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MECHANICAL PROPERTIES OF MARTENSITIC ALLOY AISI 422

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ABSTRACT: HT9 is a martensitic stainless steel that has been considered for structural applications in liquid metal reactors (LMRs) as well as in fusion reactors. AISI 422 is a commercially available martensitic stainless steel that closely resembles HT9, and was studied briefly under the auspices of the U.S. LMR program. Previously unpublished tensile, fracture toughness and charpy impact data on AISI 422 were reexamined for potential insights into the consequences of the compositional differences between the two alloys, particularly with respect to current questions concerning the origin of the radiation-induced embrittlement observed in HT9.

KEYWORDS: ferritic/martensitic stainless steels, mechanical properties, tensile properties, toughness, impact behavior, radiation-induced embrittlement

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INTRODUCTION

HT9 is a martensitic stainless steel that has been considered for structural applications in liquid metal reactors (LMRs) and is currently under consideration for similar applications in fusion reactors. The U.S. LMR program was interested in establishing the properties and irradiation-induced changes in behavior of an American alloy that closely resembles HT9, referred to as AISI 422. Only a fraction of the work originally proposed under the U.S. LMR program was completed prior to the termination of the program. Due to the similarities in because composition between HT9 and 422, however, and ~~the fact that~~ HT9 exhibits irradiation-induced embrittlement, the source of which is not completely understood, it appeared that reexamination of the AISI 422 database

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established under the LMR program might provide some useful insights into the post-irradiation embrittlement of this class of alloy.

BACKGROUND

AISI 422 is also referred to as Carpenter 636, AISI 616 and Unitemp 1420 WM. It is a hardenable steel that was designed for service at temperatures up to 650°C. It is a modification of AISI 420, with additions of nickel, molybdenum, tungsten and vanadium to improve the elevated temperature strength and resistance to stress corrosion cracking.[1,2] The composition of the LMR heat of AISI 422 is compared to that of a typical LMR heat of HT9 in Table 1. Note that relative to HT9, AISI 422 contains 60% more manganese, 30% more silicon and nickel, and more than double the amounts of phosphorus and tungsten.

TABLE 1--Compositions of AISI 422 (heat 20818) and HT9 (heat 91353).

ALLOY	C	Mn	Si	P	Cr	Ni	Mo	V	W
HT9	0.21	0.49	0.22	0.008	11.97	0.57	1.03	0.33	0.52
422	0.22	0.80	0.29	0.018	11.79	0.80	1.05	0.29	1.16

It is well known that martensitic stainless steels such as HT9 can exhibit significant embrittlement following irradiation, particularly at temperatures on the order of 350 to 385°C, where a pronounced increase in strength occurs. It is not well understood, however, whether the embrittlement arises primarily from the helium-induced cavities or the precipitation that develops during irradiation. Both factors are related to the level of nickel present in the alloy, and as such are very difficult to separate clearly. The purpose of this work was therefore to use the slight compositional variation between HT9 and AISI 422 to glean some insight into the behavior of HT9 following irradiation.

EXPERIMENTAL PROCEDURE

A 9½-inch (241.3 mm) long piece of 5¼-inch (533.35 mm) diameter AISI 422 bar stock was purchased in a normalized and tempered condition. The original ingot, produced by AlTech Specialty Steel, was melted in an electric furnace and refined by argon-oxygen decarburization (AOD). A ¼-round piece of the bar was rolled to two thicknesses (¼ and 1/8 inch [6.35 and 3.18 mm]) with intermediate heat treatments similar to those used for processing HT9. The final heat treatment for both thicknesses comprised austenitizing at 1038°C for 5 minutes and tempering at 760°C for 30 minutes. Both treatments were followed by an air cool. The final tempered martensite structure had an ASTM grain size of about 8 and a Vickers hardness of about 298 DPH (500 g load). No delta ferrite was present in the heat-treated AISI 422 microstructure, whereas HT9 generally contains about 1% delta ferrite at prior austenite grain boundaries.

Miniature (½-size) charpy specimens were machined from the thicker sheet stock, while miniature tensile and compact tension specimens were machined from the thinner sheet stock according to the drawings given in Figure 1 and in the orientations given in Figure 2. Tensile specimens were tested in the unirradiated condition only at temperatures ranging from 25 to 540°C and a nominal strain rate of $1.5 \times 10^{-4}\ s^{-1}$. Compact tension specimens were irradiated in the Fast Flux Test Facility (FFTF) at ~400 and ~540°C but ~~were~~ tested only in the unirradiated condition, at temperatures ranging from 25 to 427°C, using a single specimen electropotential technique. Charpy specimens were irradiated at ~400°C in a precracked condition to a fluence of ~4×10^{22} n/cm^2 (E > 0.1 MeV), or about 17 dpa. Impact tests were performed on both irradiated and unirradiated specimens in an instrumented drop tower. The fracture energy was normalized against the area of the fracture surface. The ductile-brittle transition temperature (DBTT) is determined as the midpoint between the upper shelf (USE) and the lower shelf. More details on each of the test techniques, demonstrating their validity as applied to miniature specimens, are given in references 3-5.

