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THE FABRICATION OF MULTI-FILAMENT NbTi COMPOSITE WIRE FOR ACCELERATOR APPLICATIONS

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Abstract

Magnets for the Fermilab Energy Doubler Accelerator will cycle from 1.0T to 4.5T and back every 30 seconds. In order to minimize thermal losses in these magnets filament size must be minimized, the matrix of the composite separated by high resistivity material, and the filaments twisted to prevent coupling. Cost considerations also dictate that the critical current be maximized in order to cut costs. This paper will review the methods used to manufacture superconducting cables that meet these criteria. The metallurgical processing parameters that affect the kinetics of optimizing the performance of these conductors are discussed in detail.

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INTRODUCTION

The Fermi National Accelerator Laboratory is planning to construct a superconducting particle accelerator at Batavia, Illinois. This device will use some 1000 dipole and quadrupole magnets wound with NbTi superconducting cable. The choice of properties and processing for this cable are discussed in this paper.

PROPERTIES

Because we need to make over 1000 magnets, the conductor should be as like copper wire as possible. This requires that the conductor be ductile and that it is able to be fabricated into magnets under industrial conditions as opposed to laboratory conditions.

High current density is required in order to minimize the total amount of wire. It is also necessary to stabilize the conductor. This is accomplished by providing a copper or aluminum matrix around the superconducting alloy. The stabilizing matrix serves two purposes. First, it provides a parallel conduction path shunting any excess current above the critical current of the superconductor. The stability criterion here is that any I^2R losses in the matrix are less than the ability of the liquid helium to cool. Secondly, both copper and aluminum have low magnetic diffusivities. This means that the movement of magnetic flux lines is slowed down, thus limiting the occurrence of flux jumps. A flux jump is a change in flux within the conductor that could cause a quench or catastrophic change to the normal state.

One can ameliorate the effect of flux jumps by making the individual filaments within the copper matrix smaller than a critical diameter. Here the criterion is that the heat generated during a flux jump does not raise the superconductor above the local critical temperature. Since the magnet-stored energy in a filament goes as the square of the diameter, the stable filament size is very small, on the order of 10 μm. It is also necessary to have small filaments to minimize ac or ramping losses. These losses go as the diameter of the filaments and the 10 μm size gives losses that are in an acceptable range. The loss model and stability model are only valid if the individual filaments are decoupled or act independently. This can be accomplished by twisting the wire around its axis, thus forcing the individual filaments to assume a helical path within the stabilizing matrix.

FABRICATION TECHNIQUES

With present technology, one is limited to niobium-titanium alloys in order to be able to fabricate conductors with all of the above properties. NbTi has the ductility, as compared with say the NbZr solid-solution, to permit the large scale reductions necessary in production. For typical conductors, one starts by assembling alloy rods into hex o.d. round i.d. copper (ASTM Spec B-170-1) tubes. These tubes are then stacked in a hexagonal array until the required number of filaments is reached. To attain the small filament sizes discussed above more than 2000 composite rods are required. An extrusion can is then slipped over the stacked assembly and filler rods are inserted to help increase the packing density. The nose and tail pieces are then electronbeam welded into the can and at the same time it is pumped out.

The assembled can is then extruded at about a 16 to 1 reduction in area. Rod drawing then follows. In this process, the composite is reduced to about 0.300 inch diameter. Standard wire drawing techniques are used to further reduce the diameter of the wire. At several points during this process the wire is annealed to soften the copper.

THERMAL AND MECHANICAL PROCESSING

In order to optimize the superconducting properties, the choice of alloy as well as the heat treatment schedule during reduction is important. The critical temperature, T_c, and upper critical field, H_{c2}, are not very sensitive to composition as shown in Figure 1.[1] On the other hand, critical current is not an inherent property of the material and benefits from treatment. Microscopically magnetic flux penetrates a type II superconductor in the form of fluxons or quantized flux lines. These fluxons interact with the transport current by means of the Lorentz force, $J \times H$. During flux motion or change, voltages are induced by means of Maxwell's relations and the superconductor becomes resistive. Thus one must limit the motion of the flux lines by "pinning" in order to optimize the critical current. Effective pinning sites are normal regions within the superconductor which can be inhomogeneities, dislocations, precipitates or voids. In the following the effects of mechanical and thermal processing are discussed.

For the high titanium alloys, those with greater than 50 weight percent Ti, the superconducting properties are optimized by a precipitation heat treatment (PHT) to form a fine distribution of normal flux pinning particles. Figure 2 shows parametric J_c curves for several alloys as a function of time for a given heat treatment temperature.[2] Here one can see typical effects that would be evident in plotting, say, mechanical properties in a PHT alloy. For example, the effects of over-ageing are plainly evident. The amount of prior cold work also affects the current density since dislocations usually provide nucleation centers for precipitation growth.

