DEVELOPMENT OF TOUGH, STRONG, IRON-BASE ALLOY FOR CRYOGENIC APPLICATIONS

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An experimental program was conducted at NASA Lewis Research Center to develop an iron-base alloy that combines the normally divergent properties of high toughness and high strength at cryogenic temperatures. Specifically, alloy properties were sought which at -196°C would exhibit a fracture toughness of 220 MPa-$m^{1/2}$ (200 ksi-in.$^{1/2}$) with a corresponding yield strength of 1.4 GPa (200 ksi). Early work showed that high toughness could be achieved in Fe-12Ni alloys containing reactive metal additions such as Al, Nb, Ti, and V. Further research emphasized strengthening of these tough alloys by thermomechanical processing and the addition of Cu. Results showed that high strength and high toughness could be achieved in a single alloy at temperatures as low as -196°C. An alloy with composition Fe-12Ni-0.5Al-2Cu exhibited a yield strength of 1.65 GPa with a corresponding fracture toughness of 220 MPa-$m^{1/2}$ at -196°C. Strengthening due to Cu additions to the Fe-12Ni base alloys results primarily from precipitation of Cu-rich ε particles approximately 20 nm in diameter. Strengthening mechanisms are discussed in terms of an elastic modulus hardening model and are supported by transmission electron microscopy examinations of selected test specimens.

TOUGHNESS/STRENGTH MODELING - I

FACTOR	TOUGHNESS	STRENGTH
CRYSTAL STRUCTURE - FCC	↑	↓
- BCC	↓	↑
ALLOYING - SUBSTITUTION	↓	↑
- INTERSTITIAL	↓	↑
- PARTICLES - ACTIVE	↓	↑
- PASSIVE	↑	↑
METALLURGICAL STRUCTURE		
- GRAIN SIZE	↑	↑
- SUBGRAIN SIZE	↑	↑
- TMP	↑	↑
- HEAT TREATMENT	↑	↑

TOUGHNESS/STRENGTH MODELING - II

$$\Delta\sigma = \sigma_o + K\pi^{-1/2}$$

$$\pi = \pi_p, \ \pi_c, \ \pi_d$$

ALLOYING
TMP
HEAT TREATMENT

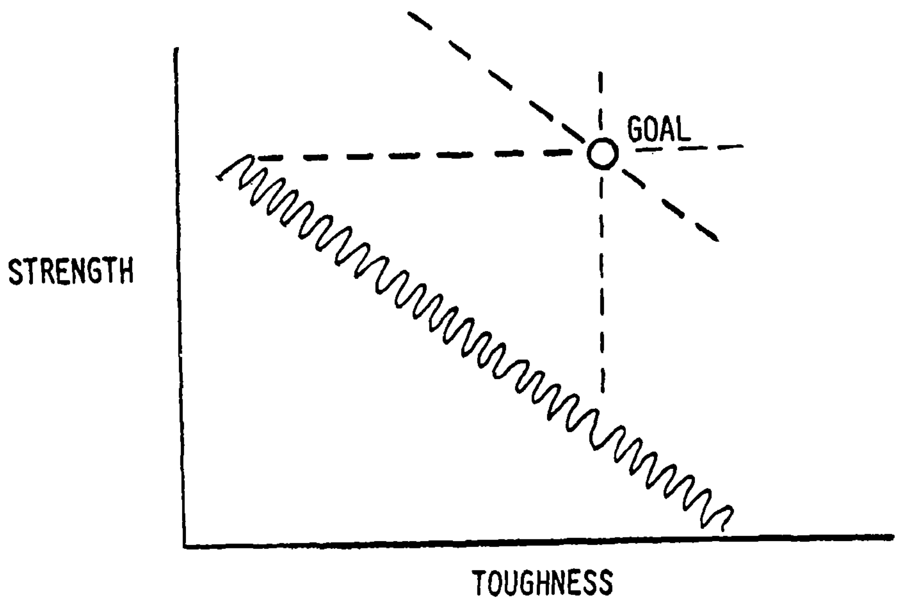
$$\Delta\sigma_E = \frac{K\,G_B}{\pi_p}\left(1 - \frac{E^2_{SOFT}}{E^2_{HARD}}\right)^{1/2}$$