RESULTS AND DISCUSSION

The tensile data obtained on AISI 422 are shown in Figure 3 in comparison with similar data on HT9. It is evident that AISI 422 is slightly stronger and somewhat more ductile than HT9 in the unirradiated condition.

The fracture toughness data obtained from the compact tension specimens of unirradiated AISI 422 are shown in Figure 4 in comparison with similar HT9 data. The toughness of AISI 422 is higher than that of HT9, although it should be noted that the tearing modulus is 20 to 40 percent lower in AISI 422, depending on the test temperature, ranging from 95 at 70°C to 81 at 427°C.

The impact behavior of unirradiated AISI 422 is compared to that of HT9 in Figure 5. While the two data sets appear to be very similar at first glance, it should be noted that the orientations and heat treatments of the two types of specimens are different. While the AISI 422 specimens were fabricated from rolled sheet in the TL orientation, the HT9 specimens were fabricated from forged bar in the CR orientation. The difference between these two orientations is shown in Figure 6. The orientation of the crack front and the direction of crack propagation are parallel to the rolling direction in the TL AISI 422 specimens, while they are perpendicular to the working direction in the CR HT9 specimens. In addition, the HT9 bar from which the specimens were machined was in a slightly different condition than that of the AISI 422 sheet, a mill-annealed condition that comprises normalization at 1150°C for more than one hour followed by hot-working and tempering at 750°C for 1 hour.

The similarity between the HT9 and AISI 422 impact data in the unirradiated condition is somewhat surprising in light of the differences in delta ferrite level and the fact that the AISI 422 is stronger as well as tougher. The orientation difference is the only factor than could account for the similarity, since the difference in heat treatment is relatively minor. The CR orientation could be considered as approximating a crack arrest geometry, particularly in the presence of delta ferrite stringers in HT9, whereas the TL orientation could be considered as approximating a crack divide geometry, where the crack might be divided along prior austenite grain boundaries.

The similarity between HT9 and AISI 422 is maintained when both are irradiated at similar temperatures to approximately the same neutron exposure, as shown in Figure 7. The HT9 specimens were actually irradiated at ~390°C,[7] but the difference between 390 and 400°C is small

minimal relative to the uncertainties in irradiation temperature. The HT9 specimens were irradiated only to ~3 x 10^{22} n/cm^2, but since it has been demonstrated that the shift in DBTT saturates at about fast fluences of 2-3 x 10^{22} n/cm^2 in this temperature range,[6] the HT9 and AISI 422 data are considered comparable.

The data in Figure 7 indicate that the two alloys exhibit the same shifts in DBTT and USE independent of the orientation differences. The data also imply that a small amount of delta ferrite has no effect on the irradiation-induced shifts in DBTT and USE.

Other data are available, however, on HT9 specimens in the TL orientation.[8] These data are shown in Figure 8, and indicate that, while the shift in DBTT and USE are slightly worse in the CR than in the TL orientation, the difference between orientations is small relative to the effect of irradiation itself. Since the data suggest that there is no orientation dependence in the irradiation-induced shifts in DBTT and USE, and since both HT9 (CR) and AISI 422 (TL) exhibit similar shifts in DBTT and USE, one can surmise that the difference between HT9 (TL) and AISI 422 (TL) in the irradiated condition reflects a difference in the original condition of the materials rather than an effect of radiation, i.e., $DBTT_{HT9(TL)} < DBTT_{422(TL)}$ for unirradiated material.

CONCLUSIONS

AISI 422 appears to be as good an alloy as HT9 on the basis of its strength and fracture toughness properties, but the impact behavior of AISI 422 does not appear to be as good as that of HT9 when orientation differences are taken into account. In addition, the impact behavior of AISI 422 (TL) is worse than that of HT9 (TL) following irradiation to a saturation fluence. With the mixture of positive and negative results, it is not really possible to draw firm conclusions concerning the effect of composition on irradiation-induced changes in behavior, and no real insights can be obtained concerning the origin of the irradiation-induced embrittlement observed in HT9. It is possible, however, to specify that the effect of radiation on this class of steel is a general phenomenon, albeit one that is influenced by the details of processing procedures and irradiation environment.

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FIGURE CAPTIONS

1. Dimensions of miniature AISI 422 specimens. (a) Charpy impact specimen, (b) Compact tension specimen, and (c) Tensile specimen. All dimensions are given in mm.

2. Orientation of miniature AISI 422 specimens relative to the rolling direction. The tensile specimen axis was parallel to the rolling direction. Compact tension and charpy impact specimens were fabricated in the TL orientation.

3. Tensile data on unirradiated AISI 422 compared with similar HT9 data: (a) strength and (b) ductility.

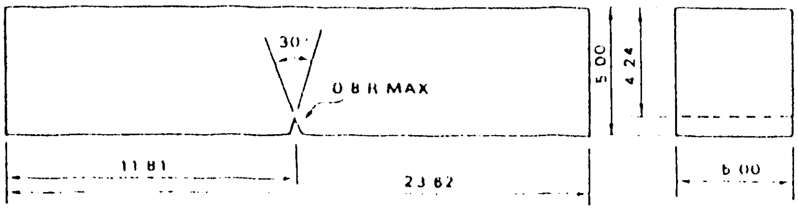
4. Fracture toughness data on unirradiated AISI 422 compared with similar HT9 data.

