. For each location, flux density $B$ was calculated at a grid of points in two parallel planes coincident with the planes in which the lower and upper loops of the gradiometer were located. Flux density was numerically integrated over the area of each of the two loops to obtain flux $\Phi$ and $\Phi$ threading through the two loops of the gradiometer; output voltage of the SQUID is proportional to $\Phi-\Phi_u$. Variation of this quantity with the scan coordinate was found to be in qualitative agreement with experimental results obtained using the SQUID based NDE set-up.

The work represents culmination of an activity comprising of fabrication of SQUID sensors, development of control electronics and the design and development of SQUID based measuring systems. In addition to the SQUID based NDE set-up described here, several other SQUID based measuring systems such as SQUID magnetometer has also been developed. A SQUID based Magnetoencephalography (MEG) system for non-invasive studies of human brain is currently being developed under a DST sponsored project at IGCAR to measure the extremely small magnetic fields associated with neural currents.


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