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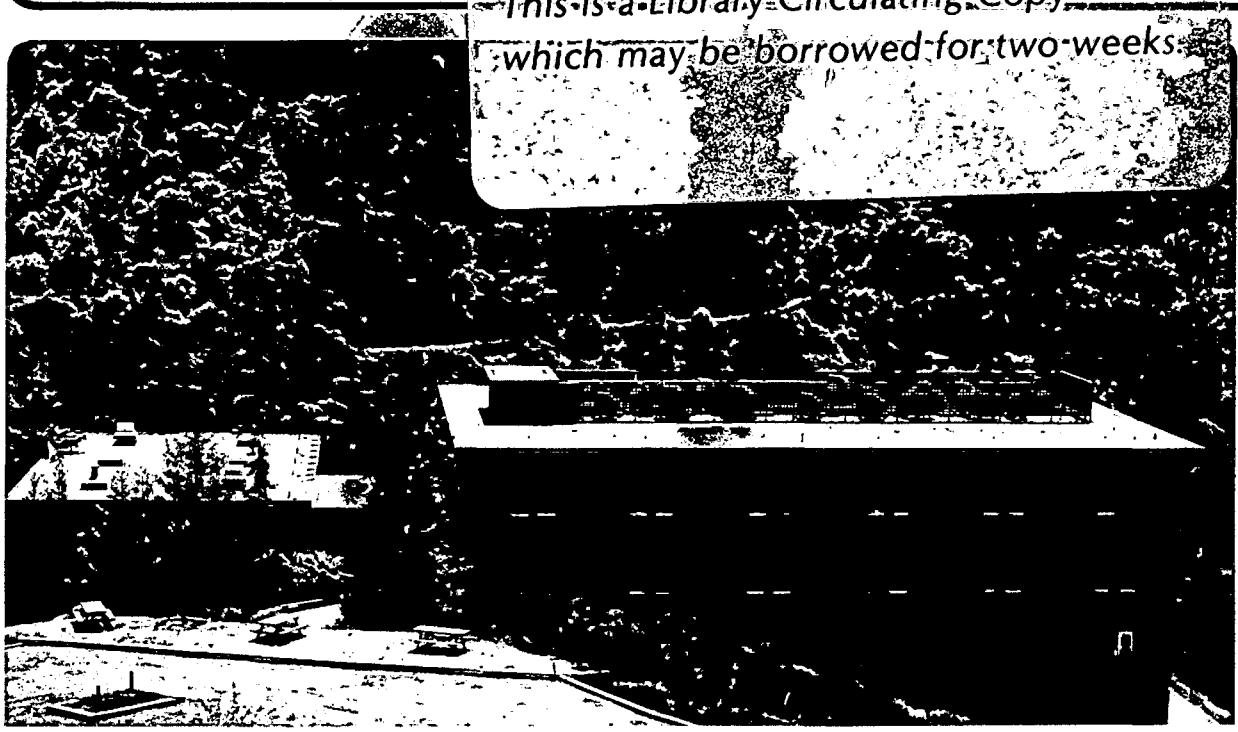

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Effects of High Magnetic Fields on the Flow Stress of 18-8 Stainless Steels

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ABSTRACT

The plastic deformation of two 18-8 stainless steels was studied in magnetic fields as large as 18 T at temperatures of 4 K, 77 K, and 290 K. Changes in stress-strain behaviour during magnetic exposure at cryogenic temperatures are reported, and are associated with an enhanced fcc→bcc martensitic transformation. In the magnetic field a reduced flow stress was observed at small strains, but at larger strains an increased rate of work hardening and a larger flow stress were observed. Additionally, a reduced elongation was found for the specimens tested in the magnetic field. Although these effects of magnetic fields are probably too small to be of engineering importance, they provide a unique means of determining how the fcc→bcc martensitic transformation affects the plastic deformation of 18-8 stainless steels.

INTRODUCTION

Their toughness, availability, corrosion-resistance, ease of fabrication and adequate strength have made stainless steels of the composition 18Cr-8Ni the most widely used structural steels for service at temperatures below 30 K. At low temperatures, however, the austenitic (fcc) crystal structure of these materials is thermodynamically metastable

against the fcc→bcc martensitic transformation, and this transformation can be promoted by plastic deformation. Mechanical effects of this martensitic transformation during deformation have been the subject of many previous studies, which have provided a general understanding of how the martensitic transformation affects stress-strain behaviour of 18-8 stainless steel. The fcc→bcc martensitic transformation is also known to be promoted by high magnetic fields at low temperatures. Mechanical effects which result from the additional martensitic transformation induced by high magnetic fields have received little previous study, and form the basis for the present research. Motivation for our investigation was provided in part by the widespread use of 18-8 stainless steels in large superconducting magnets. In many of these structures the stainless steel is simultaneously subjected to high magnetic fields, high stresses and low temperatures.

Because the magnetization of the ferromagnetic bcc phase is much greater than the magnetization of the fcc phase, magnetic fields can affect both the thermodynamics and the kinetics of the fcc→bcc martensitic transformation. It is straightforward to derive an expression for the change in temperature of equilibrium between phases of unequal magnetization subjected to an applied magnetic field [1]. It is found that the temperature of equilibrium between the fcc and bcc phases is increased by a few degrees K per Tesla of applied magnetic field. The non-equilibrium characteristics of the martensitic transformation are probably independent of the applied magnetic field, and the equilibrium estimate is useful in accounting for experimental data on the promotion of athermal martensitic transformations by magnetic fields at low temperatures [e.g. 2-4]. When the kinetics of nucleation (or growth) of martensite depend on the difference in free energy between the fcc and bcc phases, the amount of martensite observed for a specific time and temperature will be greater for materials subjected to high magnetic fields. Such effects of magnetic fields on isothermal martensitic transformations have also been observed and related to the free energy difference [5,6].