5. Impact data on unirradiated AISI 422 (TL) compared with HT9 (CR) data.

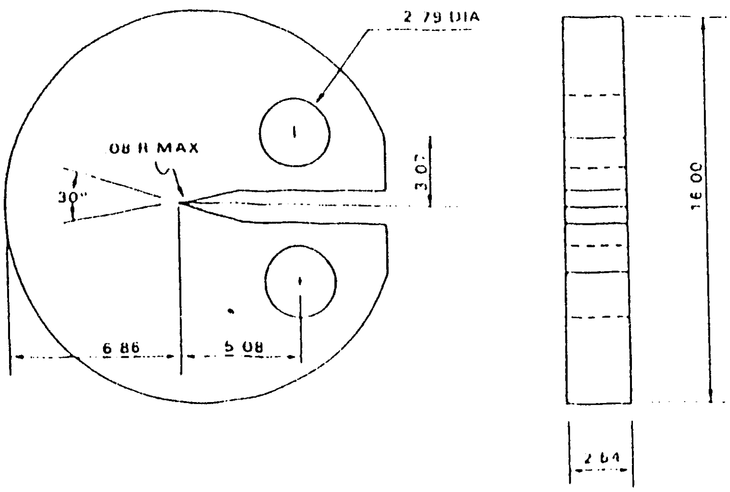
6. Orientation differences between charpy specimens of AISI 422 (TL) and HT9 (CR).

7. Impact data on AISI 422 (TL) irradiated to ~4 x 10^{22} n/cm^2 at ~400°C, compared to HT9 data (CR).

8. Additional HT9 charpy impact data, in the TL orientation.



IGURE 1. Charpy V-Notch Specimens (from Drawing H-3-46299). All Dimensions in mm.



IGURE 2. Compact Tension Fracture Toughness Specimen (from Drawing H-3-46752, Rev. 1). All Dimensions in mm.

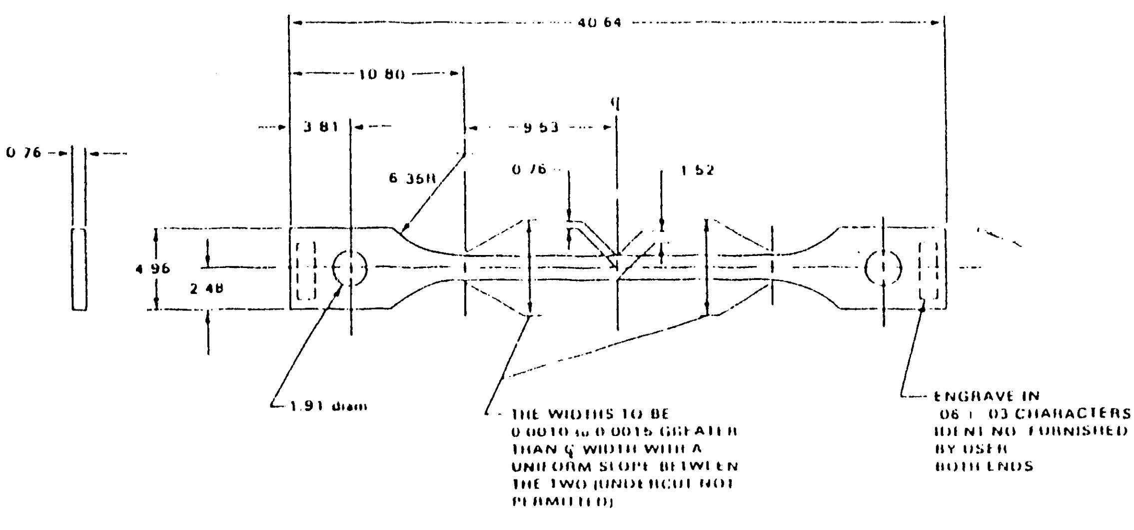
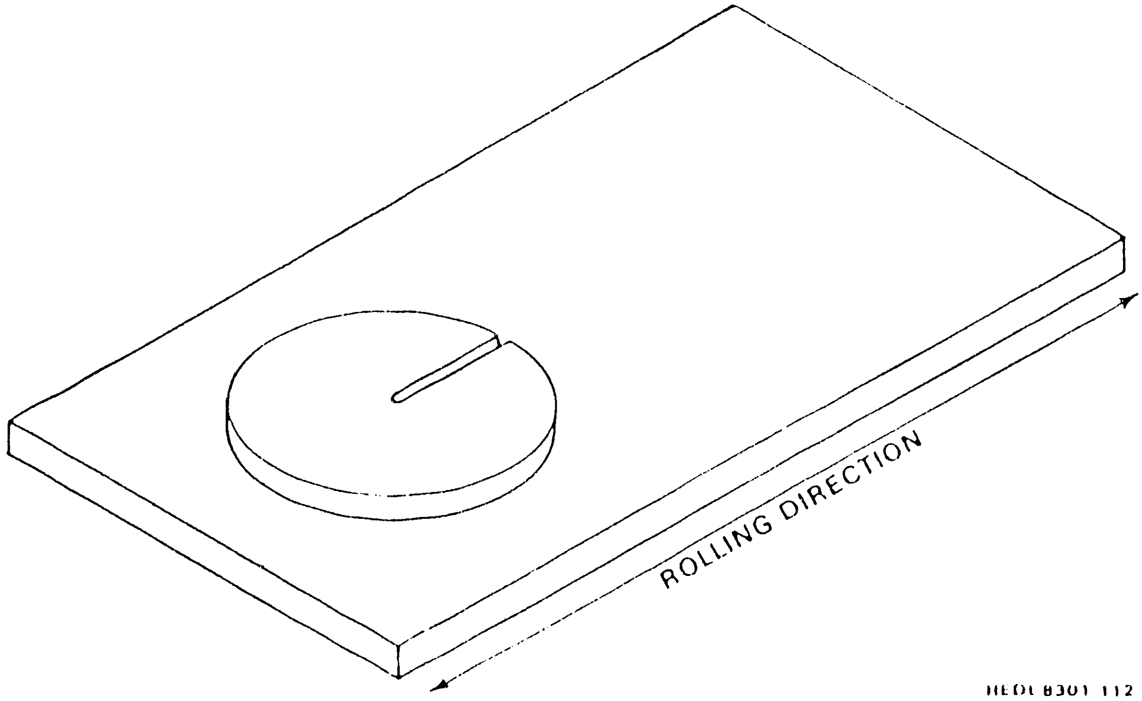


