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Weld Quality Evaluation Using a High Temperature SQUID Array

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Abstract—**This paper presents preliminary data for evaluating weld quality using high temperature SQUIDs. The SQUIDs are integrated into an instrument known as the SQUID Array Microscope, or SAMi. The array consists of 11 SQUIDs evenly distributed over an 8.25 mm baseline. Welds are detected using SAMi by using an on board coil to induce eddy currents in a conducting sample and measuring the resulting magnetic fields. The concept is that the induced magnetic fields will differ in parts of varying weld quality.**

The data presented here was collected from three stainless steel parts using SAMi. Each part was either solid, included a good weld, or included a bad weld. The induced magnetic field's magnitude and phase relative to the induction signal were measured. For each sample considered, both the magnitude and phase data were measurably different than the other two samples. These results indicate that it is possible to use SAMi to evaluate weld quality.

I. The Array, Dewar and Weld Sample Holder

A. SQUID Array

The SQUID array consists of 11 DC HTS SQUID magnetometers arranged linearly with uniform spacing along a 7.5 mm baseline. Each magnetometer has a 105 nT/Φ_0 field sensitivity and a noise level of 20 $\mu\Phi_0/\sqrt{Hz}$ at 1 kHz with DC bias [?].

B. Dewar and induction coil

Fundamental to the weld evaluation using SAMi problem is inducing eddy currents in the sample. This is accomplished by using an induction coil as shown in Fig. 1. It should be noted that the induction coil is in the liquid Nitrogen bath. The induction field is decoupled from the SQUIDs by orienting the area of the SQUID's loop so that it is orthogonal to the ϕ-component of the magnetic field of the induction coil. Since the field of the induction coil can be approximated by that of an infinite wire, which only has a ϕ-component of magnetic field, and the SQUID is only sensitive to fields normal to it's loop area, direct coupling of the induction field to the SQUID is minimized.

C. Parts Holder

The welds studied were made in short (≈100 mm) lengths of 304L stainless steel. These parts needed to be mounted in such a way that they could be both rotated and translated underneath the dewar. The apparatus shown in Fig. 2 was designed for this application. The translation is actuated with a stepper motor with resolution greater than 0.5 mm. However, the rotation is hand actuated and can only be controlled reliably in 10° steps. The orientation of the parts holder under the dewar is such that the induction coil is parallel to the diameter of the weld sample under consideration. Data is acquired by rastering the part along its long axis under the dewar. The part is rotated 10° between each scan.

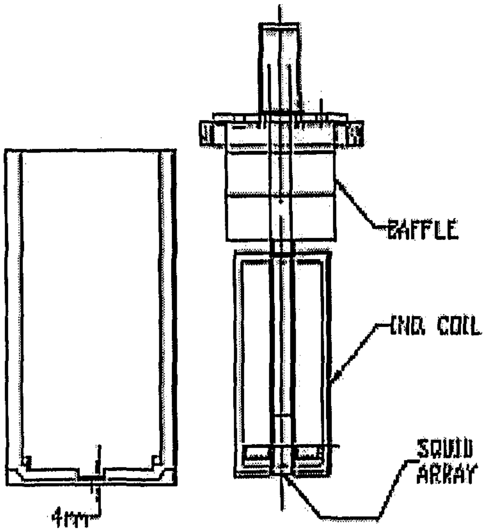

Fig. 1. Schematic illustration of SAMi dewar

II. Weld Evaluation

A. Weld Types

Data for two types of welds are presented in this paper. The first is the *upset forge weld*. In the upset forge weld, the parts being welded are statically pressed together and a large (thousands of amps) electric current is flowed over the joint. Energy deposition in the joint by the current causes the parts to be welded. The second type of weld considered is the *inertial forge weld*. In the inertial forge weld, one of the parts is held static while the other part is spun at high velocity. The two parts are then brought together and the energy dissipation from stopping the spinning part causes the parts to weld.

