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[1]*Abstract*—**The 60 T long pulse magnet operated by the U. S. National High Magnetic Field Laboratory at Los Alamos National Laboratory, Los Alamos, New Mexico failed catastrophically on July 28, 2000. The failure was investigated and the cause was determined to be unusually low toughness in the nitrogen strengthened manganese stainless steel (Nitronic-40™) reinforcing material. The source of the reduced toughness condition was a sigma phase conversion in the microstructure. The magnet failure, failure investigation and results of the investigation are described. Plans for the construction of the successor magnet, the 60 tesla long pulse Mark II, are described.**

Index Terms—**Failure investigation, high field, Nitronic-40™, pulsed magnet, sigma phase.**

I. INTRODUCTION

THE 60 tesla long pulse (60 T LP) magnet operated by the National High Magnetic Field Laboratory at Los Alamos National Laboratory was in use for 15 months before failing on July 28, 2000 [1],[2]. The failure occurred without warning and significantly before the expected design life of 10,000 full field pulses. The magnet operated well and as expected. A total of 914 pulses were made; 401 of these were full field (57.5 T or higher) pulses. It produced unique high field long pulse and controlled pulse profiles for researchers. Data were collected for over 25 refereed papers. Among these articles are six Physical Review B papers, three Physical Review B Rapid Communications, two Physical Review Letters, and an article in Nature. The Nature article presents specific heat measurements showing the collapse of the correlation energy gap above 40T in a Kondo insulator. These are the first specific heat measurements above 35T and the first ever taken in a pulsed magnet. Fig. 1 is a photograph of the 60 T LP magnet system installed in its pit.

II. THE MAGNET FAILURE

The magnet failed at peak field on the first pulse of the day. The power supplies and all control systems operated correctly and as expected during this pulse. There were no observed anomalies prior to the failure, and routine magnet inductance and resistance measurements made prior to the pulse produced normal values. Records of the power supply currents and voltages indicate that the failure likely began in the middle coil group (coils six and seven). However there are also indications that the failure could have initiated in the innermost group of coils (coils one through five). The failure was rapid and completely destroyed the magnet, its dewar and adjacent busbar and other magnet utilities. The failure engulfed the entire magnet within about 5 ms. Connections to the power supply were lost within an estimated 13 ms. It is also estimated that some of the individual coils of the magnet failed within 100 to 200 microseconds of being overloaded. Based on magnet failure simulations, the power levels experienced during magnet failure were estimated to be between 8 and 80 GW. The rapid progression of the failure precluded any mitigation by the power supply or the protection system.

There was minor damage to the magnet pit which housed the magnet and no significant damage to the nearby power supply. No persons were injured as the facility was always evacuated prior to a magnet pulse. Magnet design coupled with the nature of the failure produced a two lobed debris pattern principally directed in an outward radial direction from the magnet horizontal mid-plane. There were also indications that the failure produced a brief but significant fireball which scorched magnet pit walls and an adjacent interior facility wall. The magnet pit retained 98.5% of the magnet debris by weight. Photographs of the magnet system taken shortly after the failure are available upon request for the purposes of analyzing safety procedures required for safe operation of such a large pulsed magnet system.

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III. INVESTIGATION OF THE FAILURE

The catastrophic nature of the failure in the context of normal power supply operation indicated a complete structural failure within the magnet. An investigation of the failure was initiated. This effort included the careful recovery, documentation and inspection of the magnet debris.

The smaller innermost coils of the magnet (one through four) were found together, near a corner of the pit. They were observed to have a single, continuous longitudinal rupture through the conductors and external reinforcing shells but were otherwise quite intact.

Coils in the middle section of the magnet (five through seven) were severely damaged. The external reinforcing shells of coils five through seven were shattered into dozens of mostly tabular fragments and flung about the pit and in some cases far from the pit. The majority of the coil five conductors were found intact as individual round turns with a single ductile rupture. The conductors of coils six and seven were extremely distorted, burned, blackened and mostly lacking electrical insulation. These conductors were found as large tangles of material flung into the corners of the pit or as short twisted or straightened fragments scattered about the pit or outside of the pit, all exhibiting evidence of ductile fracture or melting.

