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DISCLAIMER

MAGNETO-MECHANICAL EFFECTS IN TWO STEELS WITH METASTABLE AUSTENITE

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ABSTRACT

Magneto-mechanical effects, or effects of magnetic fields on mechanical properties of materials, are reported for two steels containing austenite that undergoes an fcc→bcc martensitic transformation during plastic deformation. Stress-strain curves from tensile tests of AISI 304 stainless steels and 9Ni steels were measured in magnetic fields as large as 18 T at temperatures of 4 K, 77 K and room temperature. Even in 18 T magnetic fields at cryogenic temperatures the magneto-mechanical effects were small, but they were reproducible and scaled with the strength of the magnetic field and the amount of transformation. Magneto-mechanical effects in steels with metastable austenite provide a unique means of determining how martensitic transformations affect mechanical behavior. The fcc→bcc transformation makes an important contribution to the work hardening of both AISI 304 and 9Ni steel, so the more rapid transformation during magnetic exposure results in a higher strength and a reduced elongation of tensile specimens. In AISI 304 stainless steel a reduced flow stress in the magnetic field was found at small plastic strains.

INTRODUCTION

AISI 304 stainless steel and 9Ni steel are representative of two classes of cryogenic structural steels which contain metastable austenite. Hot rolled AISI 304 stainless steel is nearly 100% fcc austenite. Commercial 9Ni steel is typically prepared with about 10% precipitated austenite particles in the bcc martensitic matrix. The austenite phase in both these steels is thermodynamically unstable at low temperatures, but the fcc→bcc martensitic transformation occurs only after some plastic deformation of these materials[1,2]. It is known that as the fcc→bcc martensitic transformation occurs during plastic deformation, the flow stress is changed. It is also known that high magnetic fields promote the fcc→bcc martensitic transformation of metastable austenite[3-5]. It therefore seems reasonable that additional martensitic transformation will occur with magnetic exposure during deformation and this additional transformation will change the flow stress. However, mechanical effects of magnetically-induced martensitic transformations have only recently received attention. Magneto-mechanical effects may be of interest to fusion energy engineering because the operating environment for structural steels in large superconducting magnets includes high magnetic fields together with high stresses at low temperatures.

Recently we induced additional martensitic transformation in AISI 304 stainless and 9Ni steels by exposing them to steady 8 T and pulsed 16 T magnetic fields during plastic deformation. Small changes in deformation behavior were found during magnetic exposure[2,6,7]. In particular, the flow stress of AISI 304 stainless steels in tensile tests was found to increase during exposure to steady 8 T magnetic fields. These increases in flow stress were small, but reproducible. We have now extended these measurements of stress-strain curves of AISI 304 and 9Ni steels to steady fields of 12.5 T and 18.1 T. We have also performed a transmission electron microscopic (TEM) study of these materials, including observations of the fcc→bcc martensitic transformation. In addition to establishing the existence of magneto-mechanical effects, this recent work helps to demonstrate the microstructural mechanisms through which fcc→bcc martensitic transformations affect the flow stress of AISI 304 and 9Ni steels.

EXPERIMENTAL

The AISI 304L and AISI 304LN stainless steels had net concentrations of carbon plus nitrogen of 0.098 and 0.160 wt.%, respectively. The N.K.K. 9Ni steel was tested in both the as-received "QT" condition with relatively stable precipitated austenite, and after the following overtempering heat treatment to produce unstable austenite: (1000°C 3 hrs/WQ) , (800°C 1.5 hrs/WQ) , (600°C 300 hrs/WQ) . Specimens were machined with their tensile axes parallel to the rolling direction of the plate. Gauge sections of the specimens were 38 x 4.2 x 3.2 mm for the 12.5 T experiments, and 25 x 3.0 x 2.0 mm for the 18.1 T experiments. All tensile tests were performed in pairs; one specimen was exposed to the magnetic field and a control specimen was not. Care was taken to prepare both specimens with the same machining procedures and from the same region of the plate.

Experiments at 12.5 T were performed at 4 K with the specimen between a pair of superconducting solenoids that provided a magnetic field perpendicular to the tensile axis. Experiments at 18.1 T were performed at 4 K, 77 K and 290 K within the bore of a water cooled solenoid that provided a magnetic field parallel to the tensile axis. All tests were performed under "stroke control". For the experiments at 18.1 T the feedback control loop included an active correction of the "stroke signal" for the elastic deformation of the load frame itself, so the specimens were pulled at an approximately constant strain rate. Strain rates for all tests were $2.5\text{x}10^{-4}$/sec. Interactions between the high magnetic field gradients and the paramagnetic components of the load frame developed forces as large as 200 Nt at 4 K, but these forces were measured and later subtracted from the data.

TEM studies employed a Phillips 301 transmission electron microscope operated at 100 kV. Specimens were prepared from bulk material by cutting 400 μm sections with a slow speed diamond wafering saw under flood cooling. After further chemical thinning and mechanical grinding on SiC papers, 3 mm disks were thinned to perforation in a twin-jet electropolishing apparatus. The solution for the 9Ni steel foils was 400 ml glacial acetic acid, 75 g chromium trioxide, and 21 ml distilled water. Final preparation of foils of AISI 304 stainless steel used cooled solutions of 10% nitric acid and 90% methanol.

