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Active

Project #: E-18-645 Cost share #: Rev #: 0
Center # : R6392-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: AGR DTD 870701 Mod #: Document : AGR
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

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Project director(s):
HOCHMAN R F MAT ENG

Sponsor/division names: INNOVEX INC / HOPKINS, MN
Sponsor/division codes: 208 / 026

Award period: 870701 to ~~870930~~ 10/31 8/14/88 (performance) 870930 (reports)

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Funded	15,000	15,000
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Does subcontracting plan apply ?: N

Title: BASIC AND APPLIED STUDIES OF MAGNETIC FIELD PROCESSING

PROJECT ADMINISTRATION DATA

OCA contact: William F. Brown 894-4820

Sponsor technical contact

VLADIMIR DRITS
(612)938-4155
INNOVEX, INC.
1313 5TH STREET S.
HOPKINS, MN 55343

Sponsor issuing office

GEORGE W. POEHLMAN
(612)938-4155
INNOVEX, INC.
1313 5TH STREET S.
HOPKINS, MN 55343

Security class (U,C,S,TS): U
Defense priority rating: N/A
Equipment title vests with Sponsor

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N/A supplemental sheet
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Administrative comments -
INITIATION OF PROJECT E-18-645.

12/88

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

2-N-R-B
5R302

NOTICE OF PROJECT CLOSEOUT

Date 8/24/89

ject No. E-18-645 Center No. R6392-0A0

ject Director R. F. Hockman School/Lab Mat. Eng.

nsor Innovex, Inc.

tract/Grant No. Agreement dtd. 7/1/87 GTRC XX GIT ___

me Contract No. N/A

le Basic and Applied Studies of Magnetic Field Processing

ective Completion Date 3/31/89 (Performance) 3/31/89 (Reports)

seout Actions Required:

- None
- Final Invoice or Copy of Last Invoice
- Final Report of Inventions and/or Subcontracts -Patent questionnaire sent to P/I.
- Government Property Inventory & Related Certificate
- Classified Material Certificate
- Release and Assignment
- Other ___

ludes Subproject No(s). ___

project Under Main Project No. ___

tinues Project No. ___ Continued by Project No. ___

tribution:

Project Director
Administrative Network
Accounting
Procurement/GTRI Supply Services
Research Property Management
Research Security Services

X Reports Coordinator (OCA)
X GTRC
X Project File
2 Contract Support Division (OCA)
___ Other ___

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Georgia Institute of Technology
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July 26, 1988

REPORT TO INNOVEX CORPORATION

A Study of the Fundamentals of Magnetic Processing

by R. F. Hochman
Project E18-645

(With Contributions by N. Tselesin, Duratech, Inc.
and W. Drits, Innovex Corporation)

OBJECTIVE

This study was initiated to determine some of the atomic, electronic and crystallographic (defect structure) changes that can be produced by various degrees of pulsed magnetic field treatment. In the future, it is expected that these principles will lead to wider and more unique applications of this form of treatment in mechanical and metallurgical applications.

INTRODUCTION

For several decades, research on the effects of magnetic fields on physical and mechanical properties has been examined. Several experimental techniques for the processing of materials to control failure (in particular, the retardation of cracks) have been developed and some extremely definitive publications on the subject have been published (1,2). There are indications that fundamental changes in metal substructure can be achieved by application of constant magnetic field: stress relief, improved fatigue properties at room temperature (3), changes in fundamental diffusion coefficients and thermodynamic properties (4) have been documented. Of particular interest, is the improvement in macro-mechanical properties of ferromagnetic and paramagnetic materials. But the commercial application and industrial utilization of the magneto-mechanical effect has not been developed. This may be due to the fact that high and low magnetic fields, when applied in certain processing applications, has not provided a stable effect on variety of materials (3,5). Presently here in the United States, Innovex, Inc.* of Hopkins, Minnesota, has demonstrated that applying a series of specially designed magnetic pulses separated by periods of zero field provides stress relief on a variety of materials, e.g., carbon steel, high speed steel and cemented carbides. The system, called FluxaTron®, generates programmed pulsed magnetic fields in region of 300 to 2,000 oersted at frequencies of 2 to 30Hz. Multiple production tests have shown marked improvement (up to 200%) in the life of variety of cutting tools.

This paper has been designed to provide the reader with a background of the studies that have been performed in this area through: 1) a review of the principles of magnetism which relate to the phenomena of magnetic processing, 2) a review of recent practical studies in magnetic processing, 3) a review of industrial test results of FluxaTron® U-102 and finally 4) a brief review of ongoing basic research directed at providing a better understanding of the pulsed magnetic treatment phenomena and its application potential.

*Innovex, Inc. has basic patent application on file relating to magnetic treatment of various materials, and has established a proprietary position in methods of such treatment.

PRINCIPLES OF THE MAGNETIC FIELD TREATMENT

In all materials, the application of a magnetic field to a metal causes the angular frequency of certain electrons associated with the atoms in the material to change. In a ferromagnetic material, areas called domains are formed to minimize the sum of several energy terms related to magnetic phenomena, i.e., exchange forces, magnetocrystalline anisotropy, magnetostatic effects and magnetostriction. Magnetic domains were first observed in 1931 and the intensive study of their characteristics has been conducted over the past half century.

To understand magnetic domains, we need to look at some of the effects which bring about their existence. For example, exchange forces are responsible for an energy term which can be minimized if all the electron spins are parallel throughout a specimen. This can cause domain boundary movement, which increases the size of some domains at the expense of others, or by rotation of magnetization vectors in domains as the externally applied field is increased. These processes may be reversible, or irreversible.

The stages of magnetization are shown schematically in Figure 1 where B is the level of magnetization in the material and H is the applied magnetizing field. The first stage of magnetization is caused by reversible boundary movement enlarging the favorably oriented domains (and to a smaller extent, reversible rotation of magnetization vectors). The second stage, during which the induced magnetization increases rapidly, is due to irreversible domain wall motion and, if that is prevented, irreversible rotation of individual magnetization vectors which suddenly flip to a more favorable orientation versus the applied field. The final stage, approaching saturation, is again reversible, caused by the gradual rotation of the magnetization vectors away from the easy direction towards the applied field.

On reducing the field, the magnetization vectors return to their nearest easy direction, thus determining the drop in the magnetization from saturation to <u>remanence</u>. From the <u>remanence</u> point through the <u>coercivity</u> point to approaching reverse saturation, the mechanism is irreversible rotation of the magnetization vectors. The <u>coercivity</u> is dependent on the field strength required. Finally, there is again reversible rotation of the vectors away from the easy magnetization direction.