COPPER IN IRON

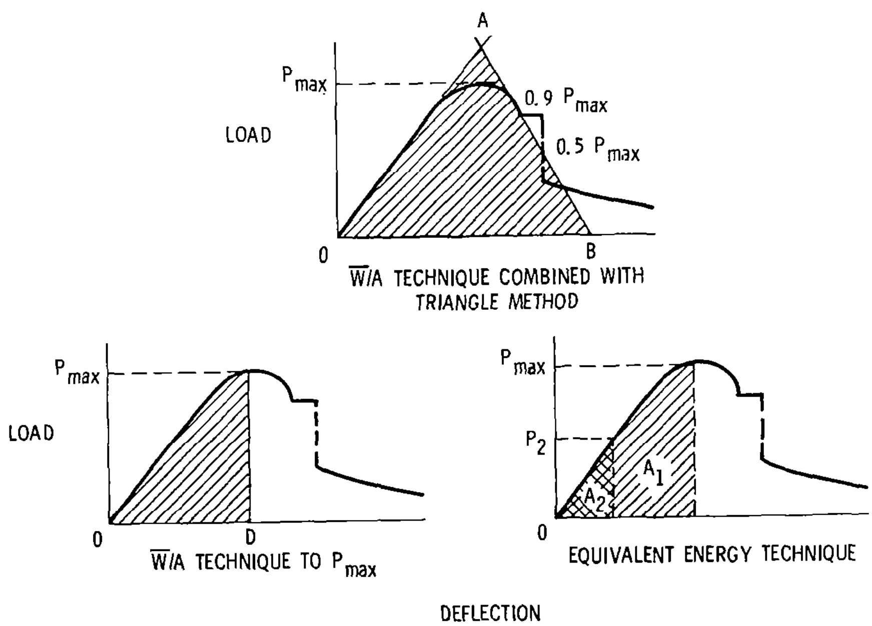
$\Delta K_{ICD} \ \alpha \ \pi_p$, SIZE, SHAPE, MODULUS

PURITY
COPPER IN IRON

PRACTICAL AND PHILOSOPHICAL CONSIDERATIONS



LOAD-DEFLECTION CURVES ILLUSTRATING AREAS UNDER CURVE THAT WERE MEASURED IN DETERMINING FRACTURE TOUGHNESS OF SMALL SPECIMENS



$$K_{ICD} = \frac{SP\left(\frac{A_1}{A_2}\right)^{1/2} f\left(\frac{a}{w}\right)}{BW^{3/2}}$$