RESULTS and DISCUSSION

AISI 304 Stainless Steels

Engineering stress-strain curves of AISI 304L and 304LN stainless steels at 4 K and 77 K are shown in Figs. 1 and 2. Three effects of magnetic exposure during testing are seen.* 1) The flow stress is suppressed at small plastic strains (this is not seen in Fig. 2b, however). 2) At intermediate strains the work-hardening rate is greater for the specimen exposed to the magnetic field, and its flow stress becomes greater than that of the control specimen. 3) The total elongation of the specimens tested in the magnetic field was less than that of the control specimens. These three effects of high magnetic fields on the cryogenic stress-strain curves of AISI 304 stainless steels are consistent with an increased amount of fcc→bcc martensitic transformation during magnetic exposure.

The effects of 18.1 T magnetic fields on stress-strain curves of both AISI 304L and 304LN stainless steels at room temperature were small, and perhaps experimentally insignificant. This is consistent with the fact that little martensitic transformation occurs during tensile tests of either material at room temperature[2].

At small plastic strains, slip in AISI 304 stainless steel occurs in well-defined bands. These bands are shown in Fig. 3 to begin as stacking faults on {111} planes. Some of the vertical bands in Fig. 3 are composed of layered stacking faults. The process of plastic deformation is generally impeded when a slip band encounters an existing slip band on another slip plane; this usually causes the flow stress to increase. However, the fcc→bcc martensitic transformation may occur at the intersection of slip bands. Crystallographically, the bcc structure can be a natural consequence of the intersection of slip bands when the bands are comprised of either hcp marten site or a dense collection of stacking faults[8,9]. Suzuki et al.[10] have proposed that the bcc martensite which forms at the intersection of two slip bands acts as a "window" to allow the second band to easily traverse the first. The more favorable the formation of bcc martensite, the easier the process of slip band crossing will be. The promotion of the martensitic transformation during magnetic exposure therefore results in a reduced flow stress for small plastic strains. A magnetically-suppresed flow stress is seen for strains less than 0.1 (Figs. 1 and 2).

At larger plastic strains the work hardening of AISI 304 stainless steel is enhanced in high magnetic fields. The flow stress of the specimen tested in the magnetic field becomes greater than that of the control specimen (Figs. 1 and 2. In part this occurs because the additional bcc martensite particles formed during magnetic exposure are hard particles. These martensite particles

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* A reduction flow stress of ~2% was observed for tensile tests in the magnetic field at room temperature but such a small change is unreliable.

will impede slip when the material becomes too defective for the crystallographically elegant "window mechanism" to operate properly. A second source of the additional transformation-induced hardening during magnetic exposure is the large local strain around freshly transformed martensite particles. These large local transformation strains cause the generation of dislocations. Such dislocation structures are seen in the TEM micrographs of Fig. 4, which were taken near the intersection of wide slip bands.

The reduction in elongation of the specimens tested in the magnetic field (Figs. 1 and 2) is also a consequence of a more rapid fcc→bcc martensitic transformation in the magnetic field. Much of the work hardening capacity of AISI 304 stainless steel is a result of the transformation, and the transformation is expended more rapidly during magnetic exposure. Therefore the work hardening capacity of the material is more rapidly exhausted during magnetic exposure, and the Considere criterion for necking occurs at a lower strain, reducing the elongation of the specimen.

9Ni Steel

Engineering stress-strain curves of commercial "QT" and overtempered 9Ni steel at 77 K and room temperature are shown in Fig. 5. The "window mechanism" for suppression of flow stress in AISI 304 stainless steel cannot operate in 9Ni steel because its microstructure primarily consists of bcc martensite particles. On the other hand, work-hardening effects due to the fcc→bcc martensitic transformation are expected for 9Ni steel. The TEM micrographs of overtempered material (Fig. 6) show particles of austenite which have partially transformed. Dislocation structures similar to those previously reported[1,11] are seen near the transformed particles, and some dislocations extend deeply into the tempered bcc martensite matrix. As in AISI 304 stainless steel, both the hard, fresh martensite particles and the dislocation structures around them will harden the material. The more rapid martensitic transformation during magnetic exposure causes an increased flow stress in both commercial "QT" and overtempered 9Ni steels during magnetic exposure. The austenite in the overtempered material is significantly less stable than in commercial "QT" material[1], and it tends to transform at smaller strains. Consequently the magnetically-induced increase in flow stress tends to occur at smaller strains for the overtempered material than for the commercial "QT" material, as can be seen by comparing Figs. 5a and 5b. The mechanically-induced transformation of precipitated austenite in 9Ni steel evidently makes an important contribution to work-hardening as it does for AISI 304 stainless steel. Because this transformation is expended more rapidly during magnetic exposure, necking occurs at smaller strains, and the elongation of the specimen is reduced. An exception to this occured for commercial "QT" 9Ni steel at room temperature (Fig. 5a), in which the martensitic transformation may not go to completion.