Since the martensitic transformation is known to affect the mechanical behaviour of steels, it seems reasonable that the additional martensitic transformation induced by applied magnetic fields should affect mechanical behaviour. However, previous studies of how magnetic fields affect mechanical properties have revealed only small or negligible effects. Reed et al. [7] found no effect of a 7 T magnetic field on the conventional tensile properties of an 18-8 stainless

steel at 4 K, although the serrated flow at this temperature would obscure small changes in flow stress. Bolshutkin et al. [8] reported effects of small magnetic fields on the flow stress of several stainless steels, but only when the fields were rapidly changing. Goldfarb et al. [9] failed to observe similar effects in an 18-8 stainless steel, and suggest that rapidly changing magnetic fields can distort mechanical properties measurements. Verkin et al. [10] reported large changes in the yield stress of several stainless steels at temperatures near their Néel temperatures. This anomaly in the yield stress, which was reported to be suppressed in the presence of a small magnetic field, was not observed in later experiments by Reed et al. [11].

In preliminary work by the authors [12], 16 T pulsed magnetic fields were found to increase the elongation of tensioned 18-8 stainless steel rods which were plastically strained at 77 K. The magnetic fields promoted more martensitic transformation and more inhomogeneous slip in the material. Conventional stress-strain curves in steady 8 T magnetic fields were obtained for 18-8 stainless steels at 77 K [13]. In the magnetic field small increases in flow stress were consistently observed for strains greater than 0.1. However, it was necessary to corroborate these small effects with experiments in higher magnetic fields. In the present work we report the results of conventional tensile tests on 18-8 stainless steels in 12.5 T and 18 T magnetic fields. In addition to verifying our previous results, the present work clearly demonstrates the effects of the fcc→bcc martensitic transformation on the flow stress of 18-8 stainless steel.

EXPERIMENTAL PROCEDURES

Specimens for tensile tests were machined directly from hot rolled plates of AISI 304L and AISI 304LN stainless steels which had net concentrations of carbon plus nitrogen of 0.098 and 0.160 wt.%, respectively. The tensile axis was parallel to the rolling direction of the plate. Gauge lengths and cross sections of the specimens were 38×4.2×3.2 mm for the 12.5 T experiments, and 25×3.0×2.0 mm for the 18 T experiments. All tensile tests were performed in pairs; one specimen was exposed to the magnetic field and the control specimen was not. Care was taken to prepare both specimens with the same machining practices and from the same region of the rolled plates.

Experiments at 12.5 T were performed with the specimens immersed in liquid helium within the gap of a split pair of superconducting solenoids which provided a magnetic field perpendicular to the tensile axis. Experiments at 18 T were performed at 4 K, 77 K and 290 K within the bore of a water cooled solenoid. In these experiments the tensile axis was parallel to the direction of magnetic field. A screw-driven load frame with feedback control was constructed for these experiments and transported to the 18 T magnet. All tests were performed under "stroke control". During deformation at 18 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 deformed at an approximately constant strain rate. Strain rates for all tests were 2.5×10^{-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. To study the effects of prior plastic deformation on the magnetically induced martensitic transformation, two sections were cut from tensile specimens deformed at 77 K without magnetic exposure. One of the sections was cooled to 77 K and exposed to a 40 T pulsed magnetic field, and the control specimen was cooled to 77 K in the same manner.

Measurements of the volume fraction of bcc martensite employed a Siemens Kristalloflex x-ray diffractometer with Cu Kα radiation. Data were taken under numerical control, and the peak intensities were digitally integrated. The volume fraction of bcc phase was determined as the ratio of the (211)bcc peak intensity to the intensity of the (211)bcc peak plus 1.3 times the average of the (220)fcc and (311)fcc peak intensities [14,15]. Surfaces for x-ray analysis were prepared by abrasive grinding followed by electrochemical polishing in fresh solutions of 40 % perchloric acid, 40 % glacial acetic acid and 20 % water. In the case of tested tensile specimens, x-ray analyses were performed on surfaces parallel to the tensile axis from the uniformly elongated part of the gauge length.

RESULTS

Fig. 1 and Fig. 2 show pairs of engineering stress-strain curves from AISI 304L stainless steel tested at 4 K and 77 K, respectively. Three differences between the two stress-strain curves are seen. 1) For strains less than about 0.1, the

specimen exposed to the magnetic field had a slightly suppressed flow stress. 2) At strains greater than about 0.1, the specimen exposed to an 18 T magnetic field during testing had a higher flow stress than the control specimen. 3) The total elongation of the specimen exposed to the magnetic field was reduced. Differences in the elastic part of the stress-strain curves were primarily due to differences in how the specimens settled into the grip fixtures during loading, and so are not significant. Data from pairs of AISI 304LN stainless steel tested at 4 K showed the same three effects of the magnetic field. Fig. 3 shows a pair of engineering stress-strain curves from AISI 304LN stainless steel tested at 77 K. The changes in flow stress induced by the magnetic field are smaller than for the AISI 304L material, and no difference at small strains is observed. However, the magnetically-induced change in elongation is larger than in the AISI 304L material. In the 12.5 T experiments at 4 K, qualitatively similar results were obtained for the AISI 304L specimens, although no effect of prior cold work was observed, contrary to our previous results [13]. No effect of the 12.5 T magnetic field was found for the AISI 304LN specimen tested at 4 K. Magnetic fields of 18 T did not affect the flow stress of specimens of AISI 304L and AISI 304LN material tested at 290 K *, and the small variations in elongation were attributed to small differences in work hardening rates between different specimens. A summary of all our results (including those in Ref. 13) for the change in cryogenic flow stress of AISI 304L and 304LN stainless steels in the presence of magnetic fields is provided in Fig. 4. Each datum was taken as the largest percentage change in flow stress in the magnetic field with respect to the flow stress of the control specimen (generally at a strain of 0.2 to 0.3).