The ease of domain boundary movement is the primary variable in determining the shape of the B-H loop and it is extremely structure sensitive. In contrast, the saturation magnetization is a structure insensitive property and is determined by the overall composition. If movement is easy, the loop is small and the material magnetically soft. If movement is restrained, the loop is broad and the material magnetically hard.

Magnetocrystalline anisotropy describes the variation of magnetic properties with crystal direction. Electron zone theory of metals shows how the energy of electrons varies with direction in a crystalline solid. Since electrons are responsible for magnetism, it is therefore not surprising that magnetic properties are influenced by crystallographic direction.

Free magnetic poles are created at a boundary whenever the component of magnetization normal to the boundary changes across the boundary. The boundary may be a free surface or a domain wall. The magnetostatic energy term is due to the self-demagnetizing field which results from the free poles in opposition to the local magnetization. A specimen of the material tends to break down into fiber-shaped domains with opposing magnetization vectors in order to minimize the magnetostatic energy as shown schematically.

The magnetostriction energy term is elastic strain energy arising from the change of dimensions occurring on magnetization. With different directions of magnetization in adjacent domains in a crystal, internal stresses and strains are developed. It may be positive or negative, i.e., the material may increase or decrease in length upon magnetization. Domain boundary motion only occurs because magnetocrystalline anisotropy makes rotation of the spin moments energetically difficult. Boundary motion is then inhibited by stress and magnetic inhomogeneity. Since the direction of magnetization changes across a domain boundary, the direction of the magnetostrictive strain will also change (except for a 180° boundary). A rather complicated stress pattern develops at a domain boundary. As a result, the boundary can interact with any nonhomogeneous stresses in the material. The interaction is stronger with a greater value of the magnetostrictive coefficient.

The presence of magnetic inhomogeneities, such as nonmagnetic inclusions, in the middle of a domain, causes the appearance of free poles. These are suppressed when a domain boundary intersects the inclusion and the domain closure area. The attraction of the boundary to the inclusion is stronger the greater the value of the magnetocrystalline anisotropy. For small fields, the boundary movement will still be reversible, but for large fields, it will become irreversible.

Magnetic inhomogeneities, the extreme case of which is the presence of a non-magnetic inclusion, can similarly cause irreversible boundary motion and hysteresis loops. The resulting magnetostatic energy is reduced by the formation of supplementary domains in the material. Therefore, on a micro scale, irreversible wall motion does not take place smoothly, but involves a series of jerks and this may produce other effects in an inhomogeneous material; i.e., one might propose magnetically induced atomic diffusion.

Based on described example, a conventional scheme of redistribution of stresses, can be offered (Figure 2). Domain wall movement under magnetic pressure may produce a more uniform distribution of the internal stress field in a material.

The different behavior of annealed and cold worked Ni in low magnetic fields can be attributed to difference in internal stresses in the material. For a cold worked material domain prealigned by the cold working must first be dissolved, and this can mean an annealing or stress relief effect before remagnetization.

Thus, it is obvious that the magnetic properties of materials are directly related to the crystallographical characteristics of the material and the mechanical properties of the material. Further, the relation between the defects in the crystallographical structure (dislocations and vacancies) will be effected by a magnetic field of sufficient intensity.

Hence, one can deduce that a magnetic field of the right intensity and duration can change the mechanical as well as other material properties depending on the history and state of the material. There is strong evidence that the magnetostrictive force and related domain movement can produce a redistribution of inner stress and may also effect diffusion and solute redistribution in a material.

A REVIEW OF SOME OF THE BASIC STUDIES ON THE EFFECT OF MAGNETIC FIELD PROCESSING ON THE MECHANICAL PROPERTIES OF METALS

The effect of dislocations in ferromagnetic materials may be studied by examining either the change in some magnetic property with a change of dislocation structure, or the change of some mechanical property as a function of magnetization. For example, dislocation structure change as a function of magnetization has been reported by Vicena (5) and Seeger et al (6). Whereas, the latter has been demonstrated by Franyuk (7) in the creep of nickel around 200° C, comparing apparently magnetized and demagnetized states of the metal, and by Cullity and Allen (8) examining the room temperature stress relaxation of a compressed nickel ring. The microcreep of iron and nickel tubes, deformed in torsion under a magnetic field was reported by C. W. Allen and J. A. Donovan (9). The experiments were undertaken to demonstrate an interaction of dislocations with domain walls and to attempt to estimate by experiment the interaction energy.

The influence of a constant magnetic field (1500 and 2500 oersted) on the mechanical properties and dislocation structure of niobium and molybdenum was investigated by V. A. Pavlov, et al (4). In his work the magnetic field brought about: 1) a change of the temperature dependence of the yield point, 2) an increase of the plasticity and stress relaxation at constant strain in a given temperature range, and 3) a decrease of the Peierls activation energy.

The effect of a magnetic field on the mechanical properties is usually associated with a decrease in deformation stresses with increased plasticity. The investigations of (4) revealed a rather complicated influence of the constant magnetic field on the mechanical properties of paramagnetic metals. When the temperature and deformation rate vary over a wide range, not only the magnitude of the effect undergoes changes, but its sign as well. It should be also noted that the effect is very sensitive to the original structure of the specimens, i.e., it is dependent on the whole thermal and mechanical prehistory of the material.

Fatigue life is influenced by a number of factors such as corrosion, temperature, stress concentration, residual stress, etc. Magnetic fields have been shown to influence the fatigue life of a ferromagnetic material. Experimental results by M. S. C. Bose (3) have shown the influence of a constant magnetic field on the fatigue life of carbon steel specimens. In comparing the S-N curves obtained in the presence of a field with that obtained in absence of a field, it was observed that the application of a saturating magnetic field (about 40 KA/m) during fatigue test produced the following changes:

a. The endurance fatigue limit shifts to a higher stress level,

b. The knee in the S-N curve shifts towards lower number of stress cycles, and

c. The low cycle portion of the S-N curve decreases.

The observed changes in the S-N relationship due to the presence of a magnetic field during the fatigue tests were attributed in general to dislocation movement and deformation characteristics as well as a change in damping capacity, and strain aging behavior. In addition, the existence of other mechanisms which may also influence fatigue life cannot be ruled out but are not obvious at the moment.

INDUSTRIAL TEST RESULTS ON MAGNETICALLY TREATED TOOLING

Multiple production tests of FluxaTron® U-102 magnetic field processing has been made on a variety of cutting tools, including drills, taps, end mills, gear hobs, etc. These studies were conducted during the past two years by a series of large, medium, and small manufacturers involved in a wide range of industries.

The results have proven magnetic treatment to be effective on HSS and carbide, both coated and uncoated.