Magneto-Mechanical Effects

Although the phenomena studied in this research are probably of little engineering concern for the present designs of superconducting magnet structures, our experimental data overwhelmingly support the existence of magneto-mechanical effects in steels with metastable austenite. We found additional work-hardening during magnetic exposure for every one of the 25 pairs of specimens tested at temperatures where the fcc→ bcc martensitic transformation occurs. These effects were measured independently with facilities at the Lawrence Berkeley Laboratory, the Lawrence Livermore National Laboratory and the Francis Bitter National Magnet Laboratory. As shown in Fig. 7, which summarizes our present and previous data, the maximum percentage change of flow stress during magnetic exposure (with respect to the flow stress of the control specimen) increases with the strength of the magnetic field. A scaling of magneto-mechanical effects with magnetic field strength is expected because the amount of magnetically-induced martensitic transformation should scale with field strength for thermodynamic reasons[2,3,7]. Additionally, the magneto-mechanical effects were largest for materials with the most unstable austenite; the more unstable AISI 304L and overtempered 9Ni steels showed larger magneto-mechanical effects than the more stable AISI 304LN and commercial "QT" 9Ni steels.

CONCLUSIONS

Magneto-mechanical effects exist for steels containing metastable austenite. The effects scale with the strength of the magnetic field, and are larger when more fcc→bcc martensitic transformation occurs during plastic deformation. Increasing the amount of fcc→bcc martensitic transformation with high magnetic fields offers a direct technique for determining how the transformation affects plastic deformation. We found three effects of high magnetic fields on the flow stress in tensile tests: 1. In AISI 304 stainless steels at 4 K and 77 K, high magnetic fields cause a reduction in flow stress at small plastic strains. Together with TEM observations these results are consistent with a "window mechanism" for work softening. 2. Both AISI 304 and 9Ni steels exhibit increased work hardening during magnetic exposure, resulting in an increased flow stress at large strains. This increased work hardening in the magnetic field results from additional particles of hard bcc martensite and the dislocation structures around them. The fcc→bcc martensitic transformation is an important mechanism of work hardening in both AISI 304 and 9Ni steels. 3. The more rapid martensitic transformation during magnetic exposure causes necking at smaller strains and thereby reduces the elongation of specimens in tensile tests.

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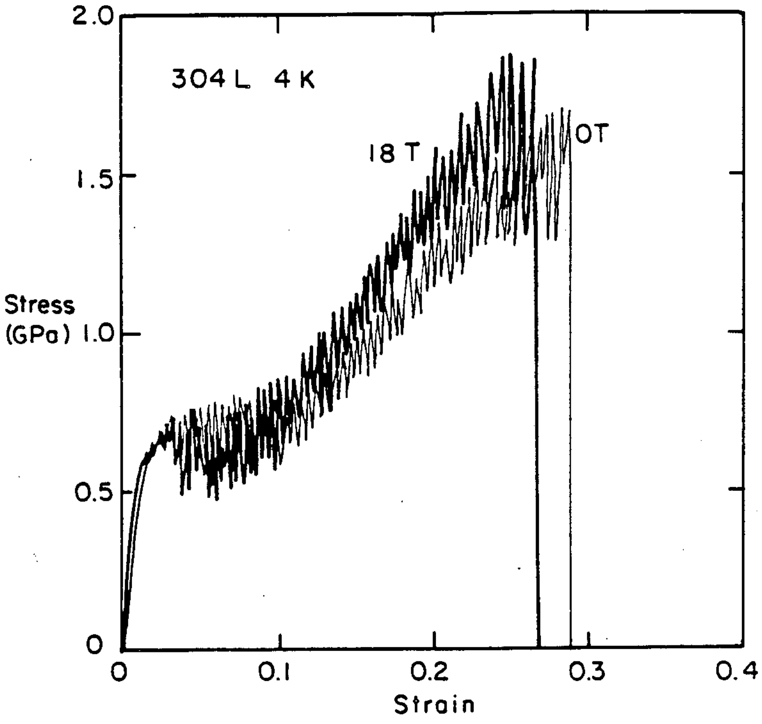
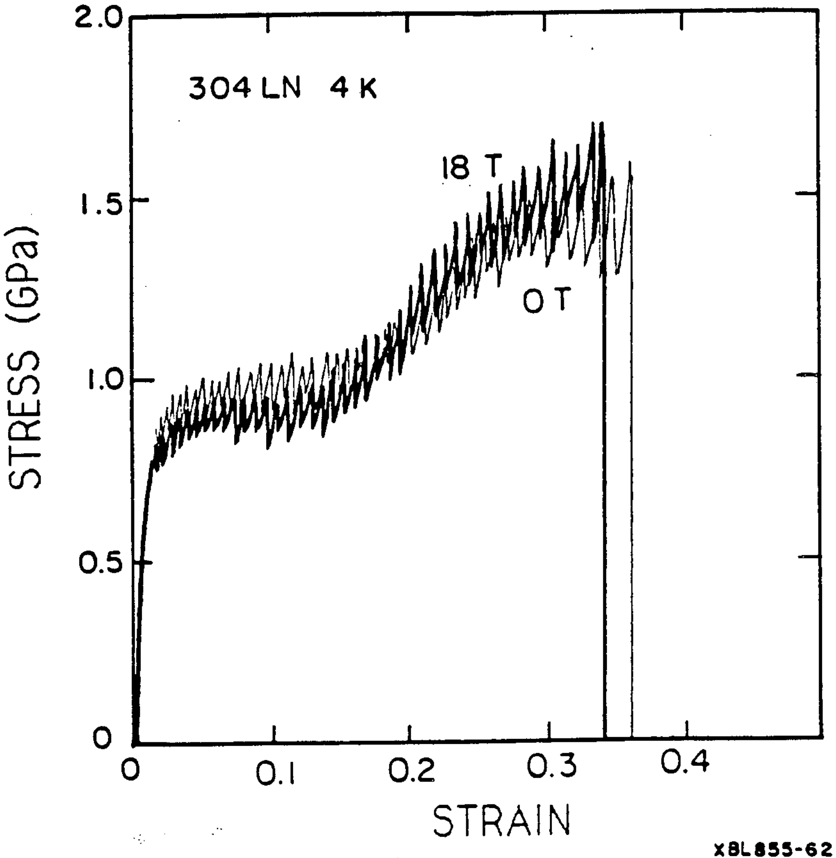