Fig. 1

IGURE 3. Flat Tensile Specimen (from Drawing H-3-44667). All Dimensions in mm.



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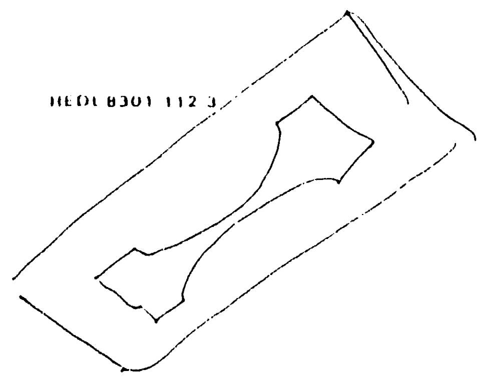
~~FIGURE 6. Compact Tension Specimen Orientation.~~



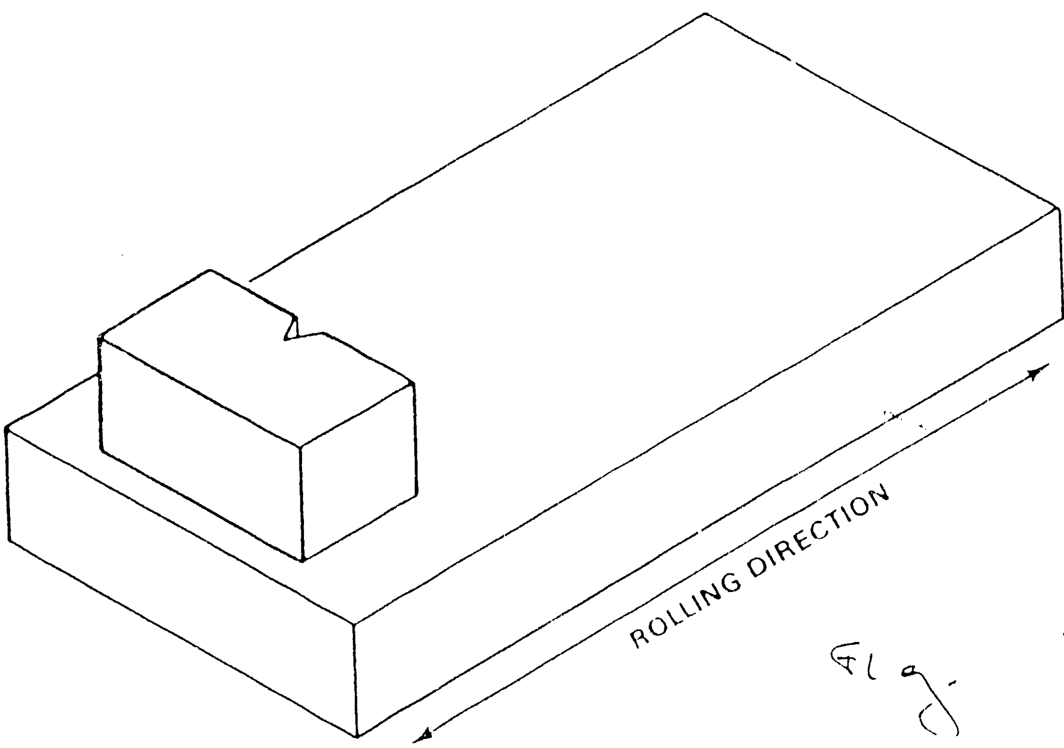