Data from the tensile tests at 18 T were obtained digitally, so it was straightforward to convert the engineering strain into true strain, and the engineering stress into true stress. The strain hardening rate was then calculated. Strain hardening rates for the data of Figs. 2 and 3 are presented in Figs. 5 and 6. Figs. 2 and 5 and Figs. 3 and 6 are consistent with the Consideré criterion for the onset of the necking instability. At strains immediately prior to necking, the work hardening rate for the specimen exposed to the magnetic field was less than that of the control specimen. However, over most of the range of uniform elongation (true strains from 0.05 to 0.23 for AISI 304L, and true strains from 0.05 to 0.34 for AISI 304LN) the work hardening rate for the specimen exposed to the magnetic field was greater.

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* The flow stress was actually about 2 % less than that of the control specimen, but such a small change is not reliable.

At strains less than 0.05, the curves of Figs. 5 and 6 for the specimens exposed to the magnetic field are probably below those of the control specimens, which is expected if the magnetic field does not affect the elastic modulus, but suppresses the flow stress immediately after yielding. Work hardening rates for AISI 304L and 304LN specimens tested at 290 K did not show a maximum at intermediate strains, but rather decreased monotonically from the strain of yielding to the strain of necking.

Results from x-ray diffractometry analysis of the volume fraction of bcc martensite formed in specimens subjected to different combinations of strains, temperatures and magnetic fields are presented in Table I. The martensitic transformation in tensile specimens of AISI 304L tested at 4 K and 77 K was extensive, and magnetic exposure during testing induced only small (but consistent) additional amounts of transformation (Table I.A.). At 290 K the amount of transformation in AISI 304L was less extensive, and much additional transformation occurred in the magnetic field. The amounts of bcc martensite found in the AISI 304LN tensile specimens tested at 4 K and 77 K were about 70 % and 90%, respectively. Unfortunately, additional effects of the magnetic fields could not be discerned because tensile specimens of AISI 304LN showed large macroscopic inhomogeneities in their necking instabilities, and the amount of transformation measured by x-ray diffractometry analysis depended on the positioning of the specimen in the

Table I. Volume Percentage of bcc Martensite

A. Tested Tensile Specimens of AISI 304L

Temp. \ Field	0 T	10.5 T	12.5 T	18 T
4 K	93	--	95	94
77 K	94	95	--	95
290 K	35	--	--	45

B. Effect of Prior Strain at 77 K

Mat'l, Strain \ Exposure	Strain	Strain +77 K	Strain +77K+40T
304L, 0 %	0	0	0
304L, 7 %	20	26	29
304L, 25 %	80	78	78
304LN, 0 %	0	--	0
304LN, 6 %	3	--	3
304LN, 15 %	26	--	26

diffractometer. The deformation of the AISI 304LN specimens at 290 K was somewhat more uniform; the amount of bcc martensite in the control specimens was 2 %, and 10 % was found in tensile specimens exposed to the 18 T magnetic field. Pulsed magnetic fields of 40 T induced little additional martensitic transformation in 18-8 stainless steel, even when the material was subjected to prior plastic strain (Table I.B.). Exposure to the pulsed magnetic field at 77 K induced additional martensitic transformation only in the case of AISI 304L with a prior plastic strain of 7 %. In this case, however, most of the additional transformation occured during thermal exposure alone.

DISCUSSION

In tensile tests in high magnetic fields, a reduction in flow stress was found immediately after yielding. This is attributable to an increased rate of martensite formation in conjunction with a mechanical effect of this martensite termed the "window mechanism" [16]. Bcc martensite is frequently observed at intersections of two shear bands in 18-8 stainless steel [16-19]. It has been previously noted that the bcc structure can be constructed from the fcc structure by two independent shears [20], for example at the intersection of an hcp shear band with a second shear band of highly faulted fcc or hcp crystal [21]. When the bcc phase is thermodynamically favorable, Suzuki et al. [16] have proposed that the formation of bcc martensite at the intersection of two slip bands will facilitate the passage of the second band through the first. They term this the "window mechanism" because the second shear deformation band passes through small "windows" of bcc martensite in the first band. Only trace amounts of hcp phase (always less than 4 %, and frequently less than our detectability limit of 1 %) were found in any of our materials by x-ray diffractometry. However, it seems reasonable that the bcc structure could be generated at the intersection of two faulted bands of fcc crystal when the average dislocation density at the intersection reaches a critical value. Exposure to high magnetic fields during deformation should further facilitate bcc martensite formation at slip band intersections, so the observed reduction of flow stress in the magnetic field suggests the importance of a "window mechanism" at small strains in our materials. The operation of the window mechanism requires both plastic strains to produce the slip bands and stresses to force their crossing. This is consistent with our observations that magnetic exposure induced more martensitic

transformation in material which was subjected to plastic strain and simultaneously held under stress, than in material which was subjected to plastic strain alone. As previously reported [12], a 16 T magnetic field at 77 K increased the amount of bcc martensite from 3 to 6 % in our AISI 304L material when it was held under the stress required for a 2 % strain. However, a 40 T magnetic field at 77 K increased the amount of bcc martensite from 26 to only 29 % in AISI 304L material when it was subjected to a prior 7 % strain. That the 40 T field did not produce a larger amount of transformation is made even more significant by the fact that the austenite in 18-8 stainless steel is substantially less stable after a prior strain of 7 % than after a prior strain of 2 % [18,22]. After exposure to a 40 T magnetic field at 77 K, no additional martensitic transformation was detected in AISI 304LN materials with prior plastic strains, although a 16 T magnetic field induced very small additional transformations in stressed specimens of AISI 304LN material at 77 K [12].