a) AISI 304L

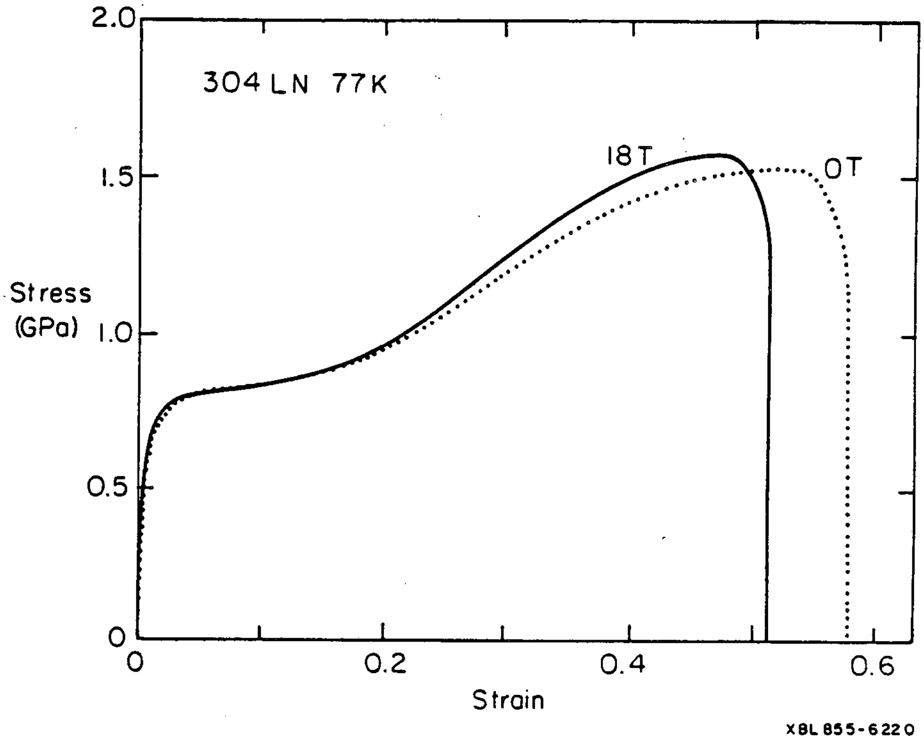
XBL855-6222



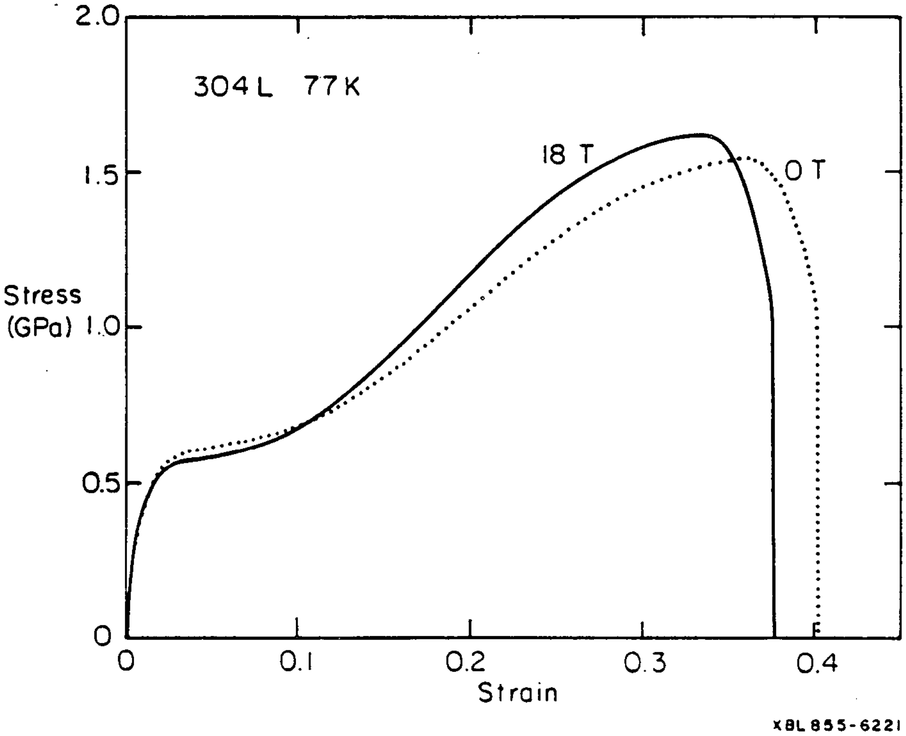
XBL855-62228

b) AISI 304LN

Fig. 1. Engineering Stres-strain curves at 4 K.