Figure 3 is a plot of the critical temperature as a function of PHT.[2] These data suggest that the heat treatment may change the chemistry of the matrix phase since critical temperature is a function of composition.

For the low Ti alloys (Nb44-48Ti) cold work is the predominant factor in attaining high J_c. Figure 4 shows the effect of heat treatment on a cold-worked Nb45Ti alloy.[1] The ideal structure is to form the dislocation networks into a cellular structure with an average cell wall separation of a few hundred angstrom units. In this work, the authors found that both the J_c and the α phase precipitate increased with cold work.

Figures 5 and 6 are from work by Neal, et al.[3] Here one can see the effects of cold work and heat treatment on the Lorentz or pinning force. In Figure 5, one can see the J_c increasing with working and in fact one can see that there is a minimum amount of working, at which point the pinning force takes a large jump. In Figure 6, one sees the effect of heat treatment time. Heat treatments in the range of 300°C for one hour produced a large increase in J_c. At higher temperatures grain growth was obviously too high and properties began to fall. Heat treatment in the 350°C range for times exceeding one hour also improved the current capacity.

INTERMEDIATE HEAT TREATMENTS

The timing of the heat treatments can produce changes in J_c for the equivalent amount of cold work. An intermediate heat treatment will result in recovery and cell wall rearrangement and perhaps some precipitation within the highly deformed structure. Additional cold work after the heat treatment will produce new dislocations which tend to tangle around the precipitates and cell walls and result in more effective pinning centers. Figure 7 illustrates the effect of increasing cold work after heat treatment at an intermediate stage.

PINNING FORCE VS. CELL WALL SIZE

That the cell wall size is an important parameter in determining J_c is shown in Figure 8.[3] A linear relationship exists between the critical current and the reciprocal of the cell size. There appear to be two processes occurring during heat treatment. First dislocation, annihilation, and rearrangement, and second, sub-cell growth. Sub-cell growth is the slower process at lower temperatures. Heat treatment at about 375°C at times greater than one hour seems to provide an optimum balance between the cell wall growth and the formation of effective pinning sites due to dislocation rearrangement. However, once the effective pinning centers have formed, cell size controls J_c.

SUMMARY

The choice of an alloy system for solid solution superconducting alloys depends more on the ease of processing. Critical current can be optimized by a combination of cold work and heat treatment.

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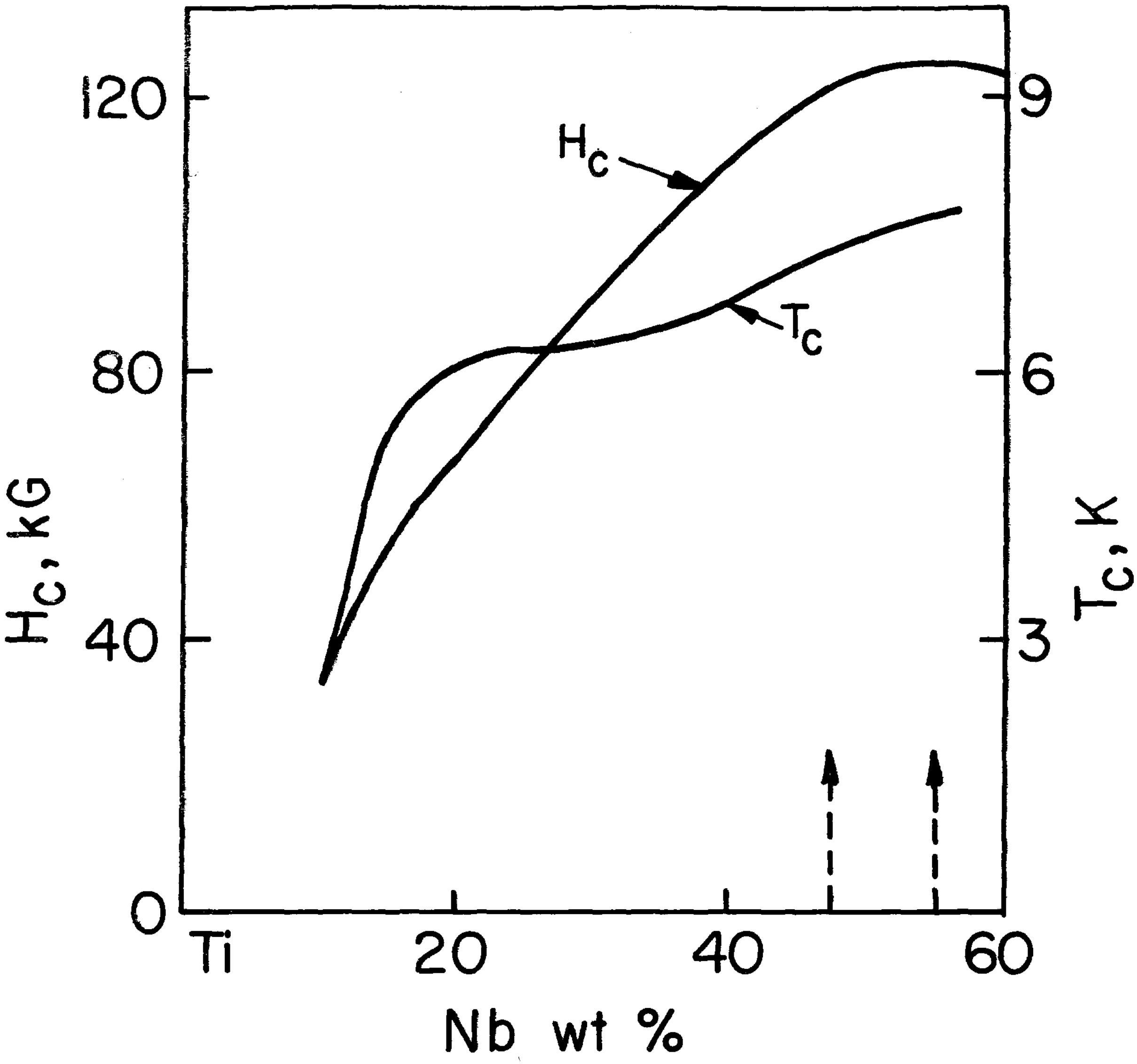