After a significant amount of slip occurs, the crystallographically elegant "window mechanism" is less important. An increasing work hardening rate is observed for strains greater than about 0.05. This work hardening is enhanced in the presence of high magnetic fields, and is attributed to an increased rate of bcc martensite formation during magnetic exposure. Thermodynamic and some kinetic arguments predict that the amount of additional martensitic transformation during magnetic exposure will scale with the strength of the magnetic field. The scaling of the magnetic effect on flow stress with magnetic field (Fig. 4) is therefore consistent with a mechanism in which the flow stress is increased in proportion to the additional martensitic transformation. This is in agreement with work by Manganon and Thomas [23]. Only about one-third to one-half as much bcc martensite forms in AISI 304LN than in the less stable AISI 304L material for the same plastic strain. It is therefore reasonable that the largest effects of the magnetic field on flow stress were observed for the AISI 304L material; the effects of the magnetic field on the flow stress of the AISI 304LN were only about one-third to one-half as large.

The elongation of a specimen in a tensile test is determined by the strain at which the work hardening rate falls below the true stress in the material (Considere criterion). Much of the work hardening of 18-8 stainless steels is attributable to the formation of martensite during deformation, but the process of martensite formation is largely complete in the uniformly elongated sections of those specimens pulled to failure at 4 K and 77 K. It seems that the

Considere criterion is met when essentially all of the fcc phase has transformed to bcc martensite, and the material exhausts its capacity for work hardening. The more rapid work hardening rate of tensile test specimens exposed to high magnetic fields should therefore result in a reduced elongation, and this is observed. The actual amount of this magnetically-induced reduction in elongation will depend more on the dimunition of the transformation at large strains than on the initial instability of the austenite. It is therefore not inconsistent that the reductions in elongation of the AISI 304L and AISI 304LN materials are about the same, even though the austenite in AISI 304L material is initially more unstable. From Fig. 4 we see that the rate of work hardening of the AISI 304LN material immediately before necking is lower than that of the AISI 304L material, so at this stage of deformation a given reduction in the amount of austenite available for transformation may have a stronger effect on the uniform elongation of AISI 304LN than of AISI 304L material. Quantitative predictions of the effects of magnetic fields on elongation require more detailed information on the mechanisms by which the martensitic transformation affects work hardening behaviour, as well as more information on other mechanisms such as the intrinsic strain hardening of the fcc and bcc phases [24].

CONCLUSIONS

High magnetic fields were found to modify the flow stress of two 18-8 stainless steels through promoting additional martensitic transformation during deformation. These changes in flow stress scaled with the strength of the magnetic field, and were larger for the AISI 304L than the AISI 304LN material. Immediately after yielding the flow stress of tensile test specimens exposed to high magnetic fields was reduced with respect to the control specimens, consistent with the "window mechanism". With further strain the work hardening rate of the specimens exposed to magnetic fields increased, and at strains of about 0.1 their flow stress became greater than that of the control specimens. This enhancement of work hardening was the largest observable effect of the magnetic field, and is attributable to hardening mechanisms associated with the formation of martensite particles. Since this second mechanism is a major source of work hardening in 18-8 stainless steels at 4 K and 77 K, the earlier completion of the martensitic transformation in high magnetic fields resulted in a reduced elongation of tensile test specimens.

The effects of high magnetic fields on the deformation behaviour of 18-8 stainless steels are probably too small to be of engineering importance in the design of large superconducting magnets. However, these effects are useful for studying how the fcc→bcc martensitic transformation affects plastic deformation. Such studies must vary the amount of transformation, and measure the resulting changes in deformation behaviour. Tuning the stability of the fcc phase with a magnetic field will vary the amount of transformation without the risk of changing other characteristics of the material, unlike experiments which vary composition, microstructure or temperature.