The outermost coils (eight and nine) were also severely damaged. The conductors of these two coils all ruptured; typically at one or two locations per turn. In addition, these conductors were significantly distorted from their original solenoid form, however large sections remained insulated and bonded together in the axial direction. The reinforcing shell of coil eight also broke into fragments, one significantly larger than the others. The rolled and welded reinforcing shell of coil nine ruptured along or near its longitudinal seam weld and opened up into a somewhat flattened shape.

The magnet dewar walls also failed along or near weld seams and opened into a flattened shape. The dewar lid and upper flange plus the upper magnet frame remained approximately in place suspended from the magnet busbar and other utilities. Conductor ruptures generally appeared to be of a ductile nature (showing necking) but many were also melted and burned and showed impact damage. The work platform around the magnet and other auxiliary equipment such as a blower, a small dewar, etc. were also destroyed by the failure.

The reinforcing shell fragments, pieces of conductor and sections of winding from each magnet coil were located and sorted. Reinforcing shell fragments were positioned back together. Fig. 2 is a photograph of the shell fragments of coil seven positioned together. It was noted that the ruptures of the reinforcing shells from coils one through four exhibited a full thickness shear lip. Fig. 3 is a photograph of the shear lip of the coil four shell fracture. In contrast, the many fractures of reinforcing shells from coils five through eight all exhibited very small shear lips. The fracture of the reinforcing shell of coil nine had a full thickness shear lip.

All of the fracture surfaces of the reinforcing shells from coils five through eight were carefully photographed and examined. All fractures were found to originate near the horizontal mid-plane of the shells or from a previously produced fracture and extend towards the ends of the shells. No fractures were found to originate from an observable flaw or mechanical shell feature such as a hole or screw thread.

IV. METALLURGICAL INVESTIGATIONS AND STRUCTURAL REANALYSIS

Two-dimensional axi-symmetric finite element stress analyses were repeated and reviewed for all coils. In addition, detailed three-dimensional solid model finite element stress analyses at the shell ends near machined features were completed. Recalculated stresses and strains again indicated levels within those required (based on material test data) to attain the design 10,000 full load cycle life.

Material specimens were taken from fragments of coil shells four through eight. The reinforcing shells of coils one through eight were forged and machined from a high-manganese, high-nitrogen austenitic grade stainless steel known as Nitronic-40™ or 21-6-9.

Chemical analyses, fractography and metallographic examinations were performed. In addition, tensile strength tests and Charpy V-notch impact tests at room temperature and at 77K were performed.

The chemical analyses were nominal and within specification limits (ASTM A314 for type XM-10 UNS S21900), but it was noted that constituents promoting delta ferrite formation, such as molybdenum, were present. Stringers of delta ferrite and the brittle inter-metallic sigma phase were noted in the Nitronic-40 shells. Fig. 4 is a photograph of converted sigma phase stringers as observed in shell material from coil eight. The 77 K Charpy impact tests of material from shells five through seven produced results that were approximately 10% of expected values. For example: in the shell of coil seven, values ranging from 5.4 to 9.5 J were produced instead of the expected 81 J. By contrast, normal Charpy impact energies were produced when material from the shell of coil four was tested.

The production and inspection records of the shells were obtained and reviewed. It was noted that the Nitronic-40™ steel for the shells of coils one through four was processed and heat treated following specification temperature recommendations. The steel for the shells of coils five through eight was processed and heat treated at or near 840 °C which is far from the recommended temperature of 1065 °C. Heat treating Nitronic-40™ at 840 °C converted delta ferrite material to the brittle sigma phase. The presence of delta ferrite and its conversion to brittle sigma phase embrittled the shells of coils five through eight [3]. Fig. 5 shows the rate of delta ferrite conversion to sigma phase[4] as a function of annealing temperature, time and cold work.