Figure 1. T_c and H_{c2} as a function of composition.[1]

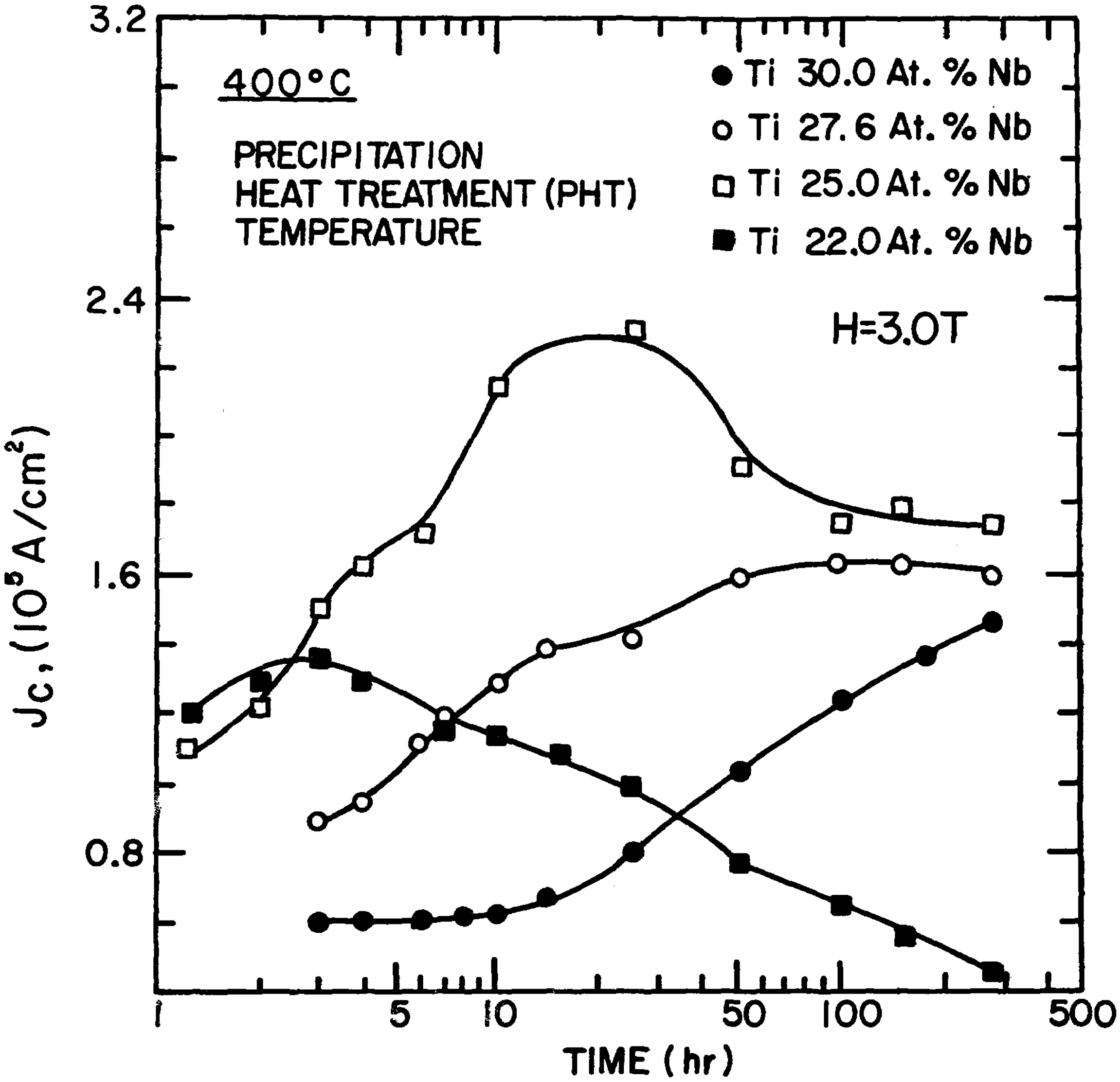

Figure 2. J_c (3T) as a function of heat treatment time for several alloys.[2]