The effect of magnetic treatment on new end mills was demonstrated by Metcut Research Associates, Cincinnati, Ohio. Tests at Metcut looked at the wear rates of carbide and HSS end mills used in machining 304SS using localized wear of 0.010 in. as the criterion for determining when a tool is to be removed for resharpening, preliminary results show that the process improved life of HSS mills by 18% and of carbide mills by 35%.

Increases in tool life are generally greater for resharpened HSS and carbide tools. For example, a major hydraulic component manufacturer reported 200% increased life of small, resharpened drills used in drilling 300 series stainless steel. Another manufacturer reported magnetically treated resharpened end mills, running on a 12 spindle machine, produced an average of 775 parts before being changed. This compared to their untreated counterparts which produced only an average of 625 parts indicating an increased tool life of approximately 25%. This also produced a marked reduction in machine down time.

A major power generation equipment manufacturer has shown that magnetic treatment increased life of reground, brazed carbide gun drills by 50%. And, at the Ford Motor Company, magnetic treatment increased the life of HSS drills used for carbon steel by 25%.

Magnetic treatment has also been demonstrated to be an important method for increasing the life of coated and uncoated carbide inserts. At Ford, magnetic treatment has increased the life of coated and uncoated carbide inserts used in machining steels and cast iron by between 17% and 83%. At Miller Fluid Power, magnetically treatment carbide inserts turn an average of 53% more Cr plated, hardened AISI 1050 steel piston rods than their untreated counterparts. At Bob, Inc., studies on a Micro-100 turning tool showed the shop was expecting tool breakdown five times daily; after using magnetic field treatment, the tools needed to be sharpened only three times daily.

Magnetic treatment produces the greatest increase in the life of carbide inserts where the primary mode of failure involves chipping. Figure 3 documents the effectiveness of magnetic treatment for reducing chipping in carbide inserts for a major bearing manufacturer and current user of magnetic treatment. The inserts shown were used to machine an equal number of gray cast iron (BHN 215) under identical machining conditions. By reducing chipping, this manufacturer more than doubled tool life.

IN PROGRESS STUDIES EVALUATING THE BASIC EFFECTS OF MAGNETIC TREATMENT OF METALS

A series of ongoing studies to examine the basic characteristics of magnetic treatment of metal is presently underway under the direction of the authors. The preliminary results of these studies are presented in the following brief summaries.

1. Defect Structure Studies by Positron Annihilation.

Positron annihilation analysis is a method of determining the concentration of defects (dislocations and vacancies) in a metal or alloy. Initial studies have shown definite variation in the defect structure before and after magnetic treatment. Positron annihilation decay experiments are underway to determine the nature of the change in these substructure defects. Paramagnetic as well as ferromagnetic materials are being examined in this study. The characteristics of magnetic stress relief are also being compared to thermal stress relief by positron annihilation.

2. Quantitative Fractographic Analysis of Magnetically Treated Tungsten Carbide Tools.

Three-point bend tests were used to measure transverse rupture strength of sintered tungsten carbide (WC) with 6% and 12% Cobalt (Co) binder. The resulting specimen fracture surfaces were analyzed fractographically to determine if differences in fracture topography resulted from magnetic treatment.

Initial results indicate that for WC-6%Co, magnetic treatment results in larger facets (see Figure 4) and a 4% increase in surface roughness. The effect of magnetic treatment was less pronounced for WC-12%

Co.

3. Tensile Stress Relaxation and Microhardness Changes.

Magnetic treatment has been shown to relax tensile stress in the plastic region by the stress strain curve by 5 to 10% for pure iron wire. The stress versus time curve in Figure 5 schematically illustrates the results of these tests to date.

In the test, the wire was loaded into the plastic region constant rate of stress. At point (A), the crosshead displacement was stopped and the magnetic treatment device, FluxaTron® U102 was turned on. During the 42 second cycle, the stress (load) was observed to relax 5 to 10%. At the end of the cycle (B), the wire was again loaded and plastically deformed (B-C). Magnetic treatment was again observed to reduce the stress.

Another example of the effect of magnetic treatment was observed when studying the microhardness on the surface of cold worked pure iron. Figures 6a and b visually show a marked variation in the size of the hardness impressions (larger impression indicates a decrease in hardness) on the surface of the magnetically treated material compared to nontreated samples. Because of the statistical variation from sample to sample and because of the characteristic difference between the surface and subsurface effects, no quantitative results are presented at this time. However, it is obvious that the effect is there and once it is better understood both physically and as a function of specimen geometry (depth vs. surface effect) effective use of the phenomena may be made.

The substructure of magnetic treated and untreated samples is now being studied by transmission electron microscopy and position annihilation.

4. Surface Composition Variation Analysis.

Secondary ion mass spectroscopy was used to examine small changes in the surface chemical composition which might be attributed to magnetic field treatment. Tool steels, basically containing chromium and vanadium, with small amounts of a titanium residual were examined before and after magnetic treatment. The various intensities of the elements were checked against the host material, iron and the normalized results obtained were as follows:

TABLE 1

Sample #	Treatment	Relative intensity V	Relative intensity Cr	Relative intensity Ti
A	Before	1.2×10^{-1}	9.6×10^{-2}	7.6×10^{-4}
	After	1.0×10^{-1}	8.3×10^{-2}	5.0×10^{-4}
B	Before	5.0×10^{-2}	7.8×10^{-2}	8.0×10^{-4}
	After	5.0×10^{-2}	7.2×10^{-2}	4.5×10^{-4}

In sample A slight changes were found in vanadium, more in the chromium concentration, and a major variation was observed in the titanium residual. In sample B, no relative change was found in the vanadium, a small but significant change was measured for chromium and again a very marked change in the amount of titanium was observed. Since these studies were performed in essentially the same area of the same samples before and after treatment, it appears that indeed changes in the surface composition, particularly for those elements low concentrations, can result. Evidently, magnetic enhanced surface or subsurface diffusion does occur. It is significant that with a relatively low concentration of titanium a significant concentration variation was found. Of course, if one goes to the higher concentrations the significant change becomes smaller percentage wise although there is still a significant atomic movement producing the variations observed. The apparent depth of this modification was found to be only of the order 10 to 20 atomic layers. However, these preliminary results do indeed indicate changes in composition due to magnetically induced diffusion is indeed possible.

5. Residual Stress Analysis by Magnetomechanical Acoustic Emission.

Magnetomechanical Acoustic Emission (MAE) is a useful method to evaluate the level of residual stress in a magnetic material. Type 410 stainless steel sheet, hot rolled medium carbon steel plate and low carbon steel sheet were all studied by MAE. Results (Figures 7 and 8) did indeed show that there was a difference in the magnetomechanical acoustic emission of materials in the nontreated and post magnetically treated conditions. However, the large magnitude of the changes which were for cyclic and multiple treatments was not anticipated. Based on Magnetomechanical Acoustic Emission it is obvious that the magnetic energy treatment does indeed produce relief of residual stress as anticipated.