a) AISI 304L



b) AISI 304LN

Fig. 2. Engineering stress-strain curves at 77 K.

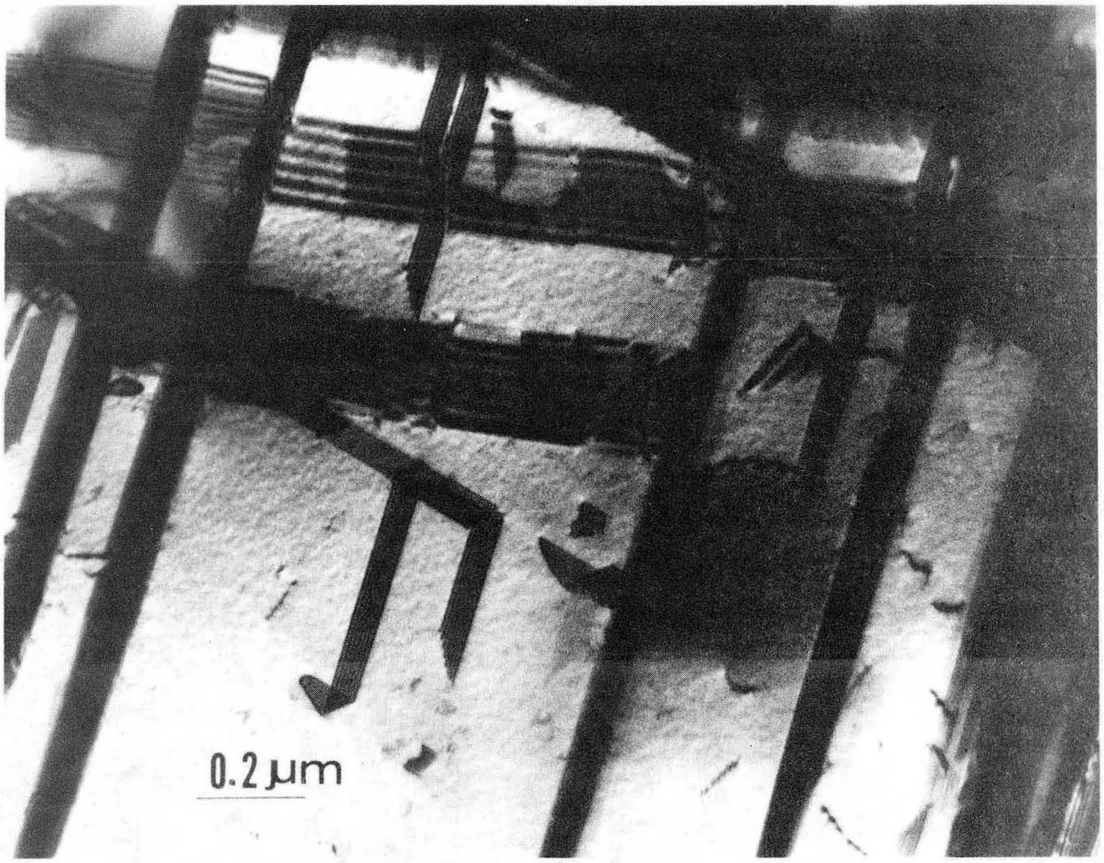


Fig. 3. TEM bright field micrograph of a region with low strain in AISI 304L strained at 77 K. Stacking faults on {111}fcc planes are seen with (000)+(002)fcc two-beam condition and [013]fcc zone axis.