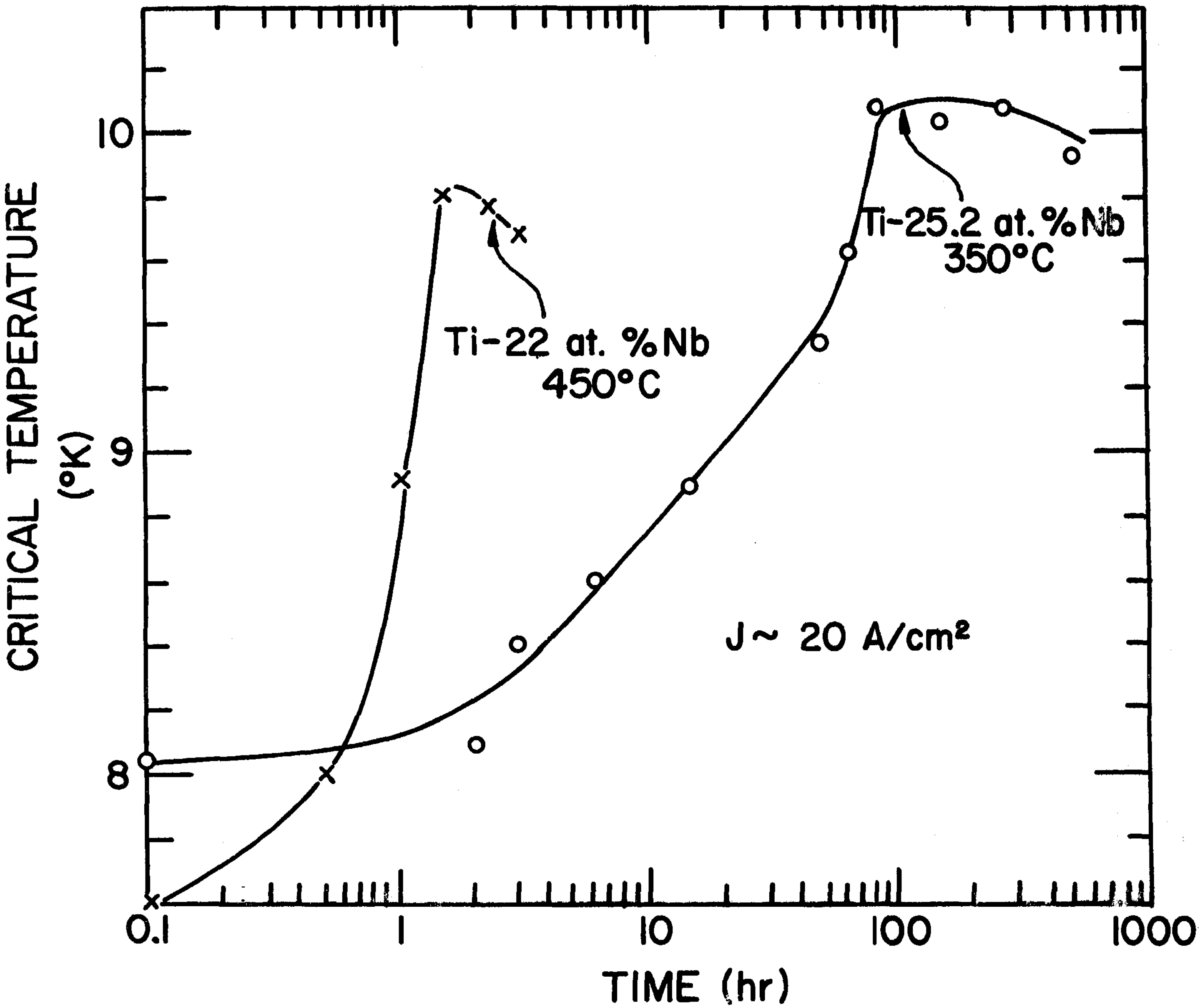

Figure 3. T_c vs. heat treatment time.[2]