CONCLUSIONS

Both the basic and practical studies which have been performed utilizing magnetic energy have shown significant changes in material properties and processing conditions. Magnetic processing has produced: 1) stress relief, 2) changes in defect concentration, 3) chemical changes through magnetically induced diffusion, 4) crack arrest and crack initiation effects, 5) changes in processing and heat treating conditions, and 6) an increased fatigue endurance limit. It is obvious that the potential for improving processing and the resistance of materials to failure, indeed extending the life of these materials, is possible. One can even consider the extension of fatigue life by removal of first stage dislocation pileups by intermittent magnetic treatment.

Fundamental interactions of a magnetic field with both the physical and mechanical nature of metals has been shown. One may also look at the prospect of locally controlling surface chemistry and even redistributing elements in a material. The potential, therefore, of improving the overall properties of materials and processing materials appears almost endless, for example, the prevention of mechanical failure, modification of heat treat properties, improvement of rolling, machining and compacting operations, etc. However, one must evaluate this potential case by case in light of the economic good that can be achieved. Certainly, the simple improvement of life of tools is well documented and in most cases very economically feasible. We are sure that continued basic research will extend the application of magnetic field processing to most of the fields touched upon in this work and many not even considered as yet. Why? Because this is a very easy procedure, suitable for incorporation into existing manufacturing processes where it can produce useful changes in material properties.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance and contribution of several researchers who have contributed to the work reported. Of particular note is the work of Dr. E. E. Underwood, Dr. A. Erdemir, Dr. K. Banerji (all at Georgia Tech), Dr. John F. Evans of the University of Minnesota and Mr. Terry L. Vanderwert of Innovex, Inc.

REFERENCES

1. V.M. Finkel, Physics of Failure, Moscow, "Metallurgia" Publishers, 1970.
2. V.M. Finkel, Physical Foundations of Failure Retardation, Moscow, "Metallurgia" Publishers, 1977.
3. M.S.C. Bose, Phys. Stat. Sol.(a), 86, 649 (1984).
4. V.A. Pavlov, I.A. Pereturina, N.L. Pecherkina, Phys. Stat. Sol. (a), 57,449 (1980).
5. F. Vicenor, Czech. J. Phys. 5, 480 (1954).
6. A. Seeger, H. Kronmuller, H. Rieger, H. Trauble, J. Appl. Phys. 35, 740 (1964).
7. V.A. Franyuk, Dokl. Akad. Nauk Bssr (Dan Bssr) 8, 228 (1964).
8. B.D. Cullity, C.W. Allen, Acto Met. 13, 933 (1965).
9. C.W. Allen, J.A. Donovan, J. Appl. Phys. 38, 3

LIST OF FIGURES

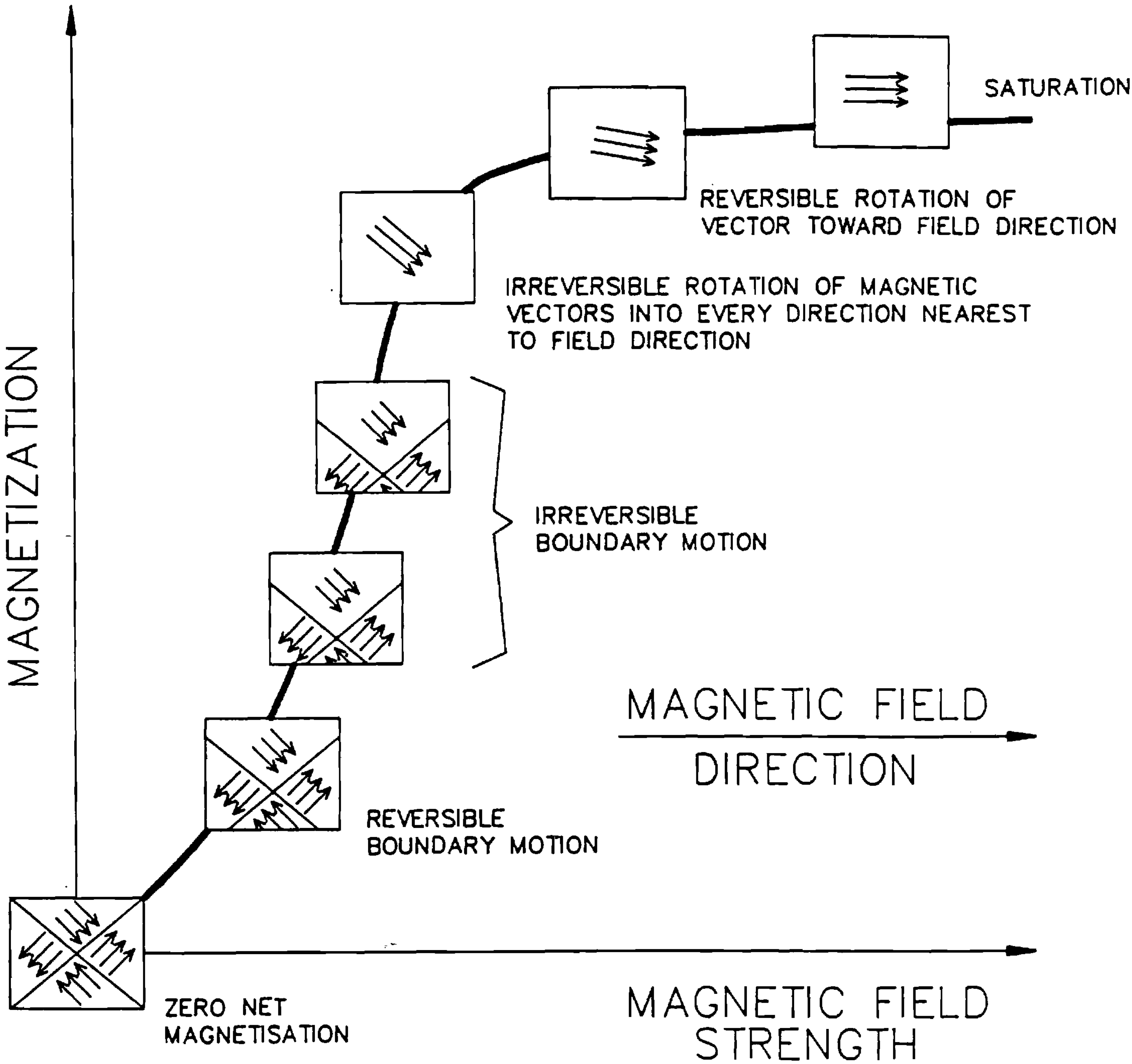


Figure 1. Domain Behavior Corresponding to Various Stages of Magnetization.