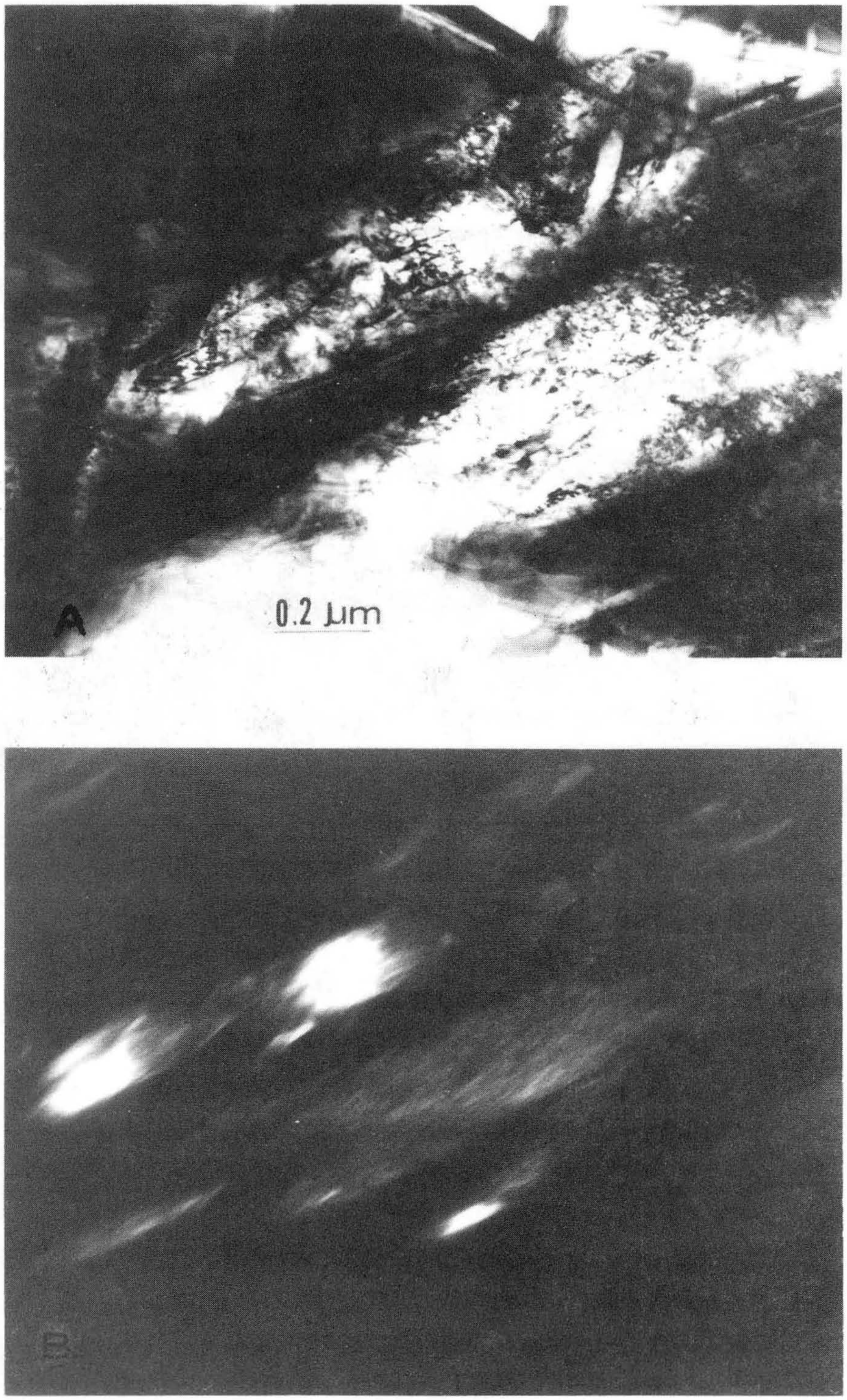
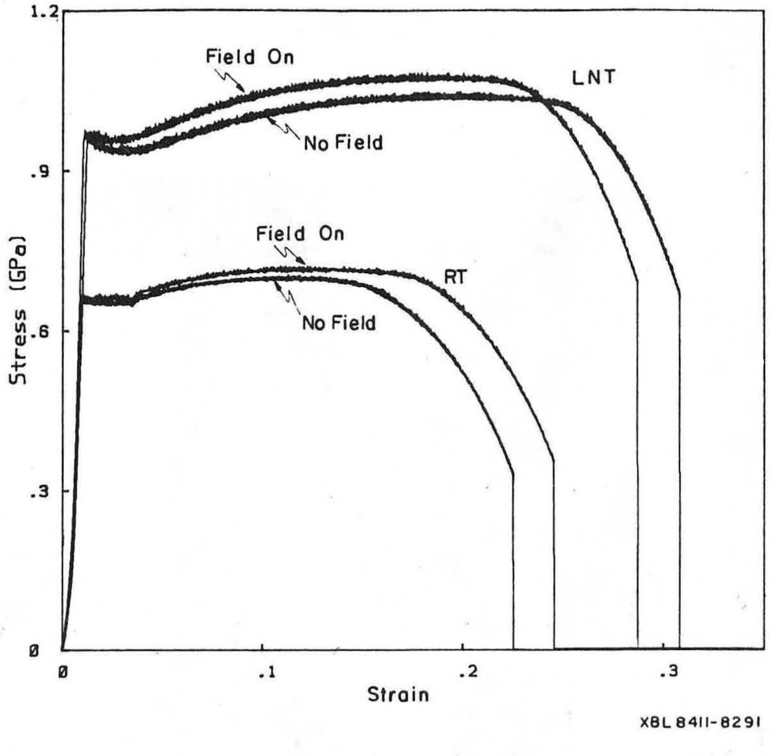
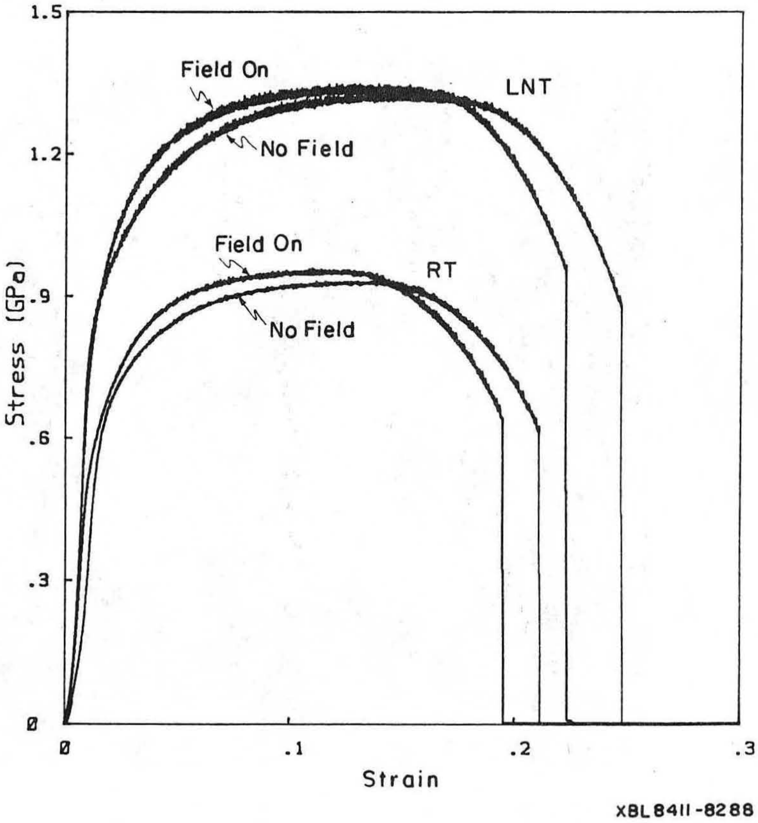