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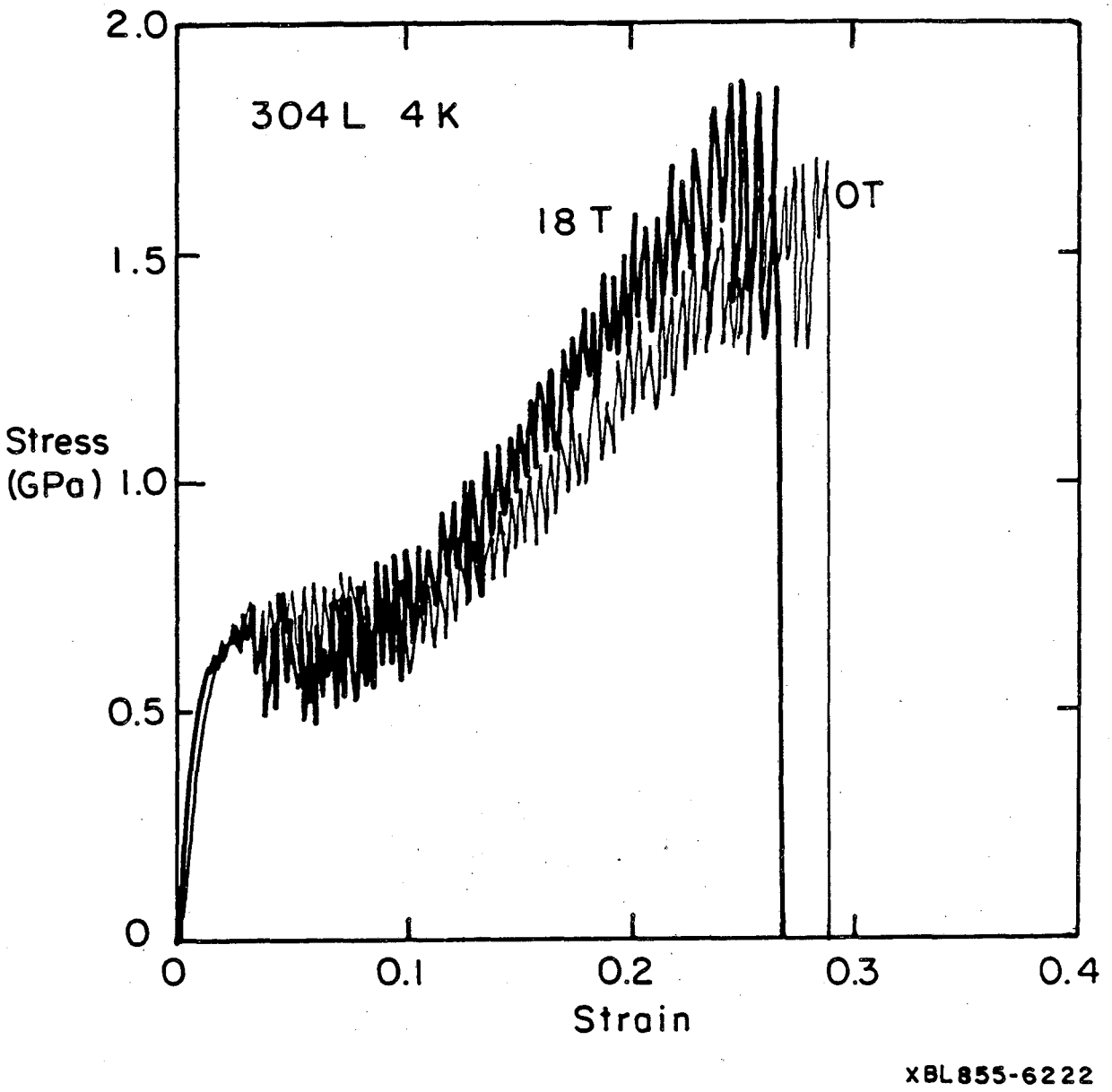

Fig. 1) Engineering stress-strain curves of AISI 304L stainless steel at 4 K.

heavy curve: with 18 T magnetic field, light curve: without magnetic field.

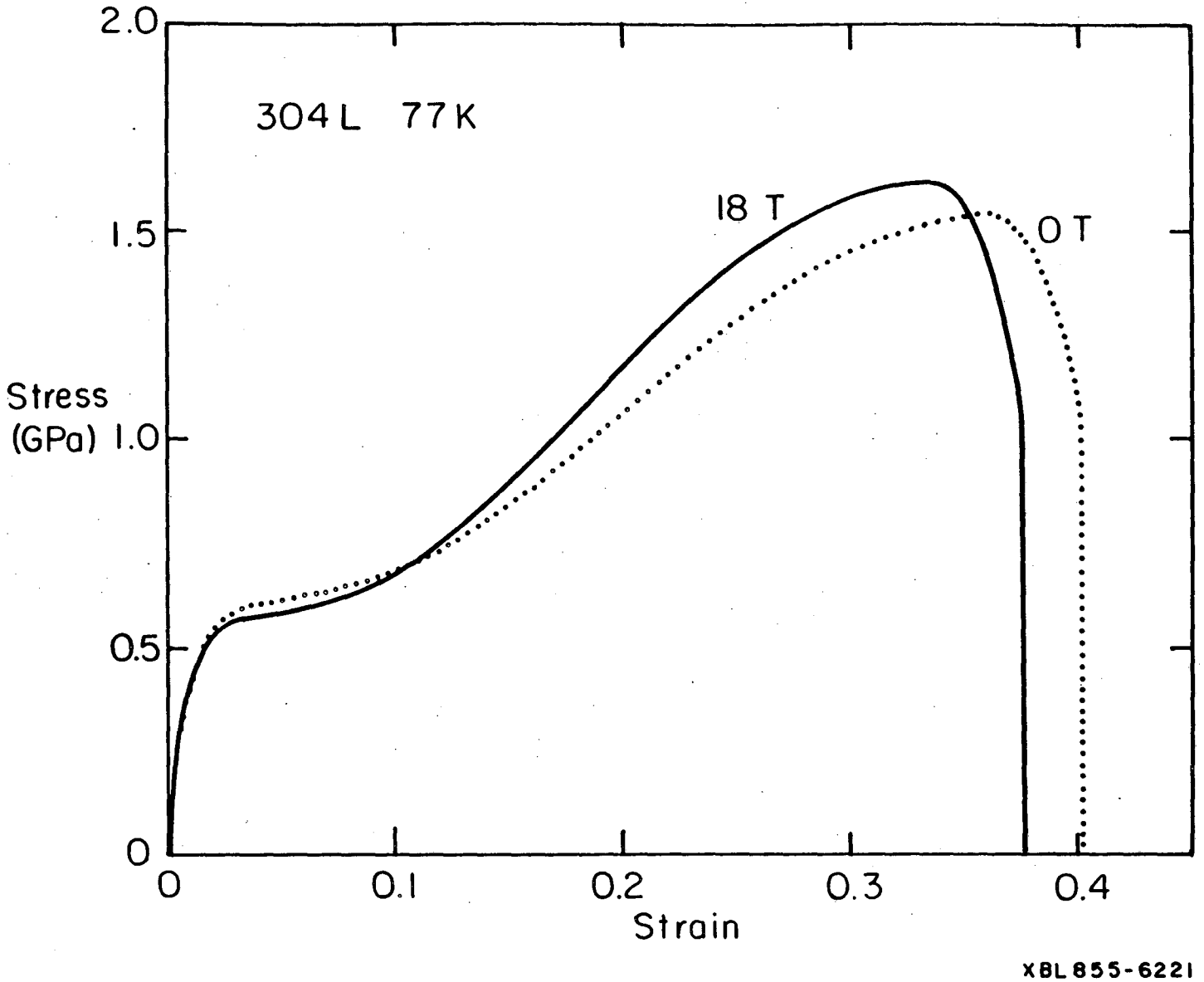

Fig. 2) Engineering stress-strain curves of AISI 304L stainless steel at 77 K.