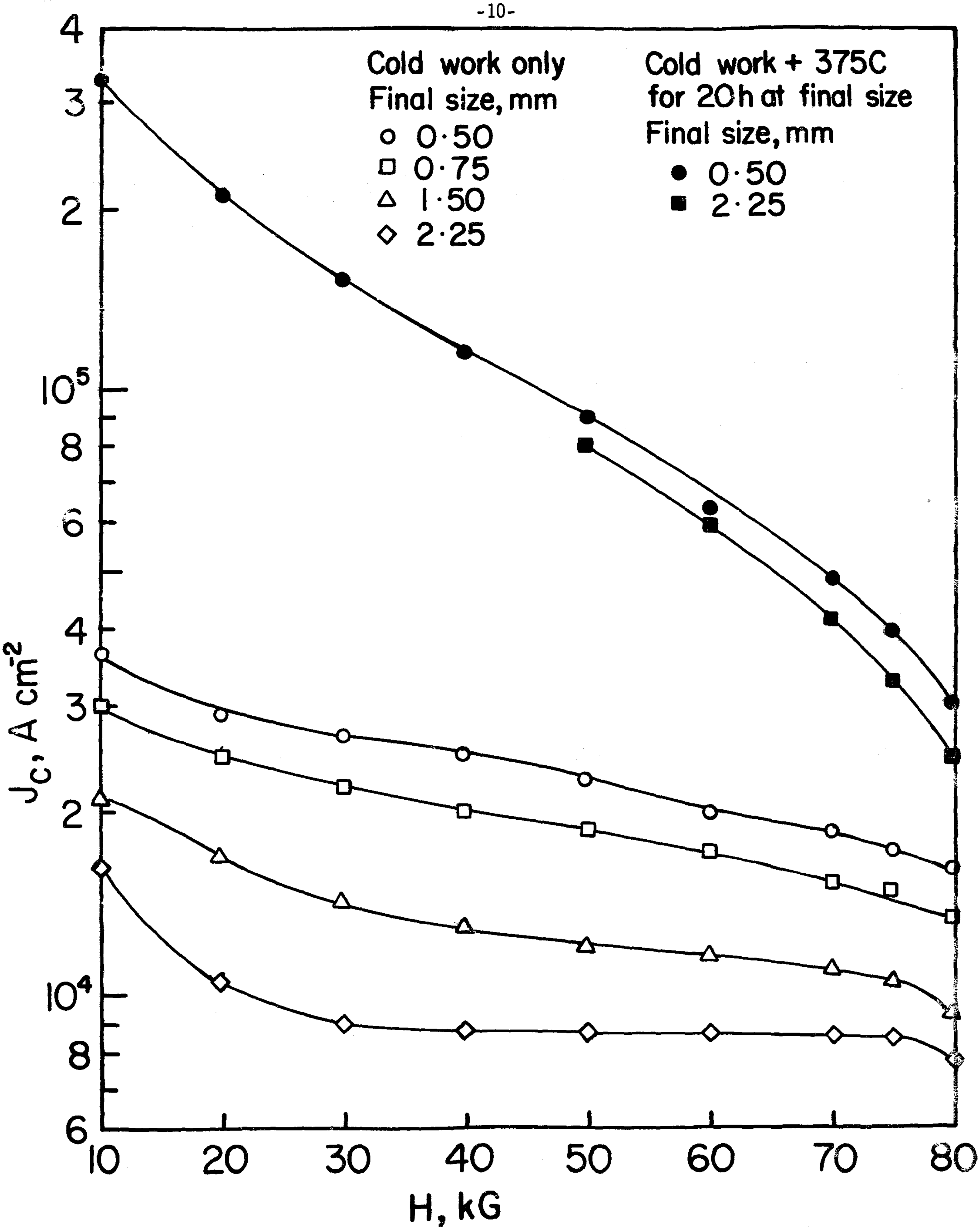

Figure 4. Effect of increasing cold work on J_c.[1]