Fig. 4. a) TEM bright field micrograph of a region with high strain in AISI 304L strained at 77 K. b) complementary dark field micrograph of (002)bcc diffraction with [012]bcc zone axis.



a) commercial "QT" treated



b) overtempered

Fig. 5. Engineering stress-strain curves of 9Ni steel at 77 K (LNT) and room temperature (RT) in 18 T field and without field.

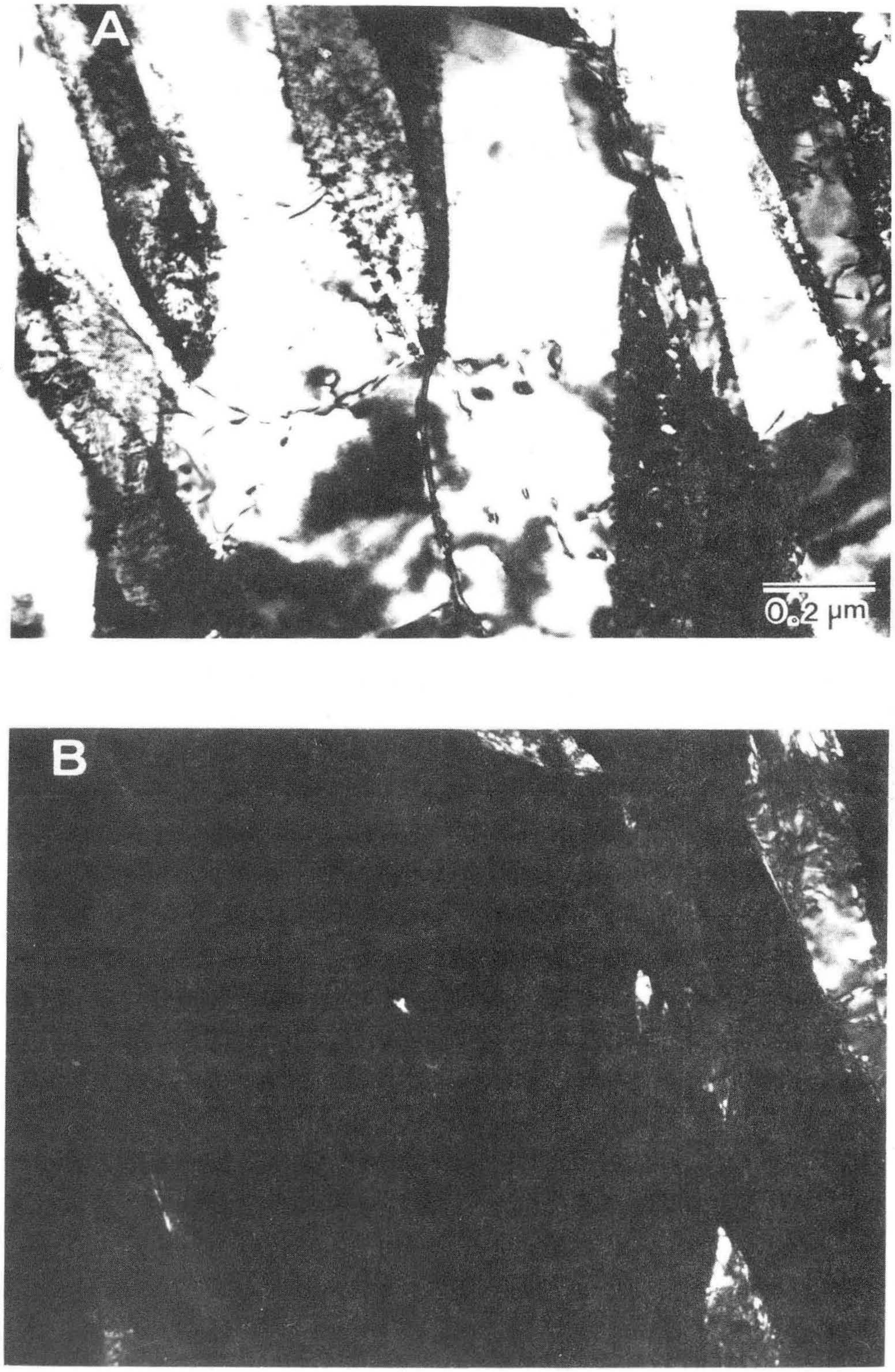