The low Charpy V-notch impact test energies correspond to low fracture toughness. The low fracture toughness combined with operational stress levels close to yield lead to a critical crack length of less than a millimeter. This crack length was below the inspection level of the ultrasonic inspection techniques used to qualify the shells for service and is below the practical crack limit for production of large forged, thick wall shells. It should be noted that no tensile tests, or Charpy impact tests, or metallographic characterizations were made to qualify the Nitonic-40™ shell material for service, as it was believed conformance to the ASTM specification would provide adequate processing control.

Magnet operation through more than 400 full load cycles, given the low fracture toughness of some of the coil reinforcing shells, may partially be explained by shells free of large void and crack type flaws (as indicated by the qualifying dye penetrant and ultrasonic test performed on the shells). A balanced coil system (great care was taken during coil manufacture and assembly to ensure the magnetic centers coincide) coupled with alternate load paths through the windings may also partially explain the system operating through 400 cycles with brittle structural reinforcing material.

V. CONCLUSION AND REBUILDING PLANS

The U. S. NHMFL 60 T LP magnet failed due to a catastrophic structural failure likely originating in the middle group of coils. The failure was very rapid. There was insufficient time for the power supplies to mitigate the failure or for dissipative processes to absorb significant amounts of energy, hence a large portion of the system's 90 MJ of stored magnetic energy was available to do destructive work on the magnet during the failure. Damage to the facility was limited by operating the magnet within a pit. Evacuating the facility prior to magnet operation prevented the injury of personnel. The structural failure was caused by the unusually low fracture toughness in the Nitronic-40™ due to the presence of brittle converted sigma phase.

A new 60 T LP magnet system (Mark II) will be built using more carefully specified, manufactured and quality tested Nitronic-40 shell material. Chemistry and processing will be more tightly controlled to minimize the presence of delta ferrite and its conversion to sigma phase. These additional quality assurance measures are also being followed for the Nitronic-40™ being ordered for the US 100 T MS magnet project [5]. There will also be minor improvements in coil insulation systems and shell mechanical features. Conductor for the replacement coil set and a spare coil set has been ordered. This conductor will be approximately 5 to 10 % stronger than what was available at the time of the construction of the original 60 T LP magnet. The 60 T LP magnet pits and the adjacent 100 T MS magnet pit are being provided with additional blast and fragment containment shielding to reduce damage caused by magnet failures that will surely occur when future pulsed magnets reach their fatigue life. The 60 T LP Mark II magnet is scheduled to be built and commissioned by late 2003.