S SPAN OF THREE-POINT BEND FIXTURE

P ANY LOAD ON LINEAR PORTION OF LOAD DISPLACEMENT CURVE

A_1 AREA UNDER CURVE TO MAXIMUM LOAD

A_2 AREA UNDER CURVE TO P

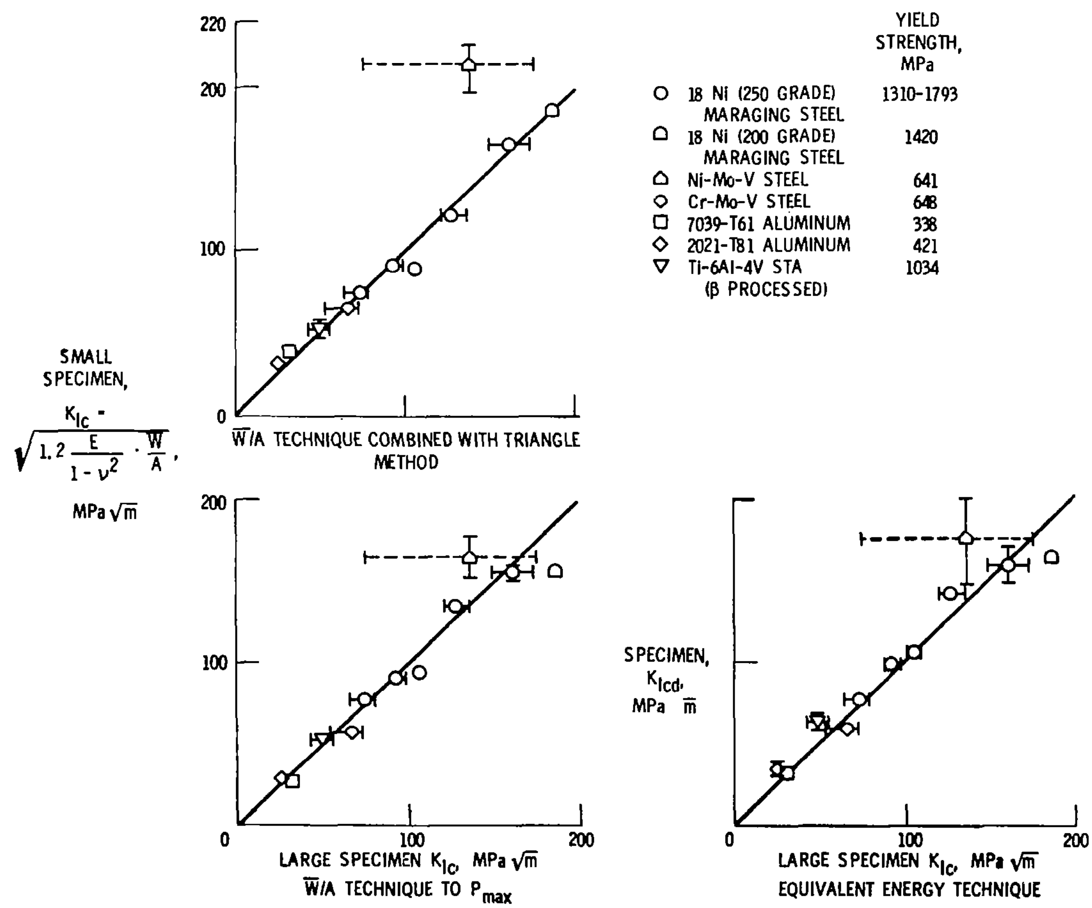
$f(a/w)$ VALUE OF POWER SERIES FOR a/w

B SPECIMEN THICKNESS

a CRACK LENGTH

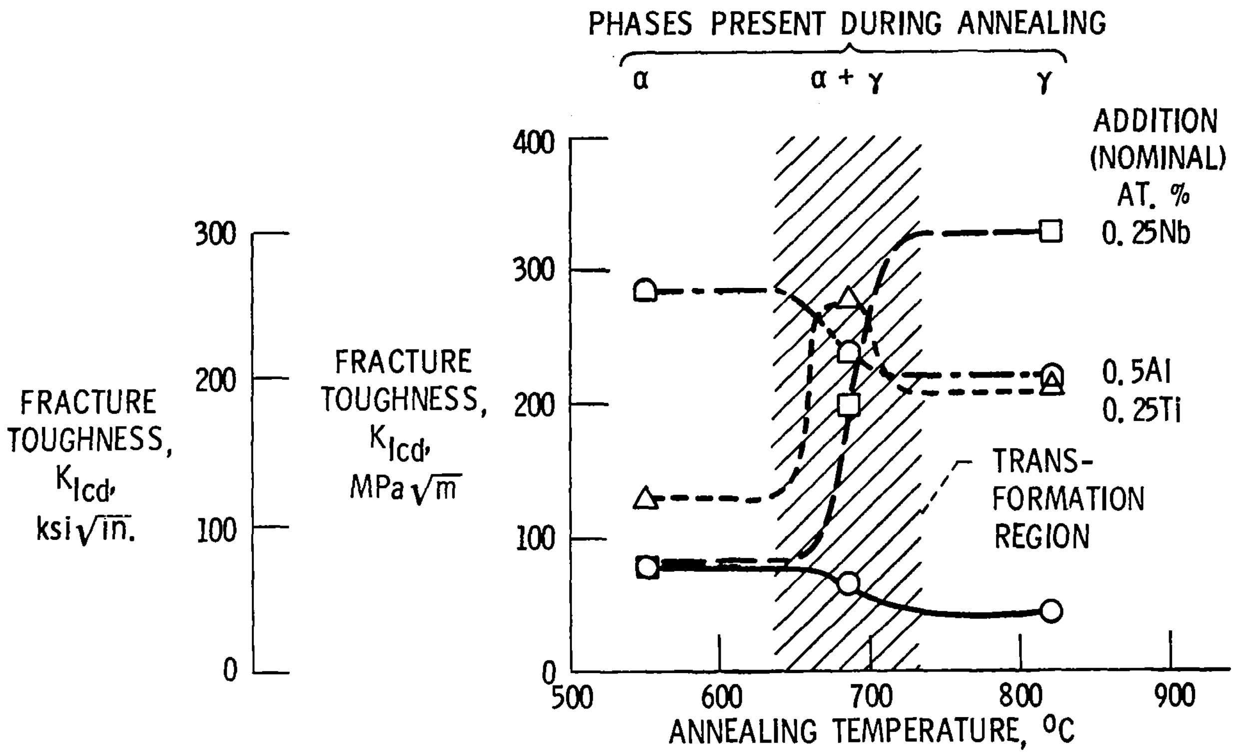
W SPECIMEN WIDTH