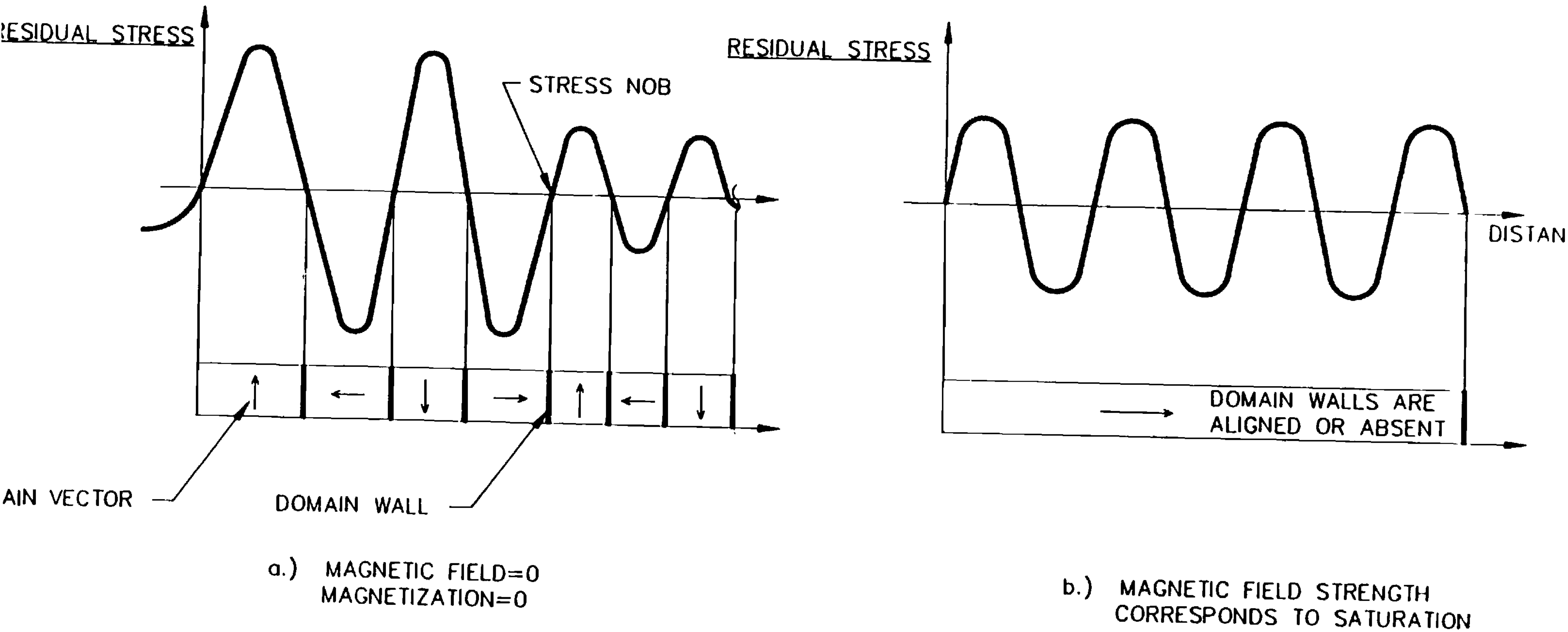
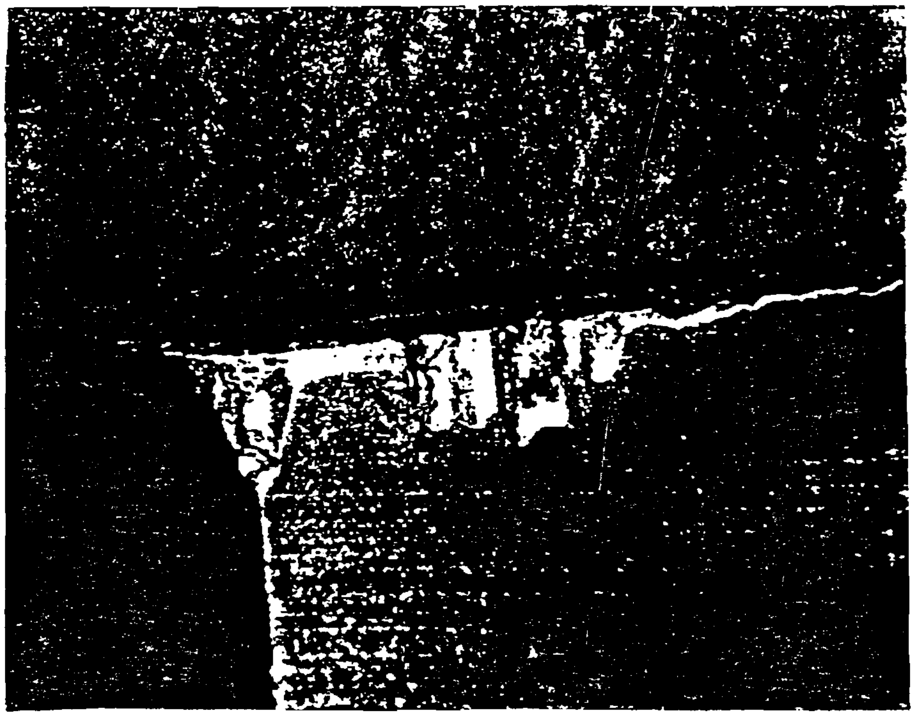
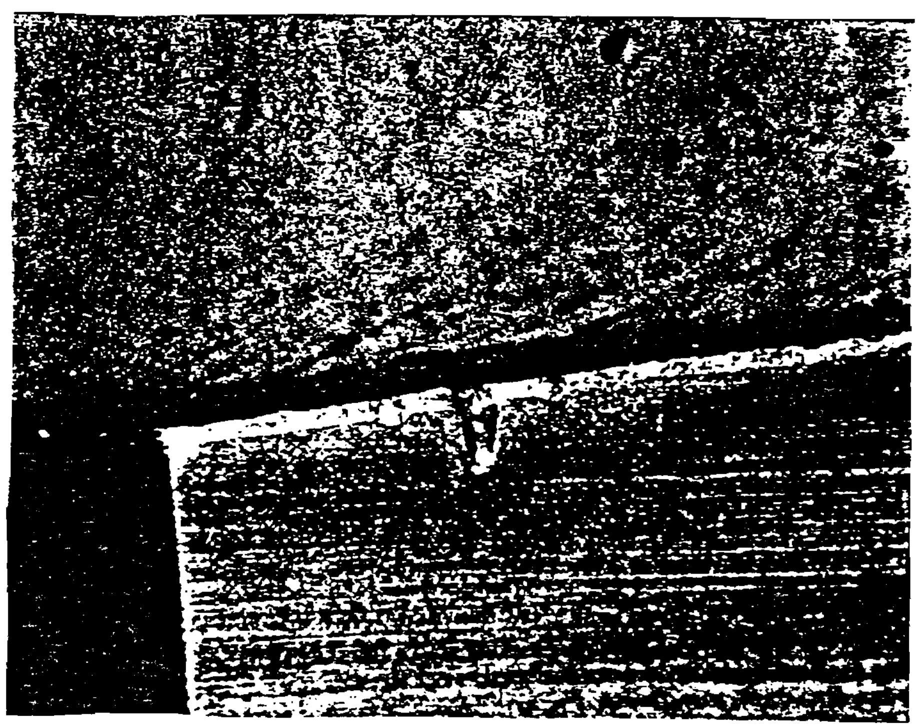


Figure 2. Conventional Scheme of Residual Microstress Changes in the Process of Magnetization.