B. Grain Growth

The key to performing NDE of welds with SAMi is metallurgical grain growth across the weld interface. Figures Fig. 3 and Fig. 4 show grain growth across a weld boundary. Fig. 3 shows grain growth for a good weld. It can be seen that the grains across the weld (which is in the center of the frame, running

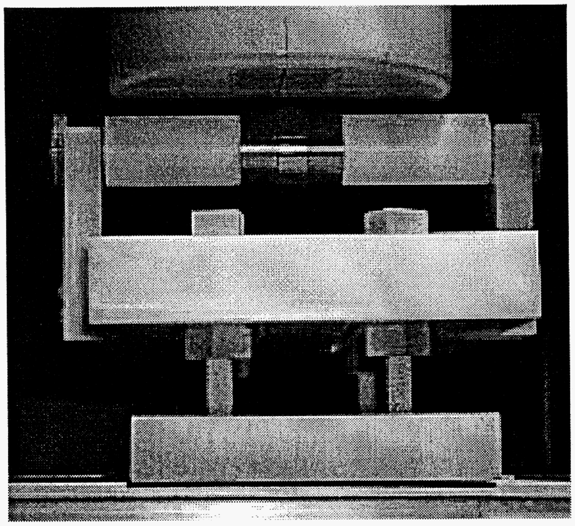

Fig. 2. Weld sample holder.

from top to bottom) are not distinguishable from the grains of the base material. In the good weld, there is no discontinuity in the conductor and a current will flow across the weld interface with no perturbation in the included magnetic field due to the weld. Fig. 4 shows the grain growth at the weld interface of a bad weld. It is our hypothesis that a current flowing perpendicular to the weld interface would forced to change direction at such an interface. The change in direction causes a perturbation in the induced magnetic field relative to a weld with good grain growth. SAMi is being developed to measure these perturbations.

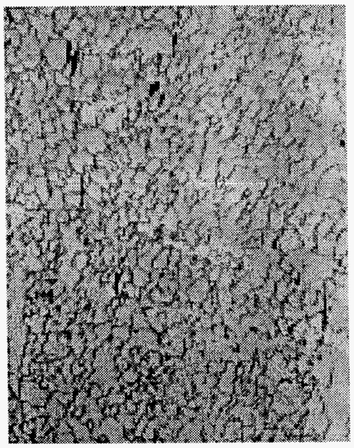

Fig. 3. Grains at the weld interface in a "good" weld.

III. Data

A. Perturbation Tests

As an initial experiment to test the feasibility of using SAMi to detect perturbations in the induced magnetic field due to physical anomalies in the conductor, a test piece was manufactured. The data shown in Fig. 5 is for a 100 mm by 100 mm, 100 μm thick Cu film with the "P-21" etched into the surface.

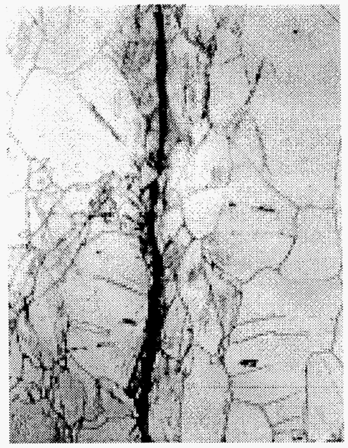

Fig. 4. Grains at the weld interface in a "bad" weld.

The figure clearly indicates that SAMi can detect perturbations in the magnetic field due to the etch marks. The "P-21" in the data appears to be skewed because the sample holder with the copper plate was bumped while the data was being acquired and changed orientation relative to the SQUID array. The problem was noticed and corrected before the data acquisition was completed.