Fig. 2

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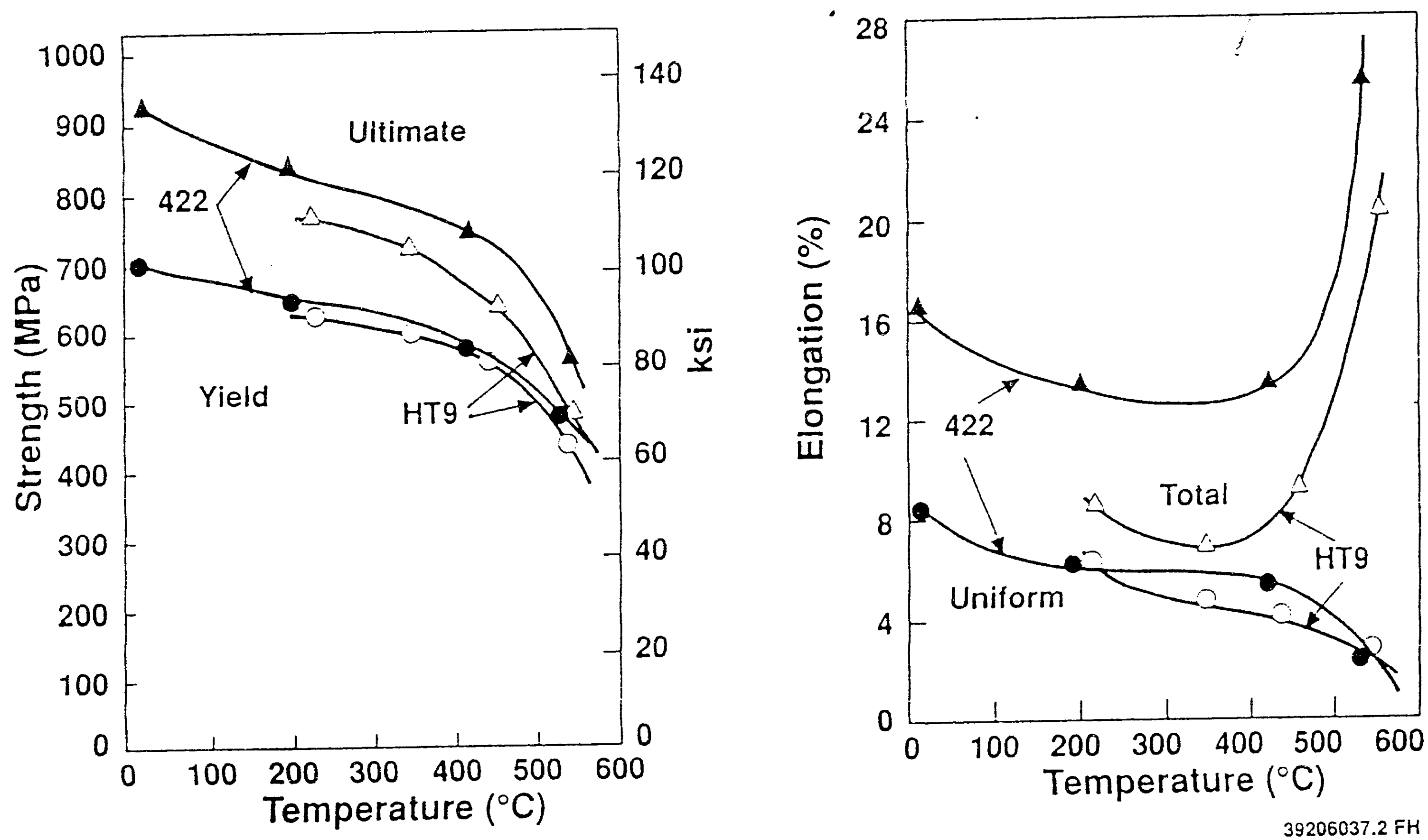
~~FIGURE 7. Charpy Specimen Orientation.~~

Fig 3

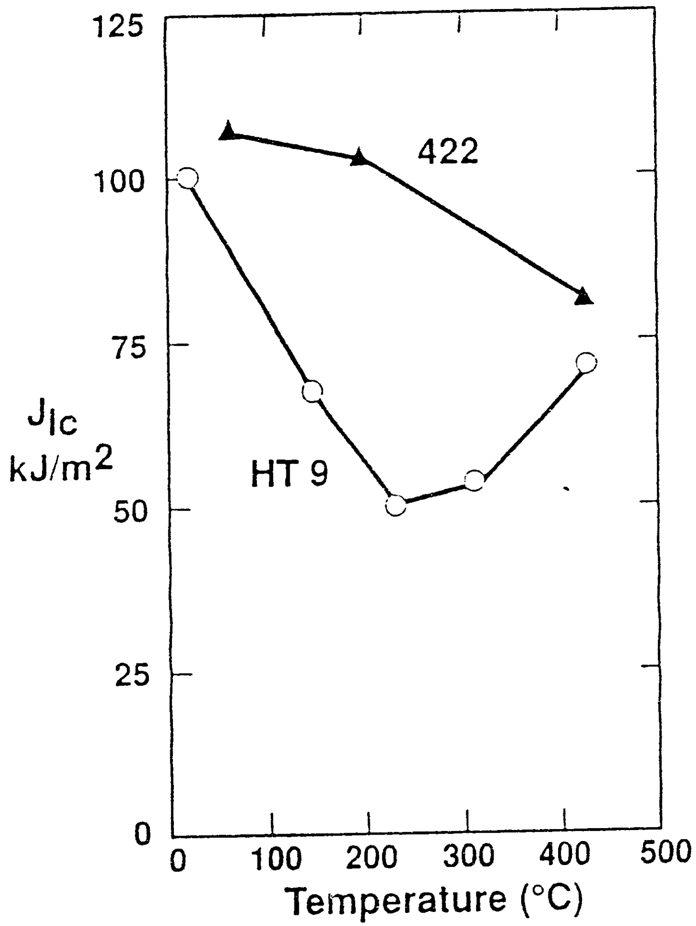
Tensile Properties of Unirradiated AISI 422 and HT9