CORRELATION OF SMALL SPECIMEN FRACTURE TOUGHNESS WITH LARGE SPECIMEN VALID K_{1c} VALUES AT 25°C*

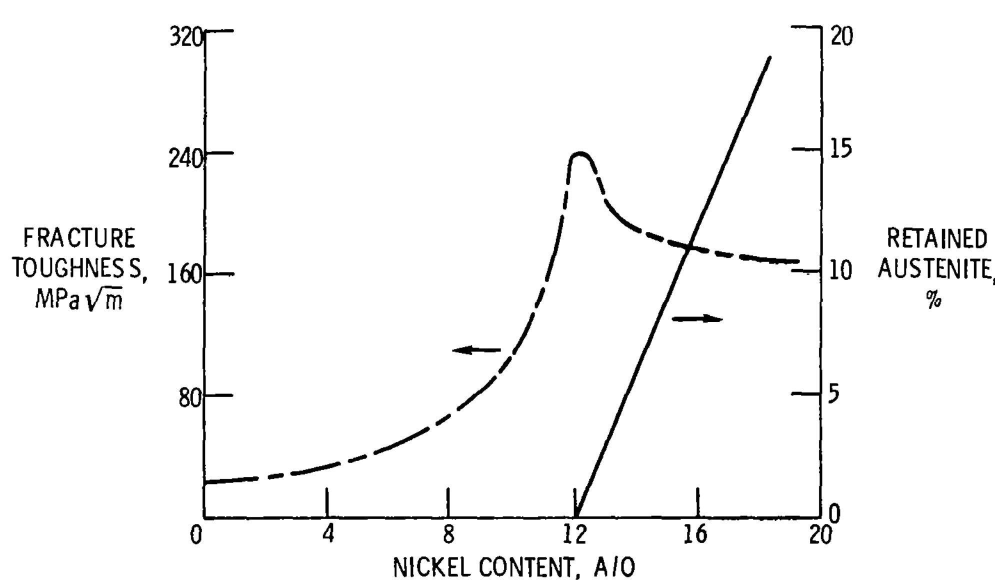


*From Witzke, W. R.; and Stephens, J. R.: Comparison of equivalent energy and energy per unit area (W̄/A) data with valid fracture toughness data for iron, aluminum, and titanium alloys. J. of Testing and Eval., vol. 6, no. 1, Jan 1978, pp. 75-79.