Fig. 5. Magnetic field data collected with SAMi for an etched Cu plate

B. Upset Forge Welds

The samples shown in Fig. 6 were welded using the upset forge technique[1]. The weld is circumferential and is located approximately in the center of the shoulder. Fig. 7 shows the magnitude and phase of the induced magnetic field for an unwelded control part. The horizontal lines on the part mark the ends of the part, the edges of shoulder, and the center line. Fig. 8 shows the magnitude data for a weld sample which were designated as "good" and "bad" and Fig. 9 shows phase data for the same

[1] All samples were provided by Allied Signal Kansas City Plant

samples. The quotation marks are to emphasize that the parts were merely labeled as good and bad and the labels do not necessarily indicate the true quality of the part. Observation of the grain structure in Fig. 3 shows that in a good weld, the grains at the weld interface are homogeneous with those of the base material. From this homogeneity in the grain structure it is reasonable to expect that the induced magnetic field of a part with a good weld would not be substantially different than that of a solid part with no weld. However, inspection of Figs. 7–9 indicate that the case is exactly the opposite. This result can be attributed to one of the fundamental paradoxes of weld quality evaluation in its current state of the art – the true quality of a weld cannot be know until it is evaluated, and evaluating the weld destroys the part.

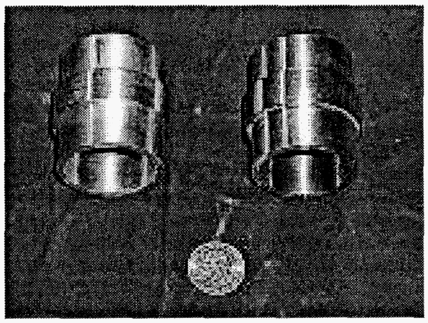

Fig. 6. Upset forge weld sample.

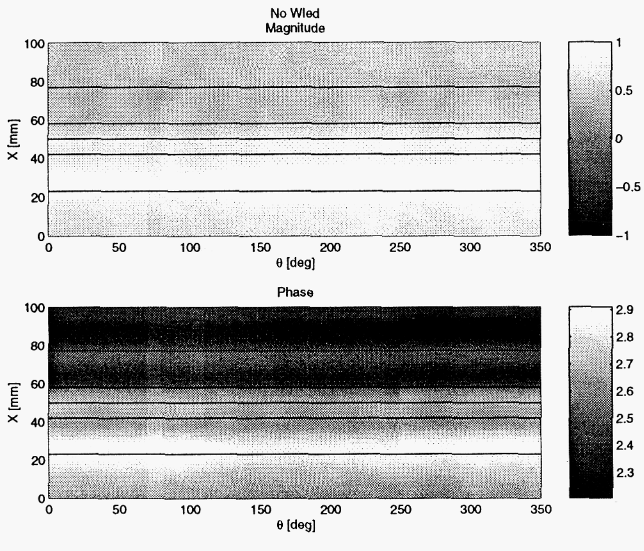

Fig. 7. Magnitude and phase of induced magnetic field for an unwelded control part.

C. *Inertial Forge Welds*

At the time this article was written, initial data was being collected on inertial forge weld samples. The inertial forge weld samples are similar to to the upset forge weld samples. The difference is that the inertial forge weld samples do not have shoulders. The data analysis software was enhanced over that

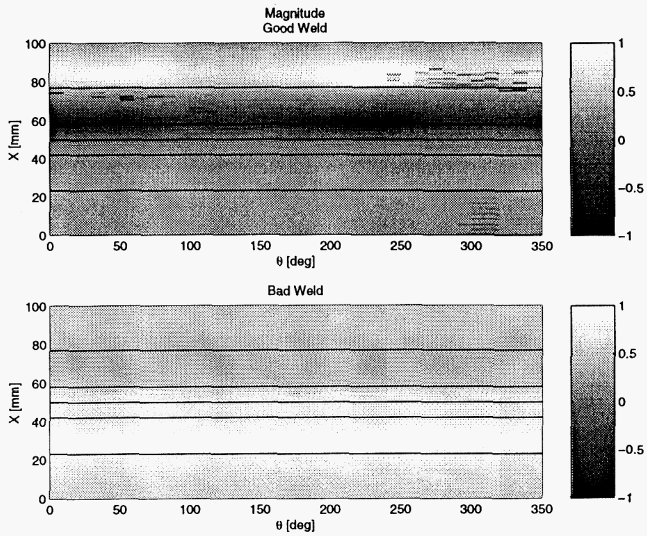

Fig. 8. Comparison of induced magnetic field magnitude for "good" and "bad" upset forge welds.