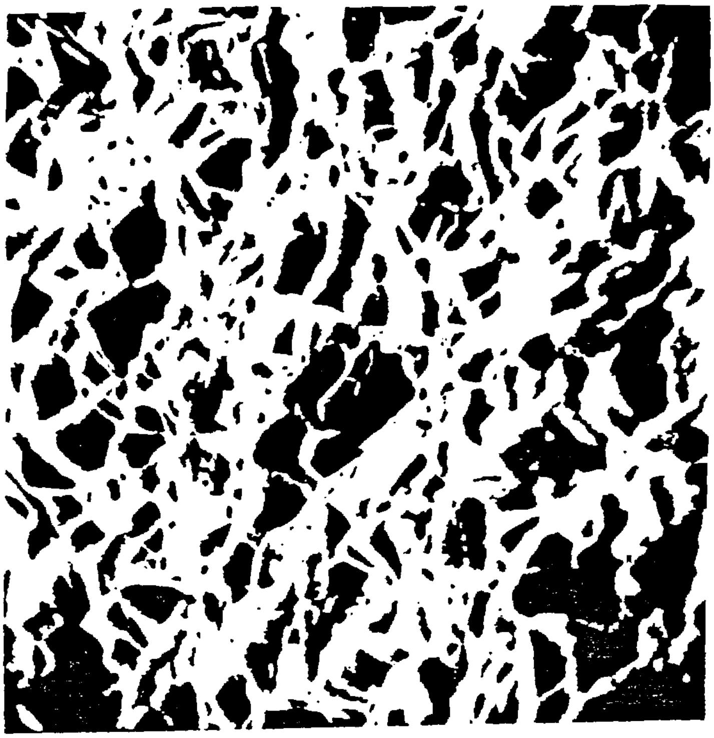


(a)



(b)

Figure 3. The Effect of Pulsed Magnetic Field Treatment on Carbide Tool Chipping: a) untreated, and b) magnetically treated.



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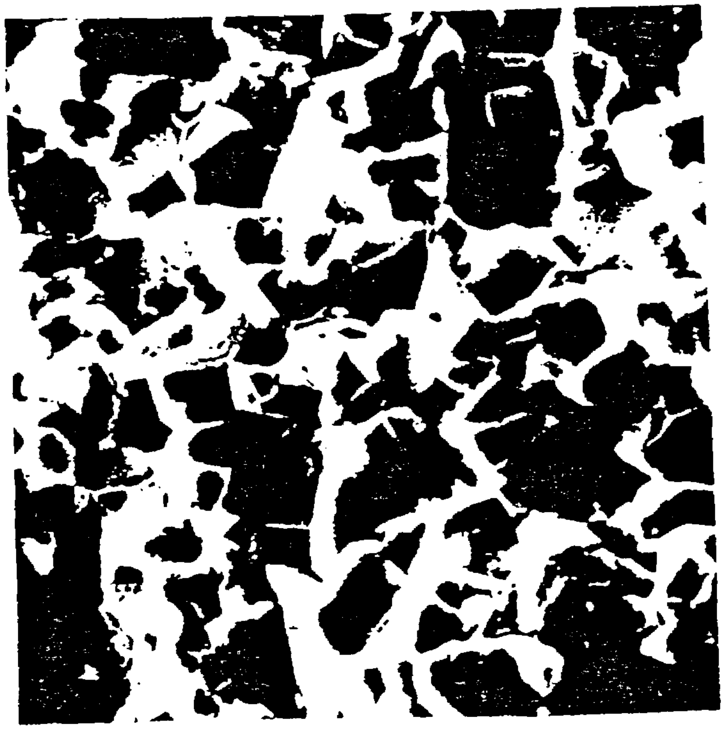


(b)

Figure 4. The Effect of Pulsed Magnetic Field Treatment on Fractographic Features of WC-6% Co: a) fracture surface of untreated sample, and b) fracture surface of magnetically treated sample (5,600 x magnification).