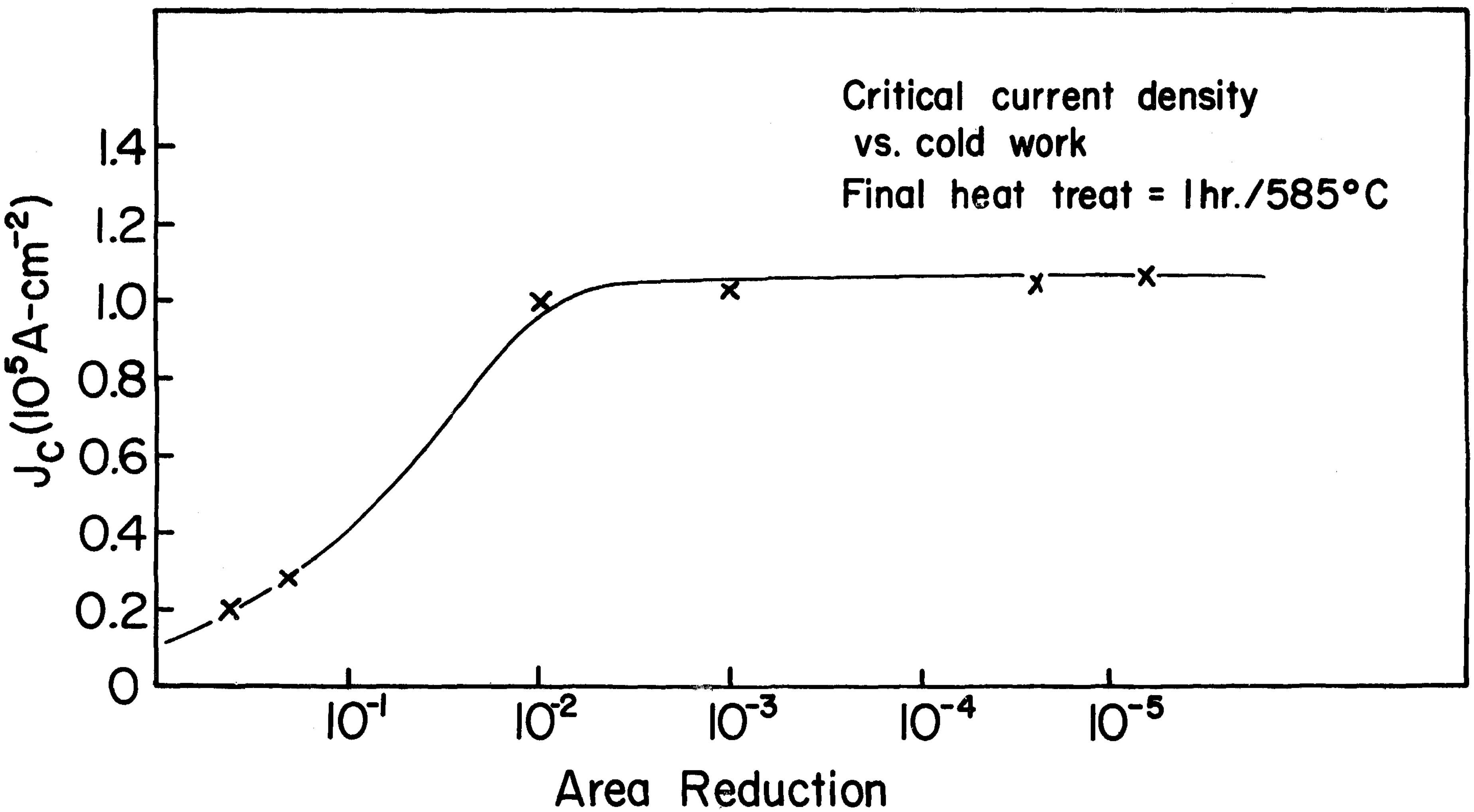

Figure 5. Effect of increasing cold work on J_c.[3]