39206037.2 FH

Fig 4

Fracture Toughness of Unirradiated AISI 422 and HT9

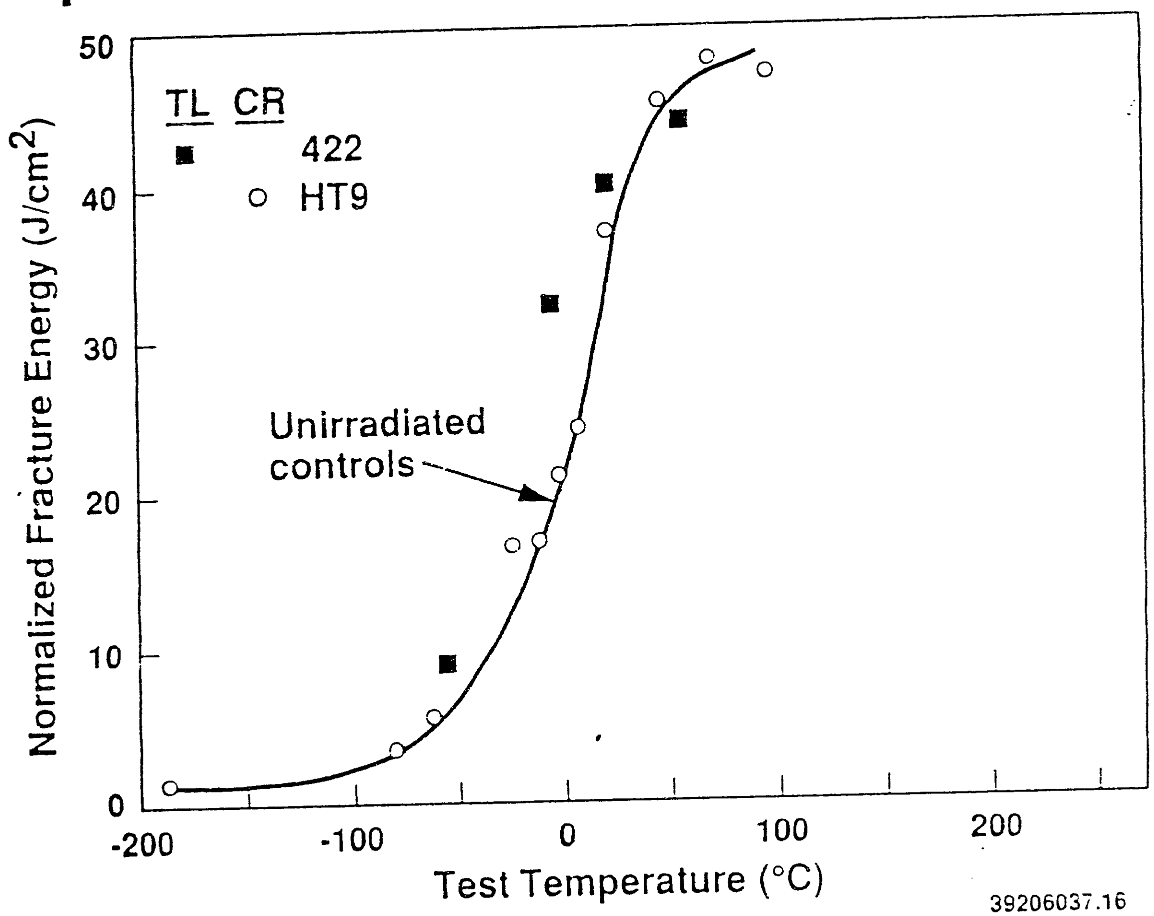


- Toughness is higher in AISI 422
- Tearing modulus of AISI 422 varies from 95 at 70°C to 81 at 427°C
- Tearing modulus of AISI 422 is 20-40% lower than that of HT 9