solid curve: with 18 T magnetic field, dotted curve: without magnetic field.

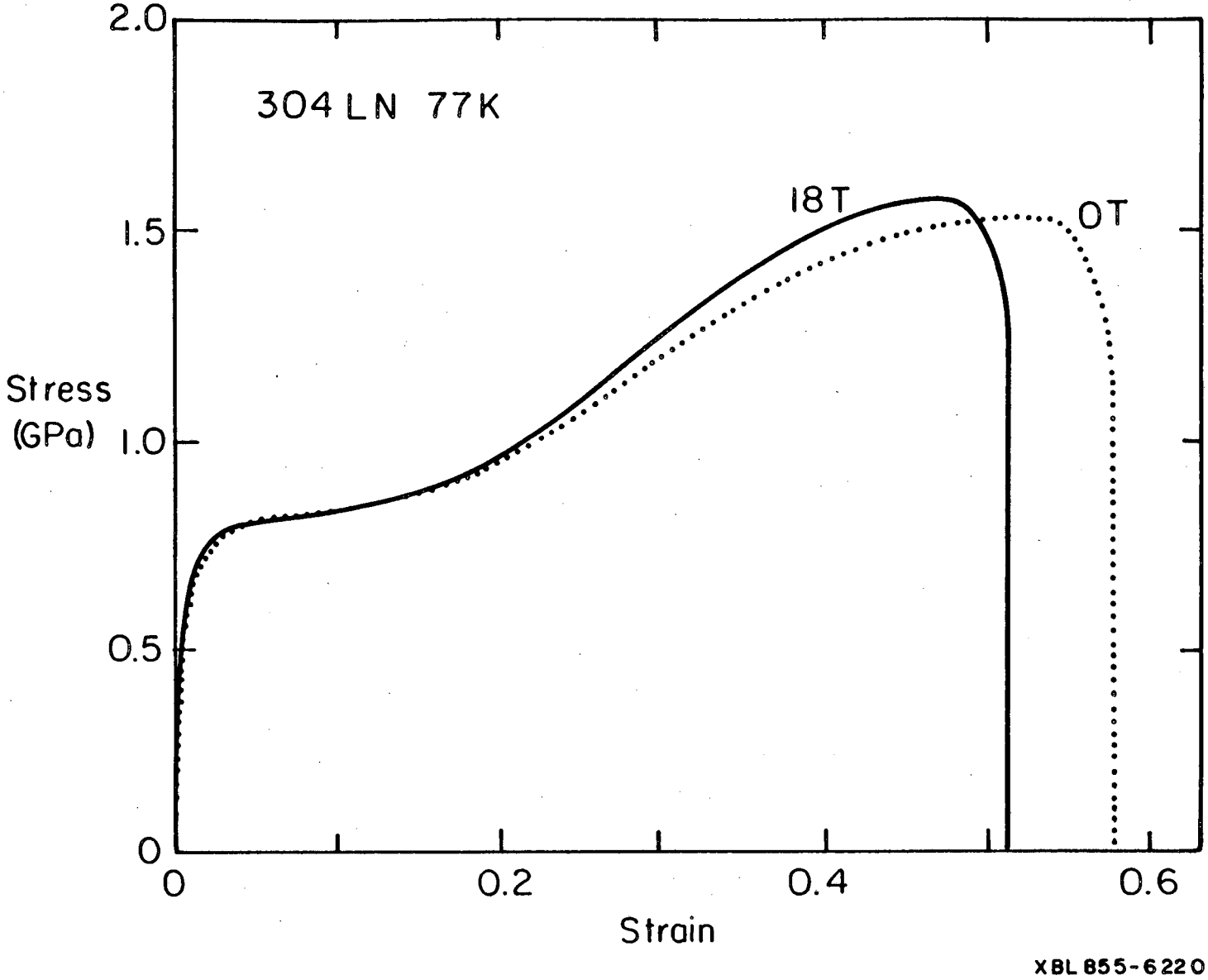

Fig. 3) Engineering stress-strain curves of AISI 304LN stainless steel at 77 K.

solid curve: with 18 T magnetic field, dotted curve: without magnetic field.