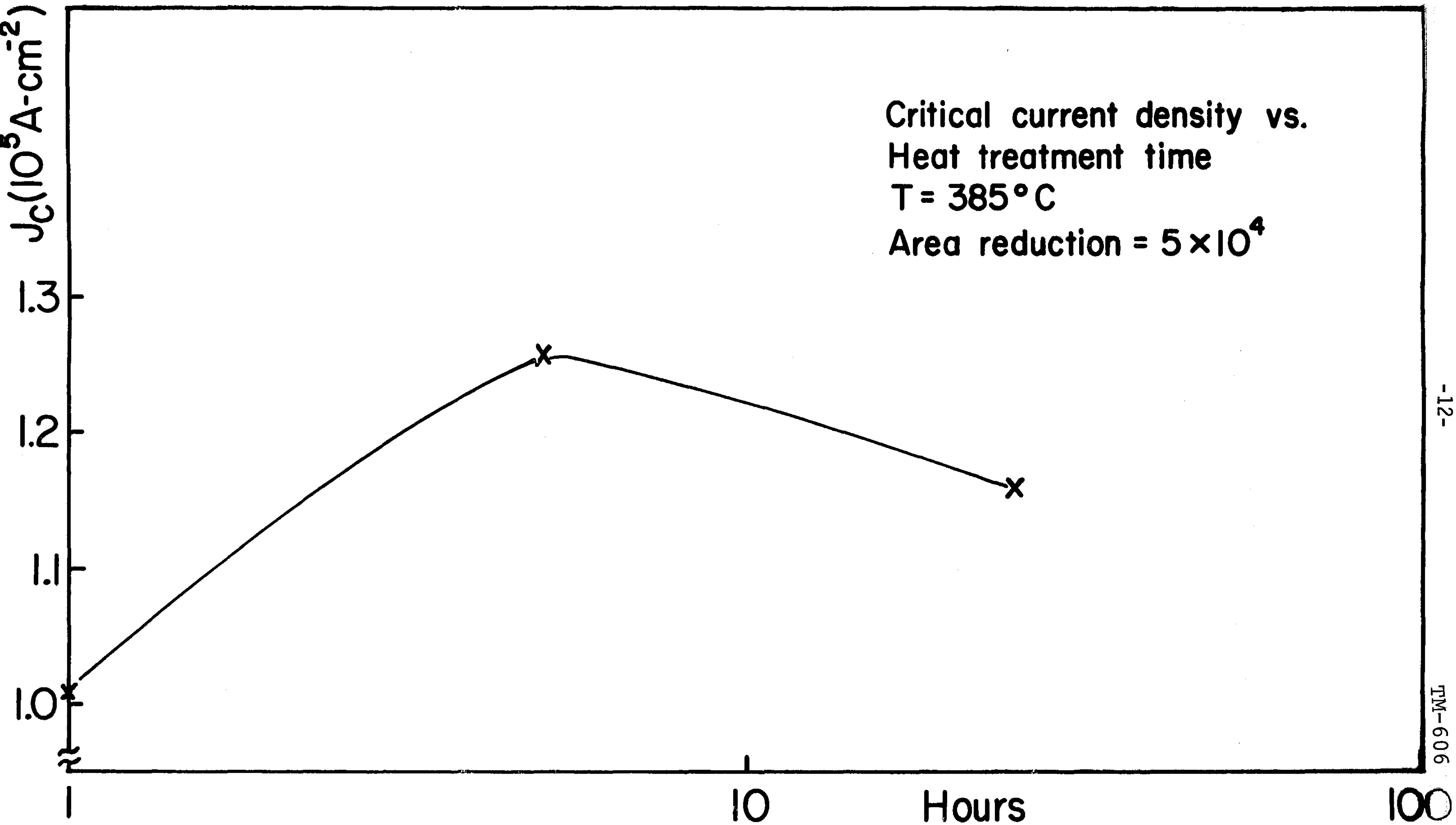

Figure 6. Effect of heat treatment time on J_c.[3]