Fig. 6. a) TEM bright field micrograph of overtempered 9Ni steel
b) complementary dark field micrograph of (002)fcc diffraction
with [111]bcc ∥ [110]fcc zone axes.

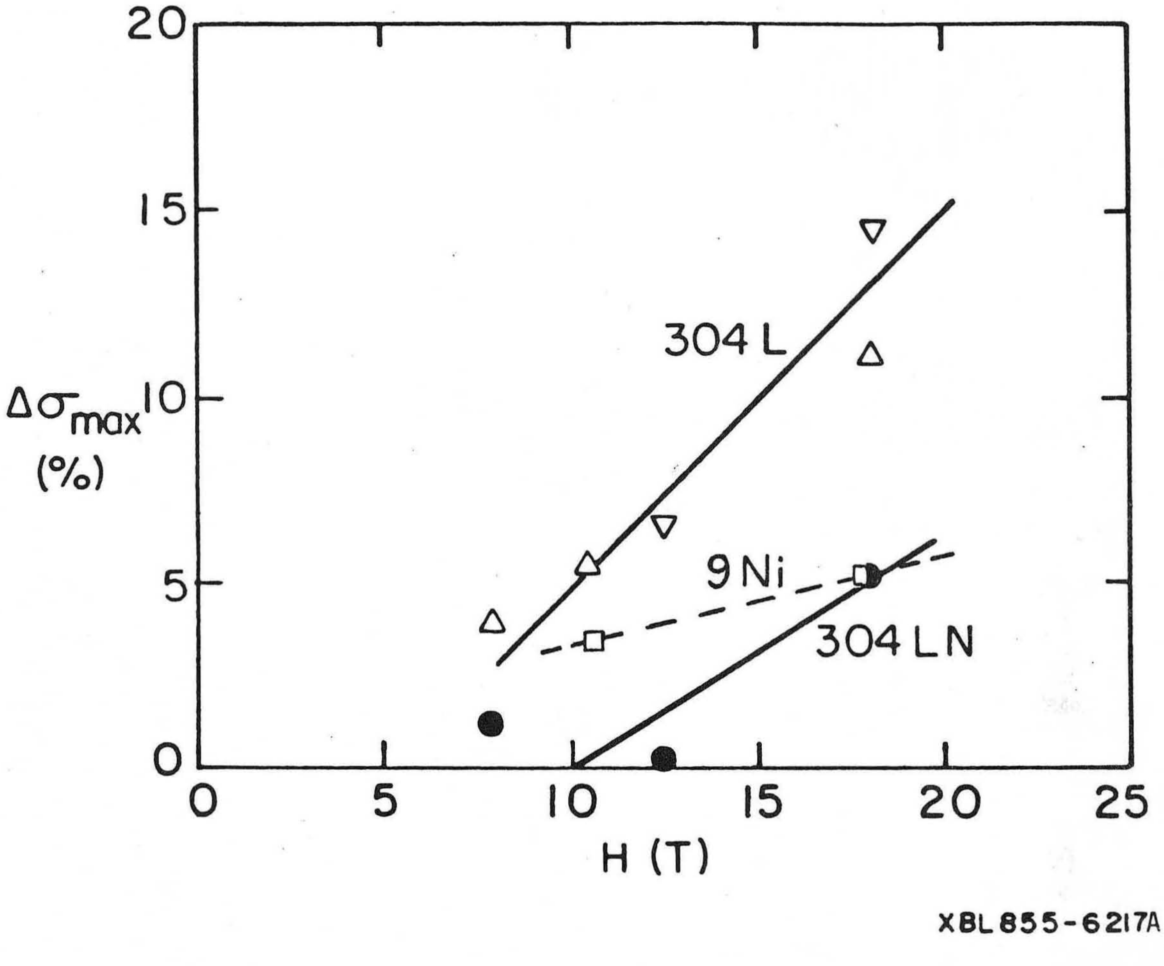


Fig. 7. Maximum percentage change of flow stress in the magnetic field versus magnetic field. point up triangles: AISI 304L at 4 K, point down triangles: AISI 304L at 77 K, dots: AISI 304LN at 4 K and 77 K, squares: overtempered 9Ni steel at 77 K.