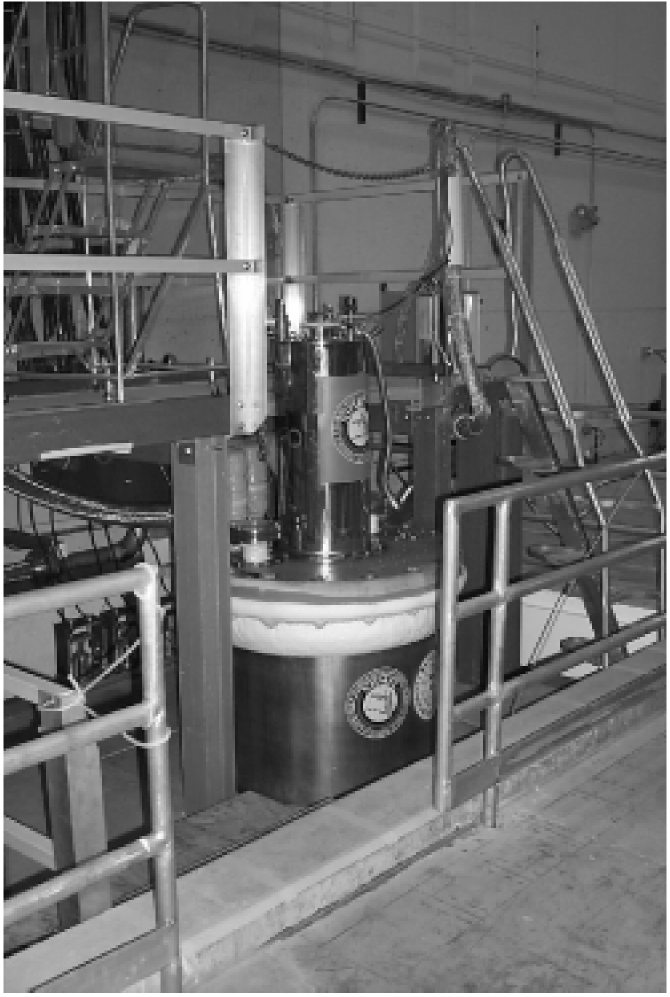

Fig. 1: Photograph of magnet before failure.

Fig. 2: Photograph of reassembled coil 7 shell fragments.

Fig. 3: Photograph of coil 4 fracture shear lip.

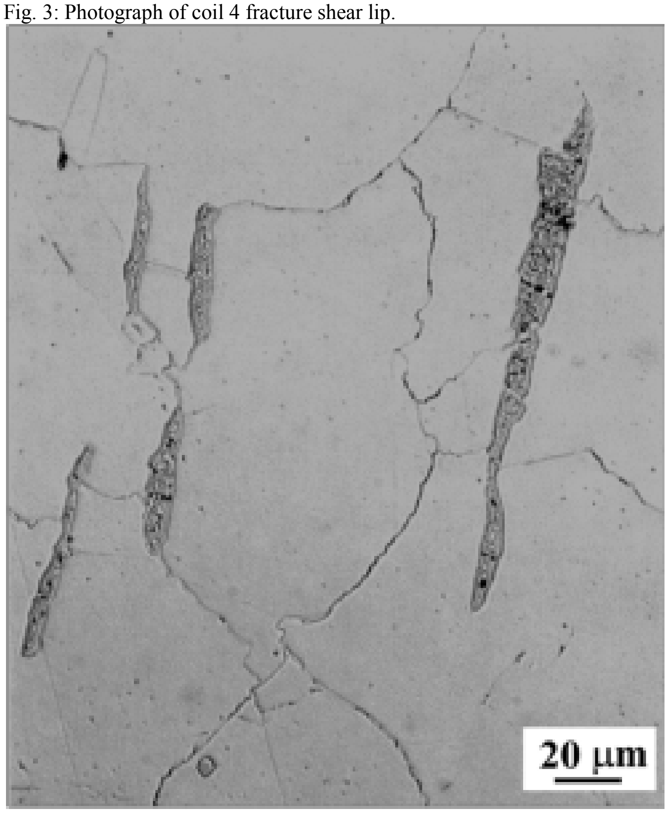

Fig. 4: Photograph of sigma phase stringers in coil 8 shell material.

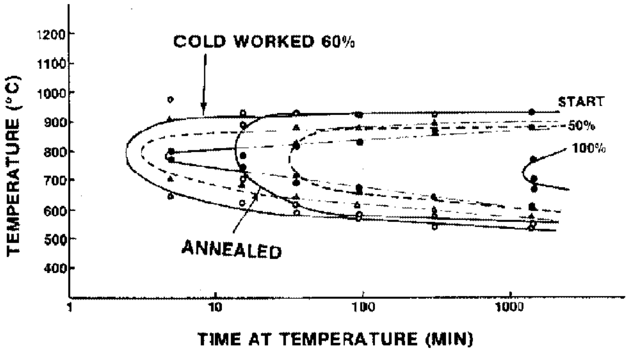

Fig. 5: Graph showing the conversion rate of delta ferrite to sigma phase.

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