STRESS RELAXATION

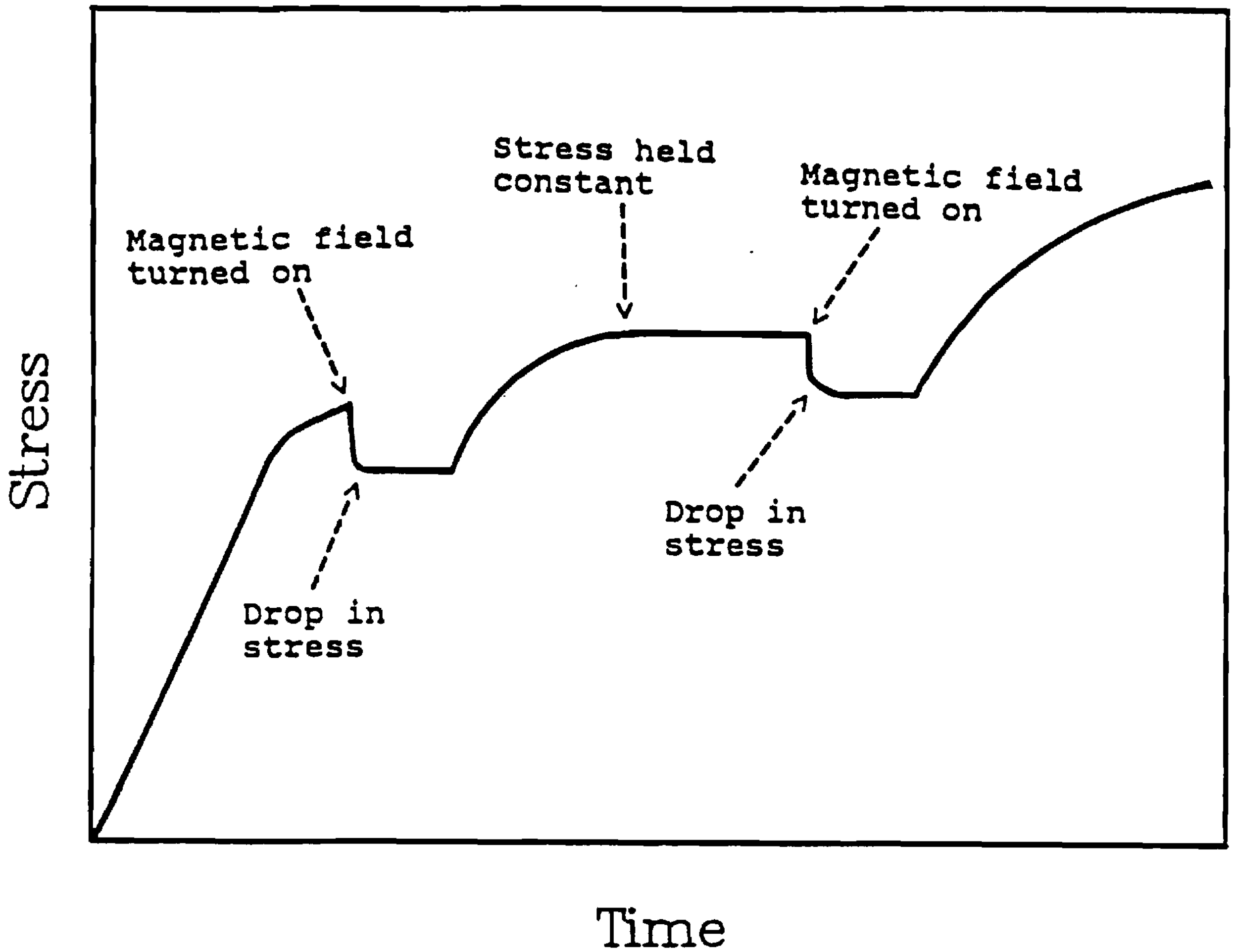
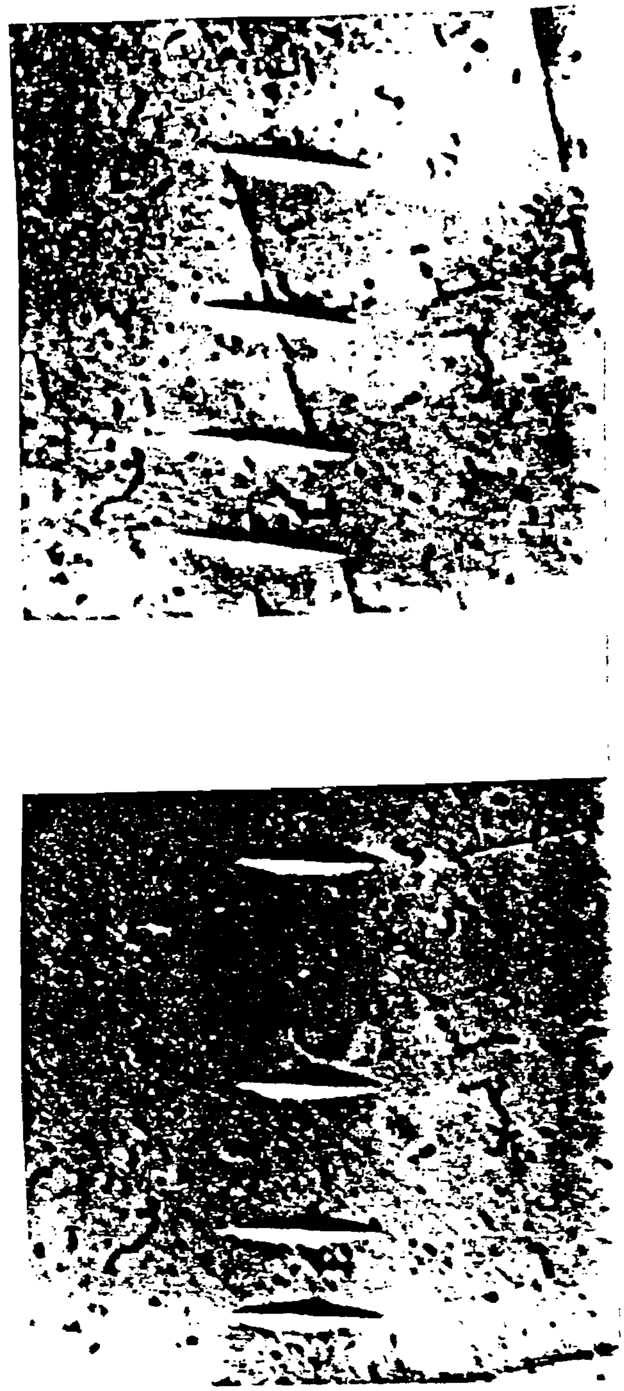


Figure 5. Schematic Diagram Summarizing the Tensile Stress Relaxation Studies Produced in the Laboratory by Pulsed Magnetic Field Treatment. (High purity iron wire 0.01" diameter.)



(a)

(b)

Figure 6. Micro Hardness Differences Produced by Magnetic Field Treatment of High Purity Iron: a) as deformed, and b) magnetically treated after deformation.