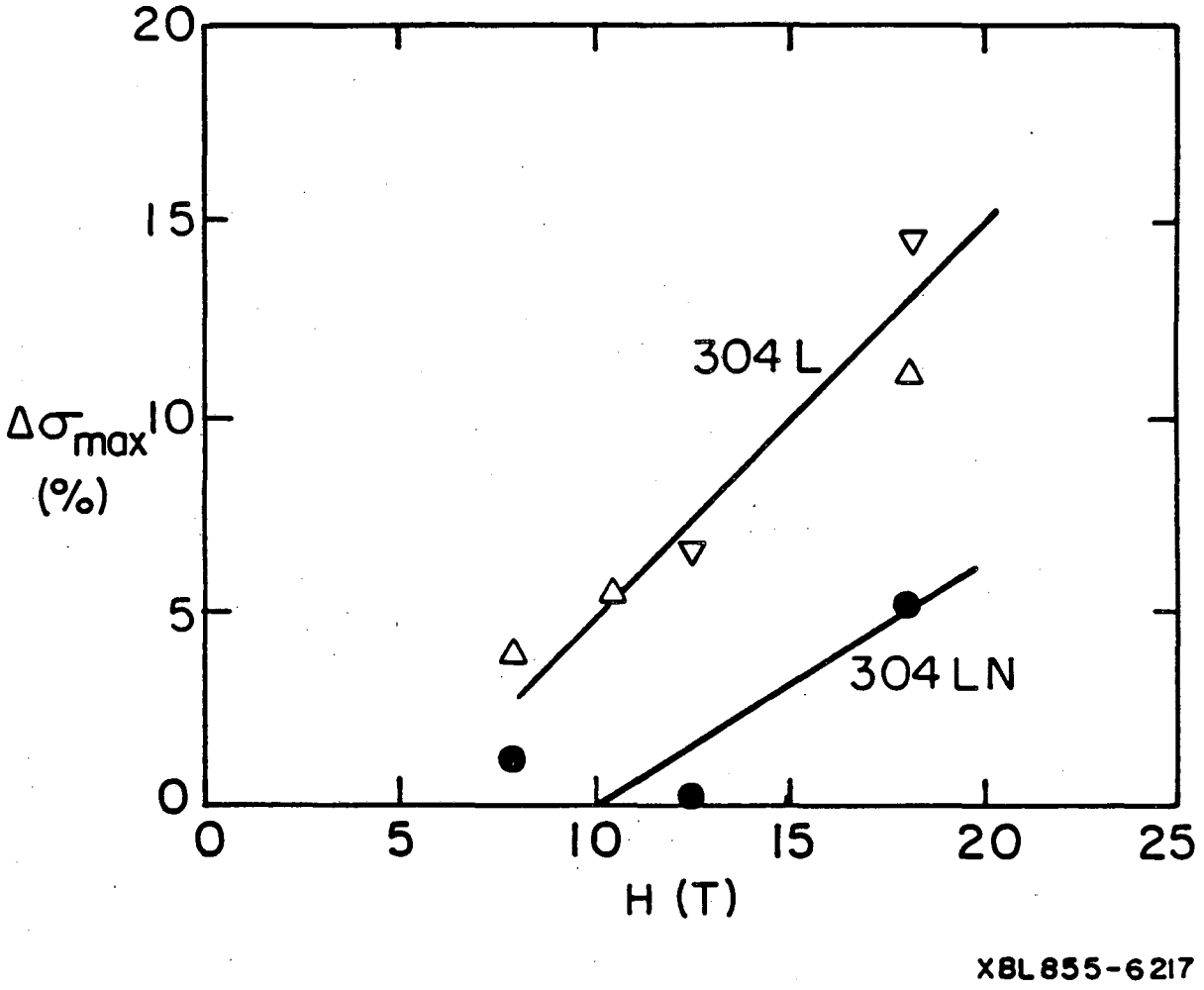

Fig. 4) Maximum percentage change of flow stress in the magnetic field versus magnetic field.

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.