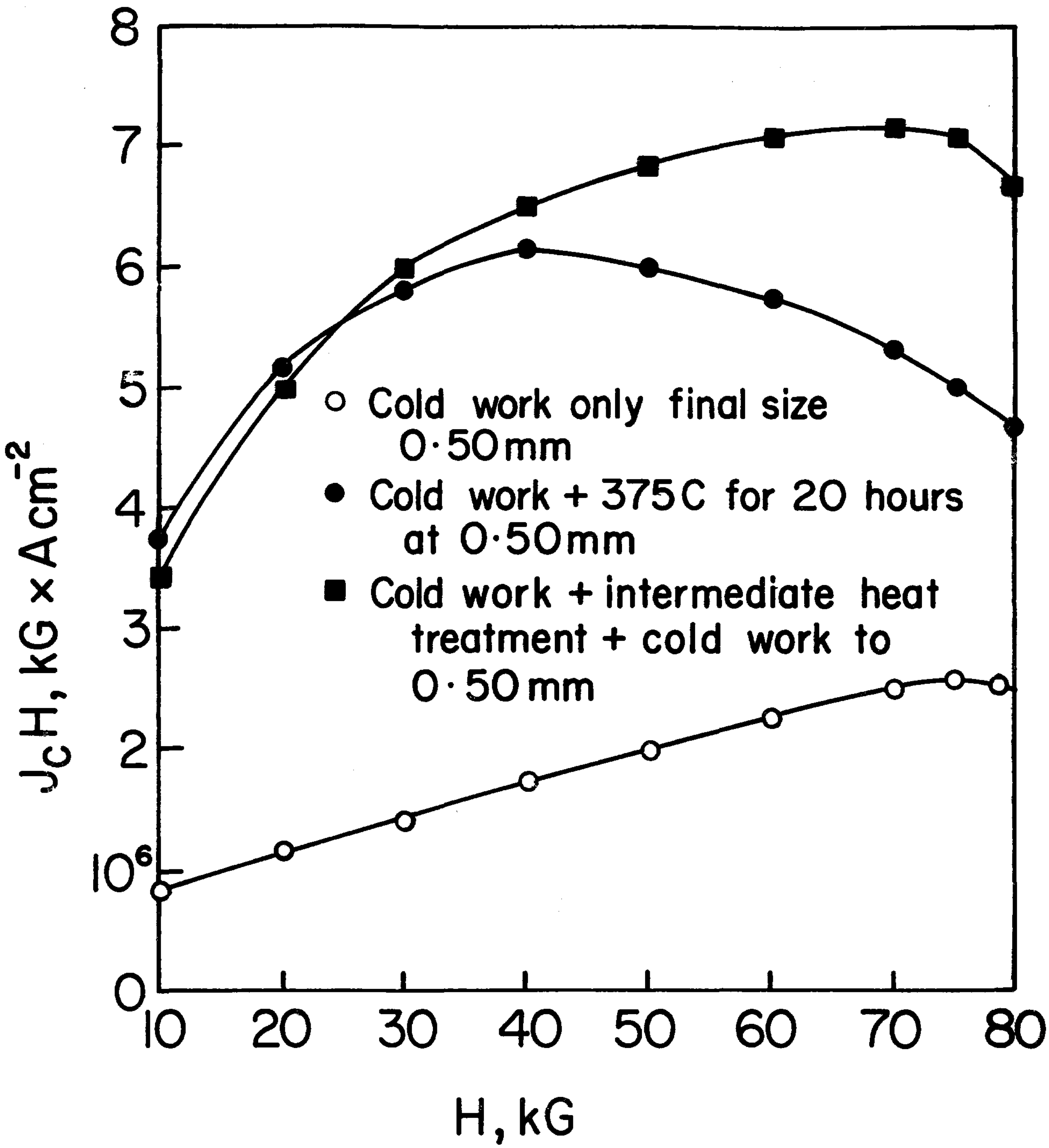

Figure 7. The response of the pinning force ($J_c \times H$) to an intermediate heat treatment.[1]

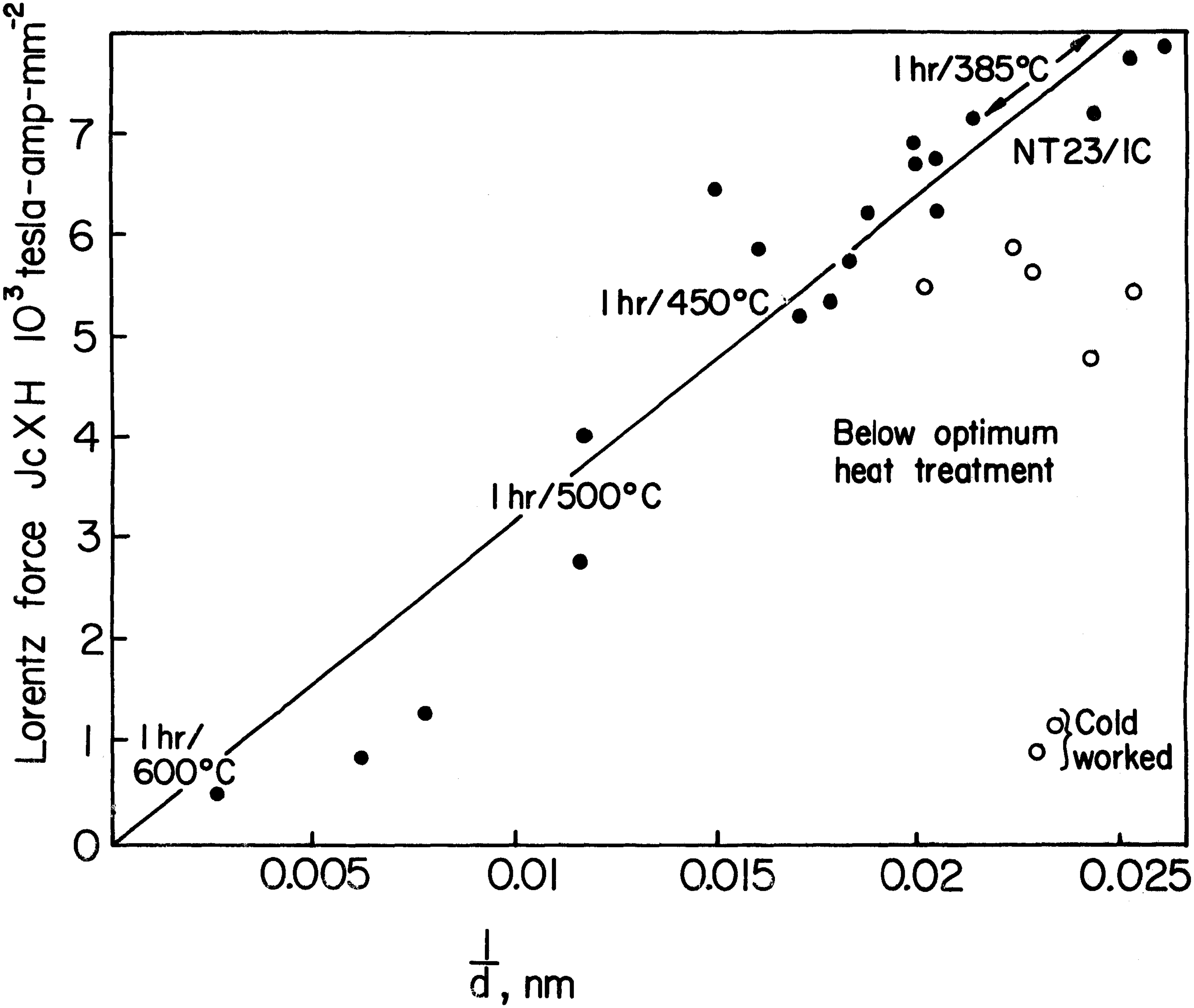

Figure 8. The pinning force as a function of cell size.[3]