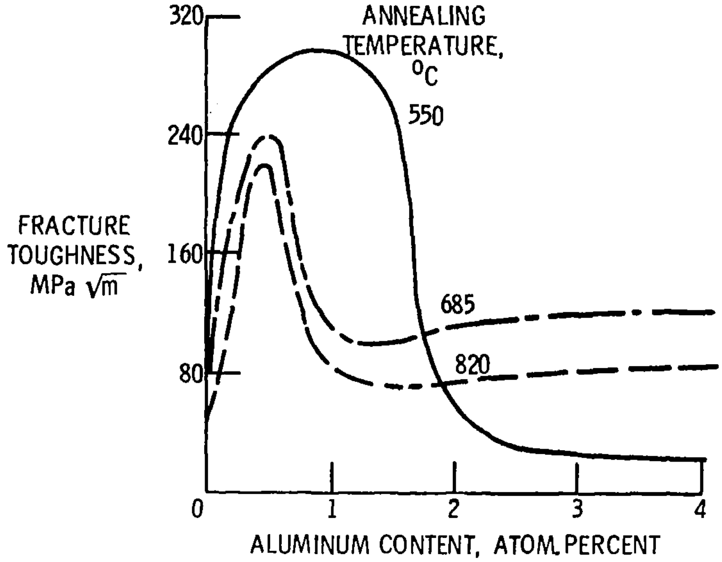
TOUGHNESS VS ANNEALING TEMPERATURE



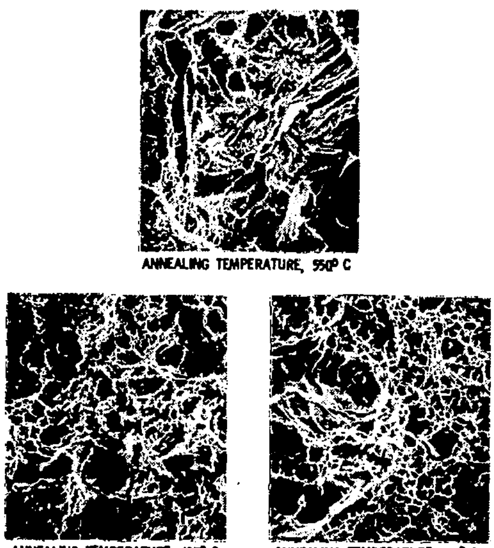
EFFECT OF NICKEL CONTENT ON FRACTURE TOUGHNESS AND RETAINED AUSTENITE OF Fe-Ni-0.5Al ALLOYS ANNEALED AT 550° C AND TESTED AT -196° C