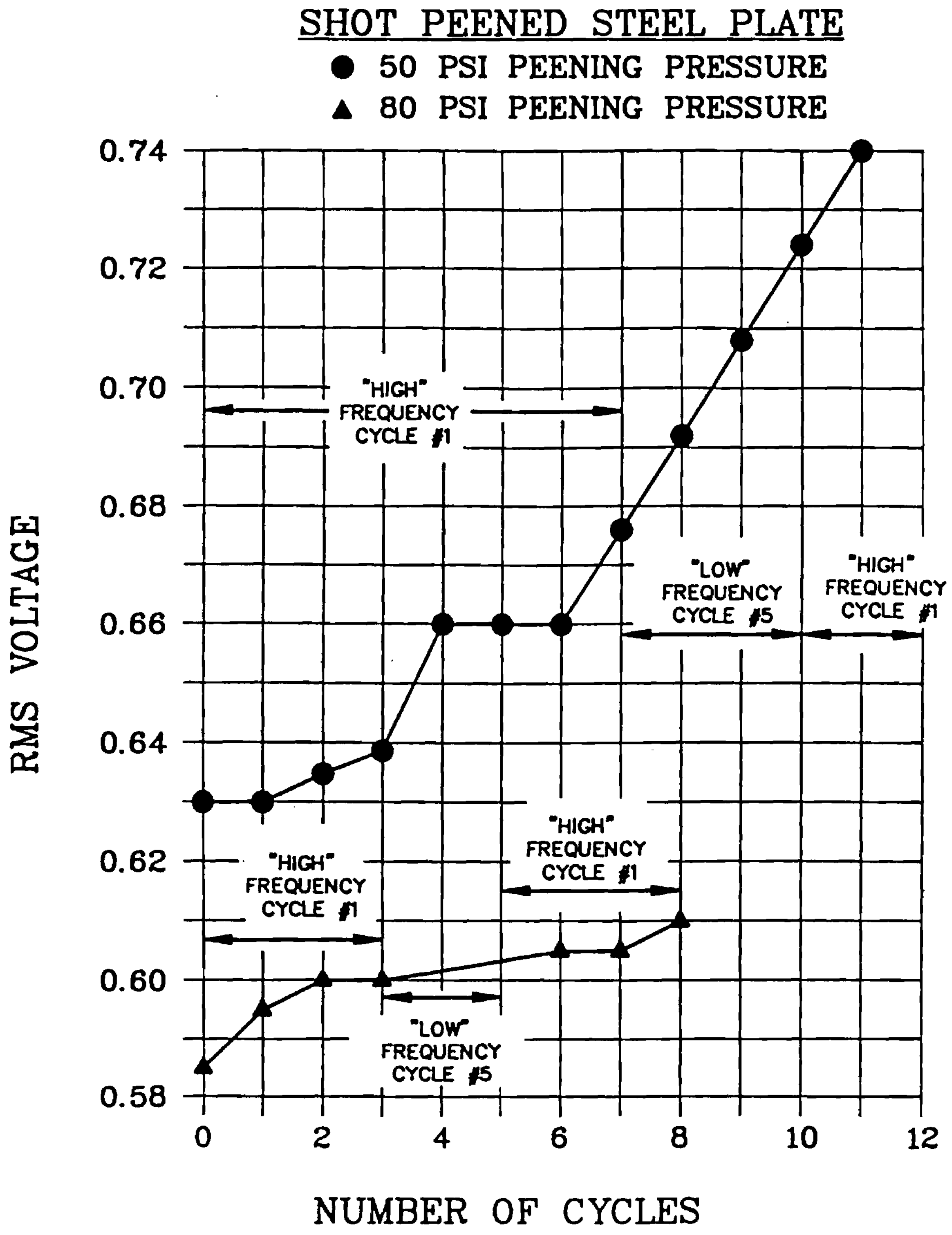


Figure 7. Effect of Fluxatron® Treatment on Magnetomechanical Acoustic Emission. Root Mean Square (RMS) Voltage as a Function of the Number of Cycles for Shot Peened Steel Plate.

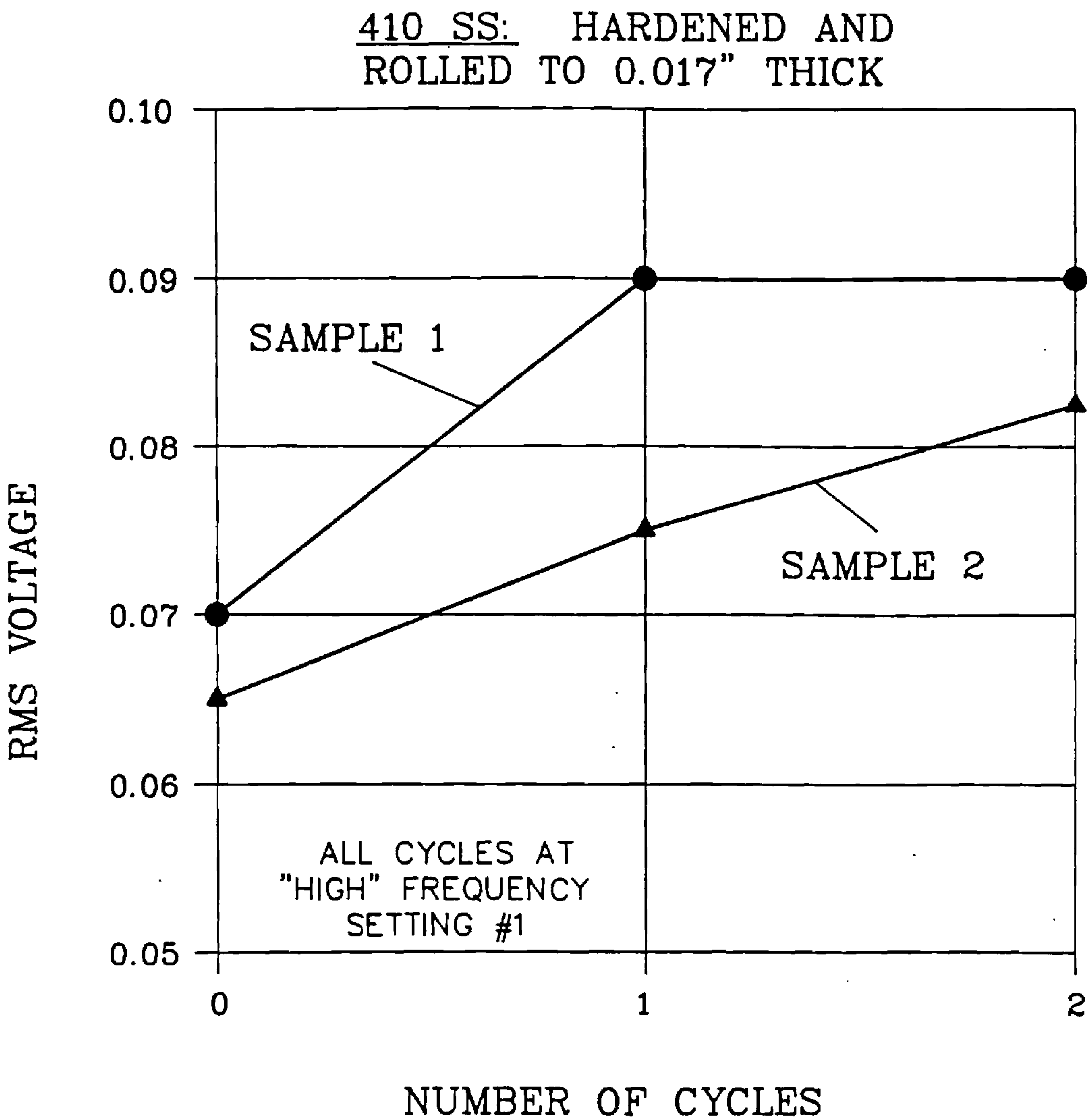


Figure 8. Effect of Fluxatron® Treatment on Magnetomechanical Acoustic Emission. Root Mean Square (RMS) Voltage as a Function of the Number of Cycles for 410 SS Hardened and Rolled to 0.017" Thick.