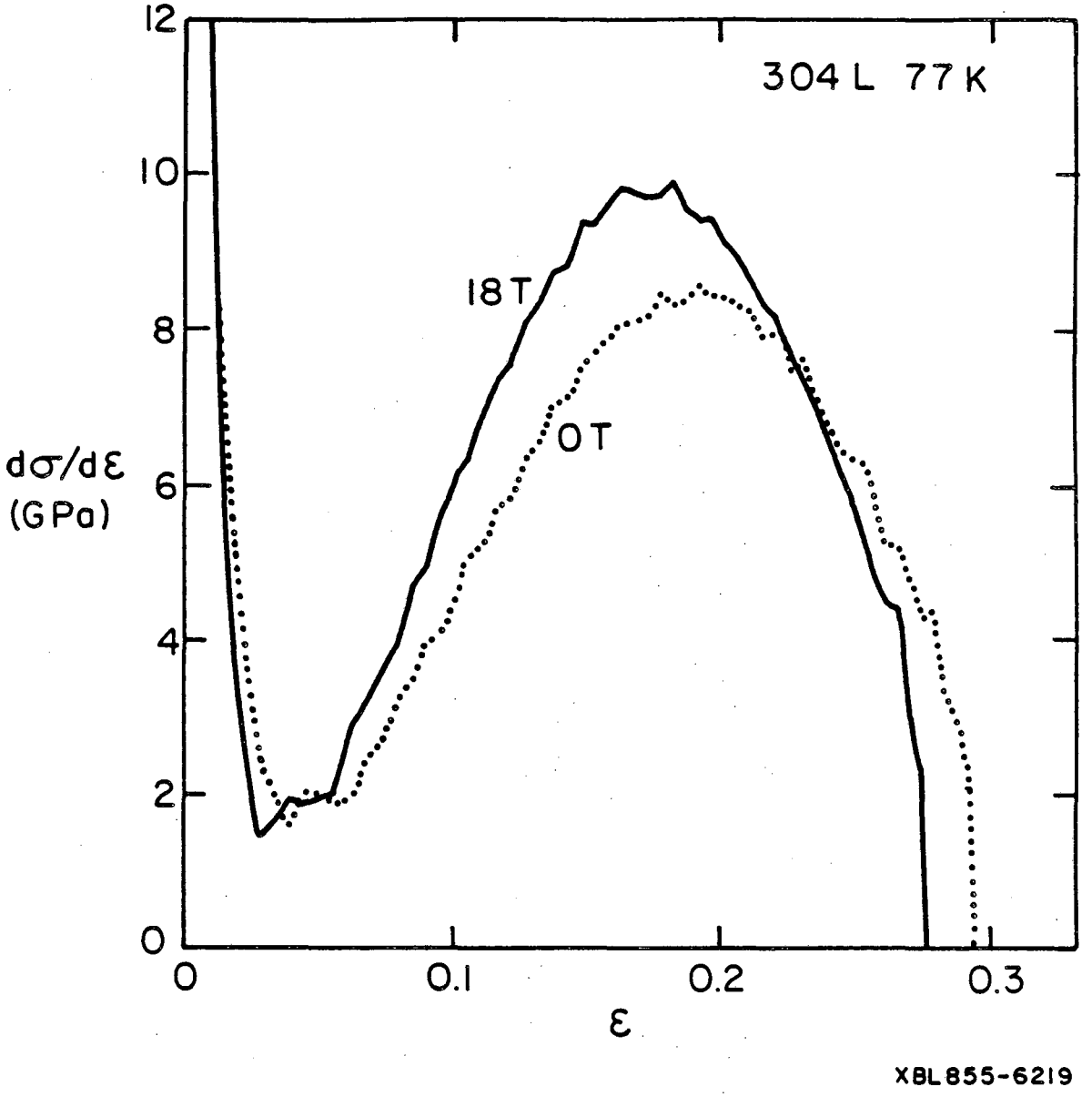

Fig. 5) True work hardening rate versus true strain for AISI 304L stainless steel at 77 K. solid curve: with 18 T magnetic field, dotted curve: without magnetic field.

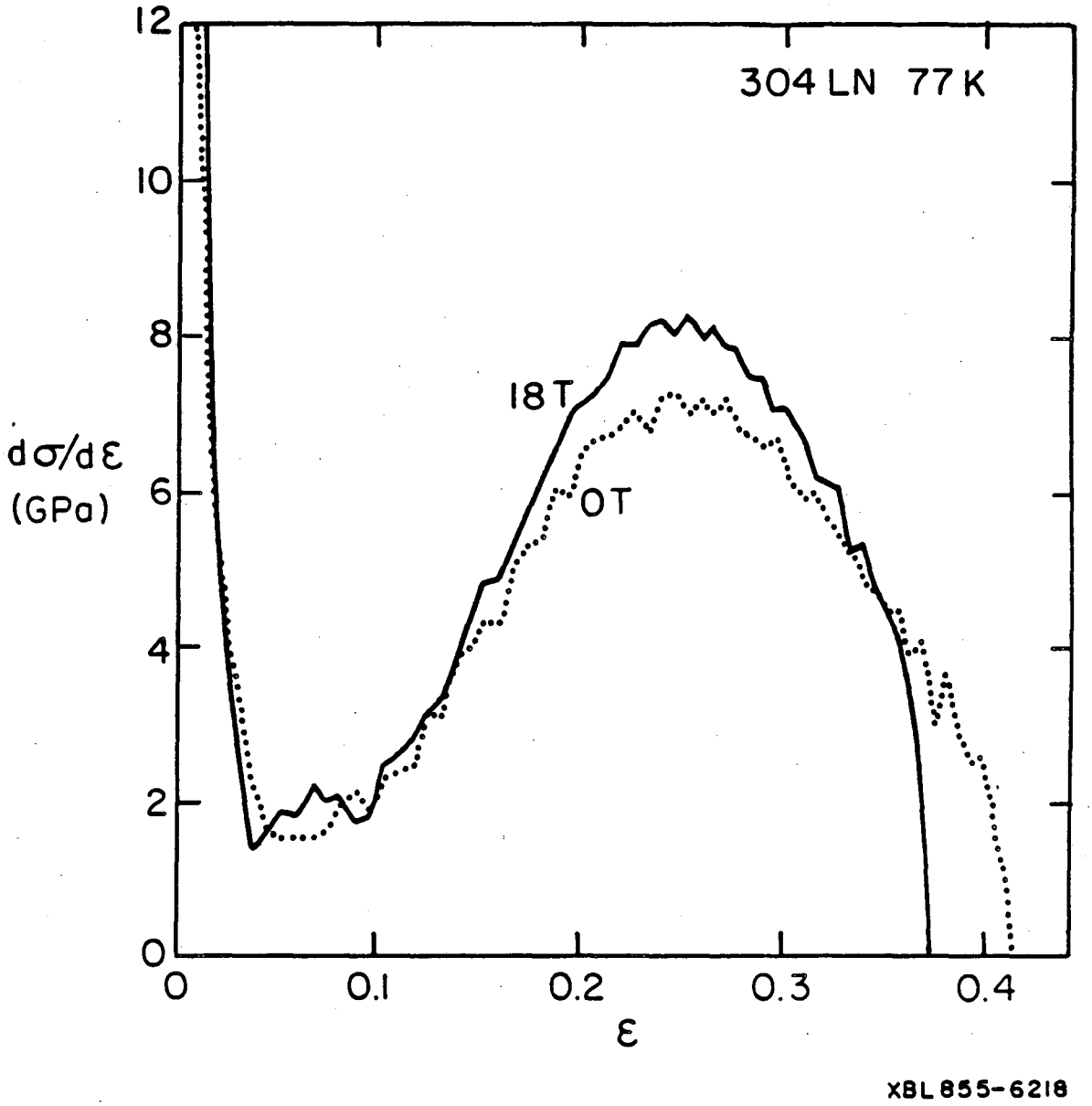

Fig. 6) True work hardening rate versus true strain for AISI 304LN stainless steel at 77 K. solid curve: with 18 T magnetic field, dotted curve: without magnetic field.

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