A SQUID NDE system for the investigation of pinch welds

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Abstract. HTS SQUID NDE systems attempt to achieve both high spatial resolution and high signal sensitivity, though often the more important parameter is determined by the sample of interest. SQUID microscopes offer micron-sized resolution by either bringing the sample into very close contact with a small SQUID sensor or by using a “flux guide” that is located in the tail of the cryostat. Conventional SQUID NDE systems typically have a larger sensor cooled by a liquid cryogen (or possibly a cryocooler) and place more import on signal resolution. Our system is a hybrid of the above ideas, developed specifically to permit the characterisation of small, irregular-shaped stainless steel samples containing pinch welds. We have investigated using a ferromagnetic flux guide with our system, but for convenience have simply attached it to the tail of the cryostat 4 mm below a washer SQUID magnetometer. To increase the signal resolution we have chosen to employ local electromagnetic shielding around the measurement system. We detail the characteristics of the system and present experimental NDE data as individual time series traces of the SQUID output for a set of samples that were fabricated using a broad range of weld parameters.

1. Introduction

SQUID microscopes have been increasingly used in basic physics [1], biological and geological [2] and NDE [3] applications over the past decade, with several commercial systems now available incorporating HTS SQUIDs. The main feature of a SQUID microscope is the ability to bring the sample into close proximity to the sensor and thus achieve a high spatial resolution. This typically involves either having the sample at the same temperature as the SQUID or having the SQUID located in the cryostat vacuum space and separated from the sample by a thin («1 mm) window. In addition, by locating a ferromagnetic “flux guide” between the sample and the SQUID it is possible to achieve «100 μm resolution [4] for dc signals.

Our interest in pinch welds is related to a specific Los Alamos requirement that this type of weld (in 304L stainless steel) should exhibit zero failures while in service. We have been involved in a collaborative project that involves acoustic emission techniques for monitoring the in-process parameters, ultrasound and SQUID-based nondestructive evaluation (NDE) for characterisation of weld quality and finally, destructive metallographic analyses of the welds to ascertain the true weld quality. The end use of the pinch welds is to seal off stem tubes in high-pressure gas transfer systems.

We have evaluated 17 pinch welds and several dummy samples as part of this study. The results of the SQUID-based evaluation are discussed with reference to the accompanying acoustic emission and ultrasound data and also the results of destructive metallographic analyses of some of the welds.
2. Pinch Welding

Pinch welding is a resistance welding technique that is often used to seal small diameter stainless steel tubes. The weld is achieved by passing a large current (typically in the few kA range) through electrodes (C and D in figure 1a) located on either side of the tube. Prior to the application of the current, a large force (order of 1000 lbs) is applied to the tube by the electrodes and also by the confining dies (A and B in figure 1a). Due to the electrical resistance of the stainless steel tube, the applied current generates heat and it is the combination of this elevated temperature and the applied force that produces the weld as the tube collapses. A metallurgical bond is created at the surfaces that were initially the inside diameter of the tube. As with most welding techniques, careful consideration of the welding parameters such as current (the input current has a complicated, quasi-sinusoidal profile) and force is required to achieve a weld of high quality.

3. The LANL SQUID system

The Los Alamos SQUID system has operated in the past in the open laboratory with no electromagnetic shielding. The SQUID sensors are small, autonomous washer-style magnetometers with a transfer coefficient of ~10^5 nT/Φ₀, aligned horizontally (i.e., to measure the B_z component of the field). The SQUIDs are located in the cryogen, but the thin cryostat tail means that they are at most 4 mm from room temperature. The intrinsic white noise of the SQUIDs is in the range 1-10 pT/√Hz.

3.1. Ferromagnetic flux guides

In most systems where flux guides have been used, the guide has penetrated the tail of the cryostat or the thin window. Typically the guide will be several mm long, have sub-mm diameter and have a tip radius of a few μm. The tip-sample distance is usually less than 100 μm, and the guide-SQUID distance is of the same order. In some instances, the end of the flux guide has even penetrated the substrate [4]. High permeability materials such as Permalloy™ (μ>50,000) are most commonly used.

Of interest to us was whether simply by adding a high-permeability foil needle (length ~5 mm, width ~2 mm) to the tail of our cryostat we would improve our spatial resolution (see figure 2a, b) for these particular samples. Figure 2c clearly shows that the naive approach does not work. Not only has the peak signal decreased, but also the spatial resolution (in terms of the full width half maximum) has reduced by around 10%. It was thus decided not to employ flux guides during this study, given the limitations on equipment modifications (i.e. drilling a hole through the tail of the cryostat).