39206037.1 FH

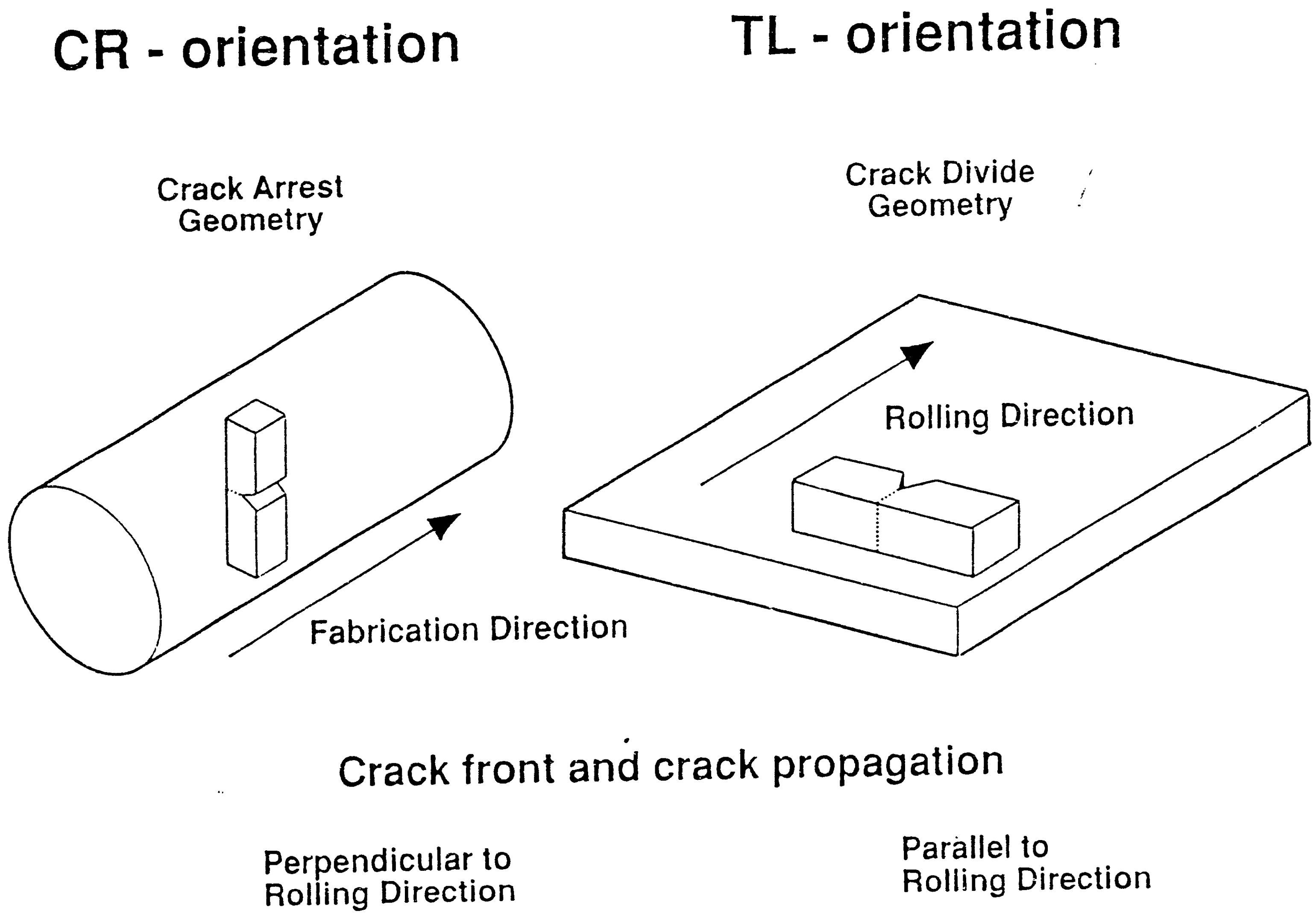
Fig 5

Impact Properties of AISI 422 and HT9



39206037.16

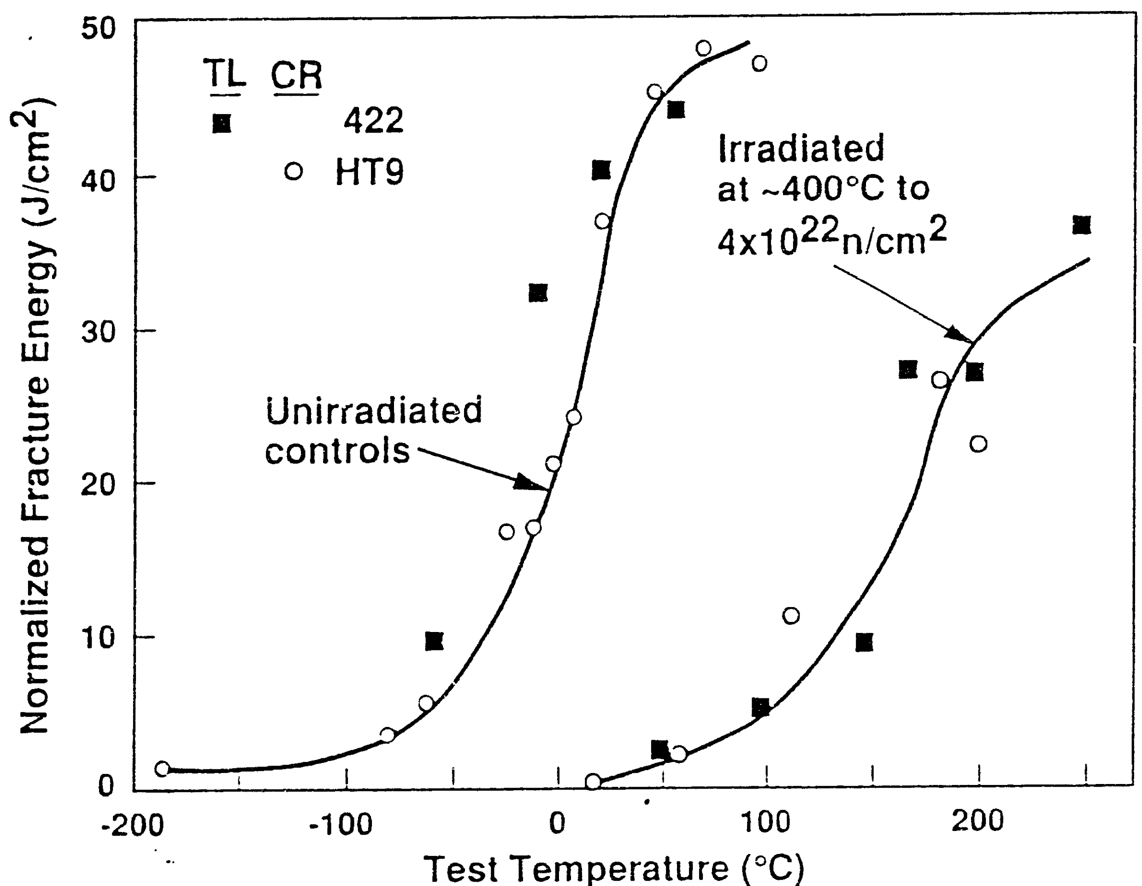
Fig 6.