EFFECT OF ALUMINUM CONTENT ON FRACTURE TOUGHNESS OF Fe-12Ni-Al ALLOYS AT -196° C



FRACTOGRAPHS OF FRACTURE TOUGHNESS SPECIMENS OF Fe-12Ni-0.5Al TESTED AT -196°C X500



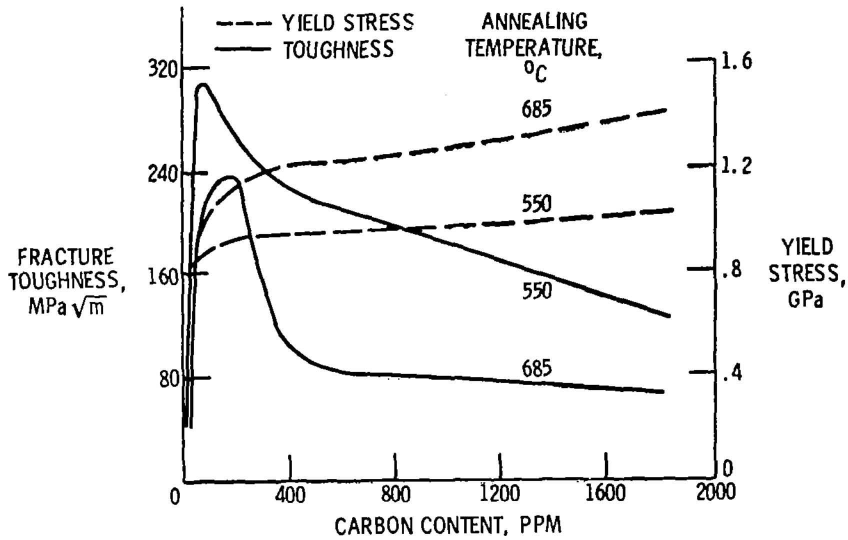
ANNEALING TEMPERATURE, 550° C

ANNEALING TEMPERATURE, 685° C

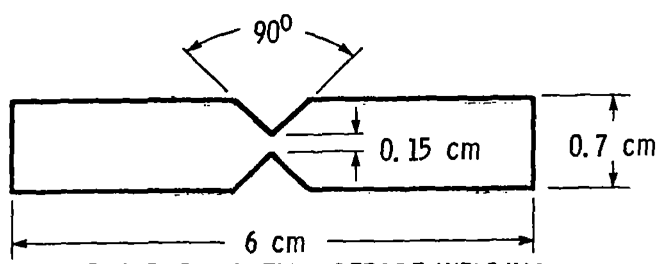
ANNEALING TEMPERATURE, 820° C

From Witzke, Walter R.; and Stephens, Joseph R.: Effect of minor reactive metal additions on fracture toughness of iron-12-percent-nickel alloy at -196° and 25°C. NASA TN D-8232, 1976.

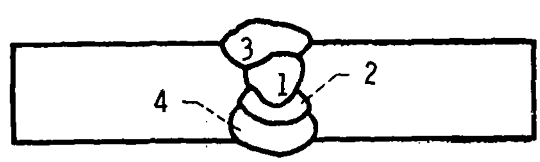
EFFECT OF CARBON CONTENT ON FRACTURE TOUGHNESS AND YIELD STRESS OF Fe-12Ni-0.5Al ALLOY AT -196° C