Figure 1. (a) Schematic of the pinch welding process. A & B are the confining dies while C & D are the contact electrodes. A photograph of one of the pinch welds evaluated as part of this study is shown in (b) and (c) with horizontal and vertical weld orientations respectively.
3.2. Electromagnetic (e-m) shielding

Historically, most HTS SQUID NDE work is performed in an unshielded environment in an attempt to maintain “real-world” conditions. However, we have chosen to use a single layer mumetal shield (diameter = 22”, length 40”) around the cryostat and scanning mechanism due to the desire to limit the potential for ambient fields to cause large edge effects (see figure 2(d) for the effect of a magnetic source being moved during another experiment being conducted in the same laboratory). At the location of the SQUID, the dc shielding factor is ~40 dB and the 60 Hz peak is attenuated by ~48 dB. The mumetal shield is placed on a hydraulic lifting table and is moved vertically through 30” into its measurement location prior to each scan. During the motion of the mumetal shield, the SQUID is switched off, and is switched on and reset after a short period of time has elapsed.

4. Experimental Results

We have investigated two sets of samples; for the first set we only measured the dc response. The same parent material was used for all welds and they were scanned using the same parameters (scan speed = 1 mm s⁻¹) with no flux guide. In figure 3(a) we see the different response is dependent on the orientation of the sample, indicating that the weld itself has a signature that is almost dipole-like. In figure 3(c) we see the variation in response for all of the first set of samples. The samples were fabricated using increasing voltage amplitudes (from left to right in figure 3(b)) and from previous studies [5], too little voltage resulted in a cold (bad) weld and too much voltage resulted in excessive melting and was denoted a hot (bad) weld (see figure 3(b)). There is an intermediate range of voltages where optimal welds are fabricated. Apart from the sample labeled “c5” in figure 3(c), there is a definite peak in the data with a fall off as the voltage moves away from the peak. Whether weld quality is directly correlated to SQUID response is the issue here; we are currently in the process of evaluating all the available data for these samples.

Figure 2. Scanning scenarios: (a) with flux guide and (b) with the minimum possible standoff. In (c) the response to the same pinch weld is shown (results obtained in open laboratory). In (d) the effect of the local e-m shielding is shown. In the unshielded case, a nearby magnetic source is moved at a time corresponding to point “A”, while for the shielded case, the corresponding point is “B”.

Figure 3. (a) Variation of SQUID response with weld orientation. In (b) a schematic shows the expected relationship between weld fabrication voltages and weld quality, while in (c) the actual data from the dc response experiments are shown.
The size of these samples is such that a typical wire-wound double-D coil is several times larger than the region of interest and is therefore not entirely suitable for high spatial resolution imaging of the weld region. However it has been suggested that the phase component of the magnetic field gives an insight into the material electrical conductivity [6].

The second set of samples was scanned inside the shield with the phase response recorded for various frequency settings. Figure 4 shows the variation in SQUID response for two specific frequencies (namely 700 Hz and 3150 Hz).

Any agreement between in figure 4(b) masks the fact that the responses do not correlate with any trend expected from the fabrication parameters. There exist in the weld samples three distinct groupings namely cold (11-13), hot (8-10) and optimal (4-7) as well as other subsets. What is evident is that there is no pattern arising between these groupings, and the fact that the dummy samples (18-20) exhibit responses that are indistinguishable from samples 1-5 indicates that this present setup lacks the required sensitivity (spatial resolution) to investigate the samples in terms of material conductivity.

Conclusions and Future Work

The aim of realizing a simple SQUID microscope for operation in a magnetically hostile lab has not been fully realised due to present technical constraints. The investigation of pinch welds needs further research since the sample dimensions make it difficult to use common SQUID NDE techniques. A true high-resolution SQUID microscope may be able to reliably infer information about the material conductivity from the eddy current phase response and hence characterise the weld quality.

Recent work by colleagues at Los Alamos and co-workers [6] has concentrated on the frequency content of acoustic emission signal gathered during the period immediately after the weld cycle has finished. This period, lasting approximately 0.09 seconds, contains valuable information relating to the metallurgical integrity of the weld interface. We will investigate whether there is any correlation between the acoustic emission data and the SQUID-based results. We also intend to compare all the existing data with ultrasound data, but at time of writing, tests on these weld samples using ultrasound techniques have yet to be performed.

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