39206037.45 FH

fig 7

Impact Properties of AISI 422 and HT9



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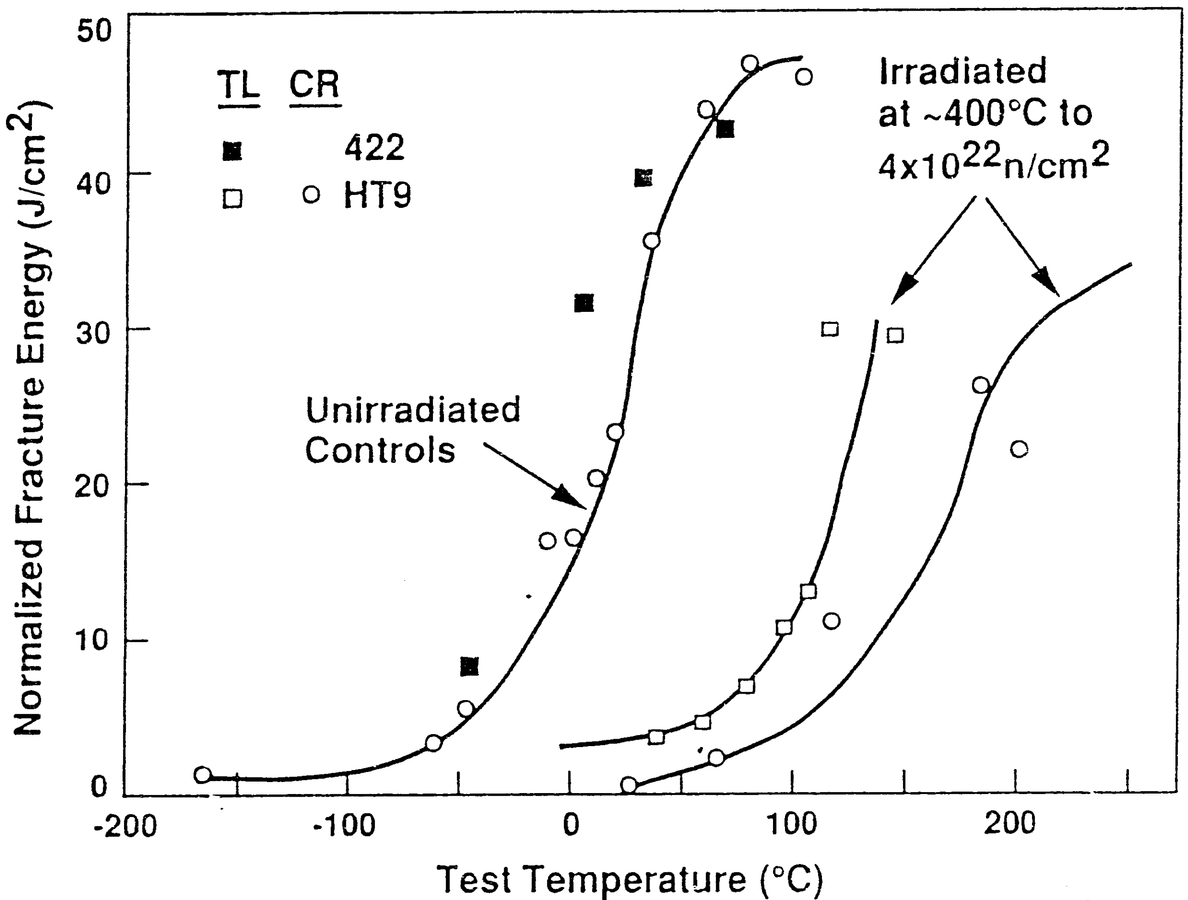
Impact Properties of AISI 422 and HT9



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