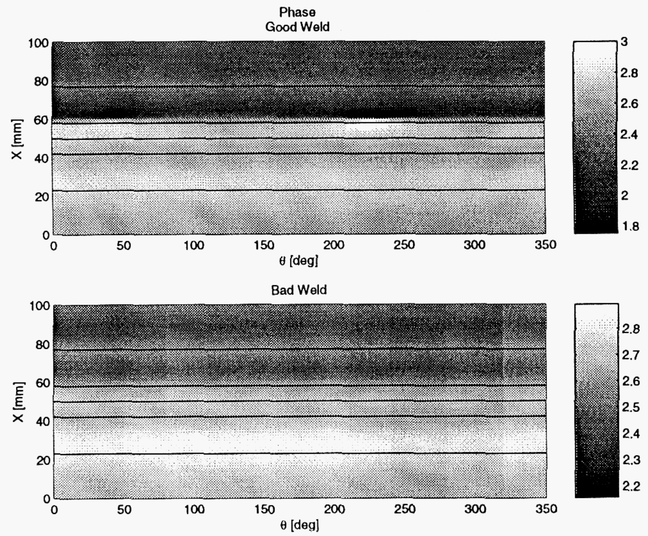

Fig. 9. Comparison of induced magnetic field phase for "good" and "bad" upset forge welds

used to analyze the upset forge weld data. It is difficult using the pseudo color plot in the previous section to relate features in the data to physical locations on the sample. The software used for the inertial forge weld data analysis is a a 3-D visualization tool which maps the data to the surface a a virtual cylinder so that spatial relationships can be more readily visualized. Fig. 10 shows a sample display of the magnitude of the induced magnetic field.

IV. Discussion

The data presented for the upset forge weld clearly indicates that there are measurable differences in magnetic field perturbation for "good" and "bad" welds. The differences are manifest in both magnitude and phase of the induced magnetic fields as

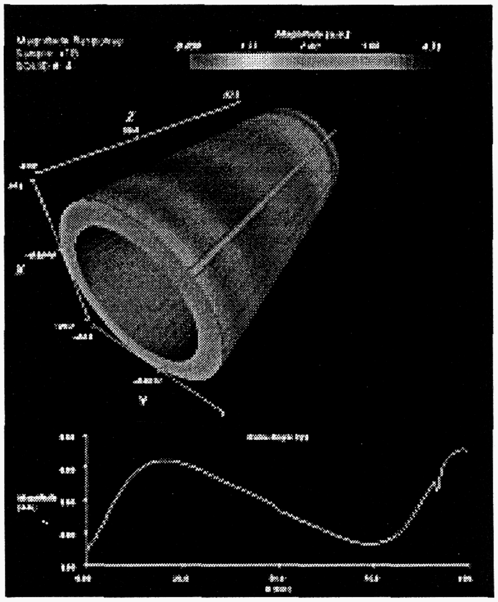

Fig. 10. 3-D visualization of the magnitude of the induced field for a inertial forge weld part.

measured with SAMi. At the time this paper was written metalography data was not available for correlation with the SAMi data.

The data for the inertial forge welds is in such a preliminary state that no definite conclusions can be drawn from it. However, it is proving useful in the development of high quality visualization software. The upset forge weld data has demonstrated that

Since the data indicates that there are measurable differences between "good" and "bad" welds, the samples have been sent to a metallurgist to have grain growth metalography performed. If the metalography indicates that SAMi has accurately detected perturbations due to weld quality, work will continue to develop better part actuation for higher resolution data, 3-D depth data using the white noise induction technique described in [?], and weld quality classification using neural networks or other pattern classifying techniques.

References

[1] Michelle A. Espy, Andrei N. Matlashov, John C. Mosher, and Jr. Robert H. Kraus. Non-destructive evaluation with a linear array of hts squids. *IEEE Transactions on Applied Superconductivity*, 11(1):1303–1306, March 2001.