GAS-TUNGSTEN ARC (GTA) WELD JOINT

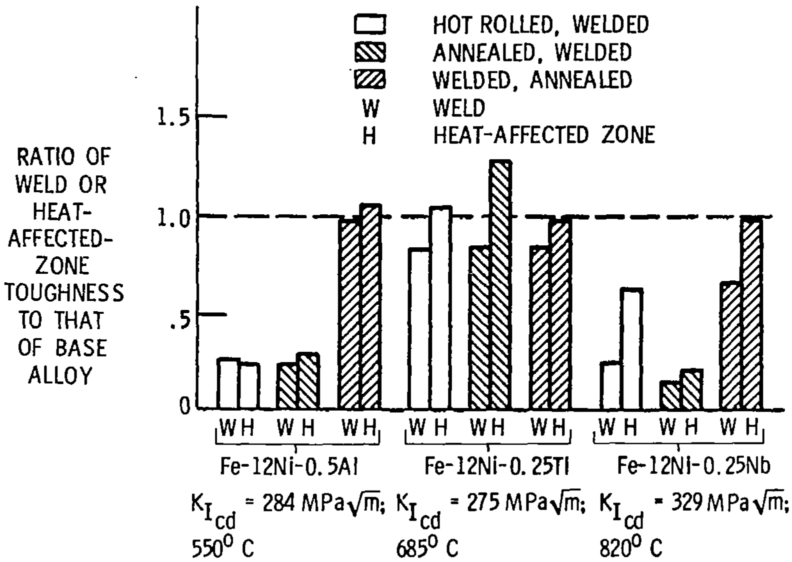


WORKPIECE PREPARATION BEFORE WELDING

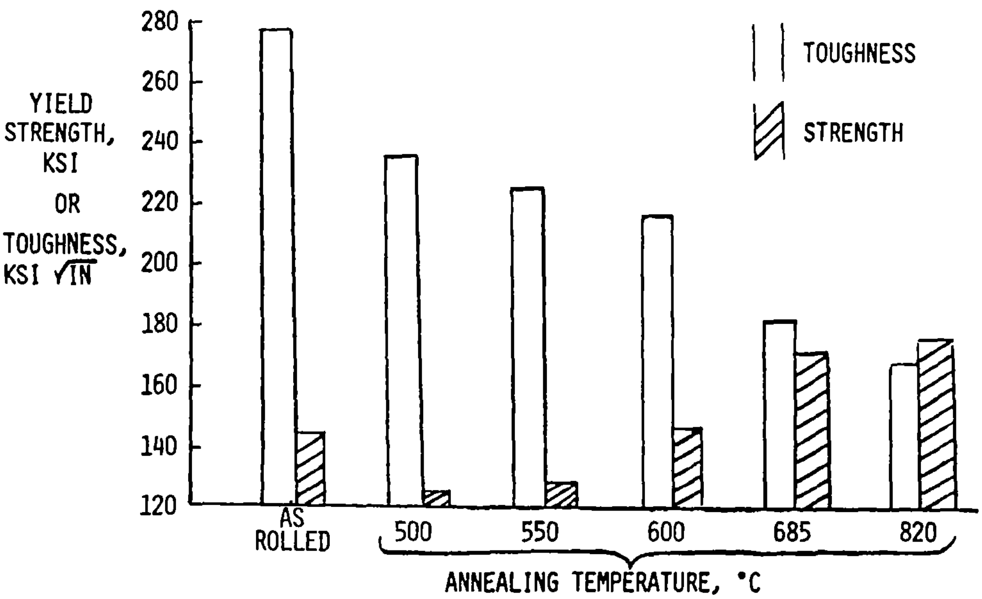


SUBSEQUENT AS-WELDED CONFIGURATION SHOWING WELD-PASS SEQUENCE

COMPARISON OF WELDED TOUGHNESS WITH BASE ALLOY AT -196° C



TOUGHNESS/STRENGTH PROPERTIES OF Fe-12Ni-0.5Al AT -196°C (350-LB INGOT)*



*From Rhat, G. K.: Evaluation of mechanical properties of electroslag-refined Fe-12Ni alloys. NASA CR-159394, 1978.

ESTIMATED COST

7000 LB. INDUCTION MELT

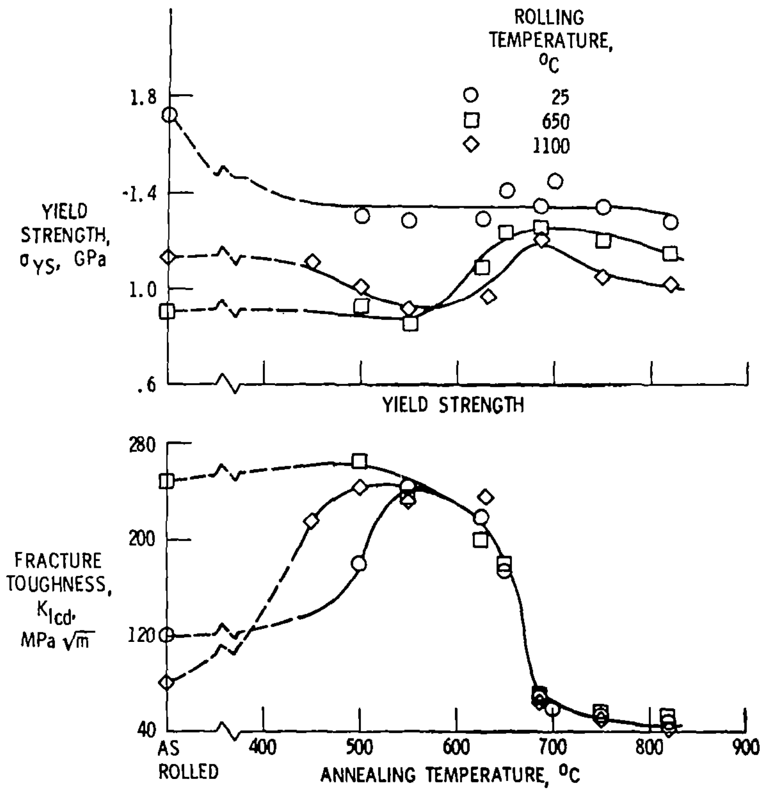
ESR REMELT

FORGE

ROLL TO PLATE

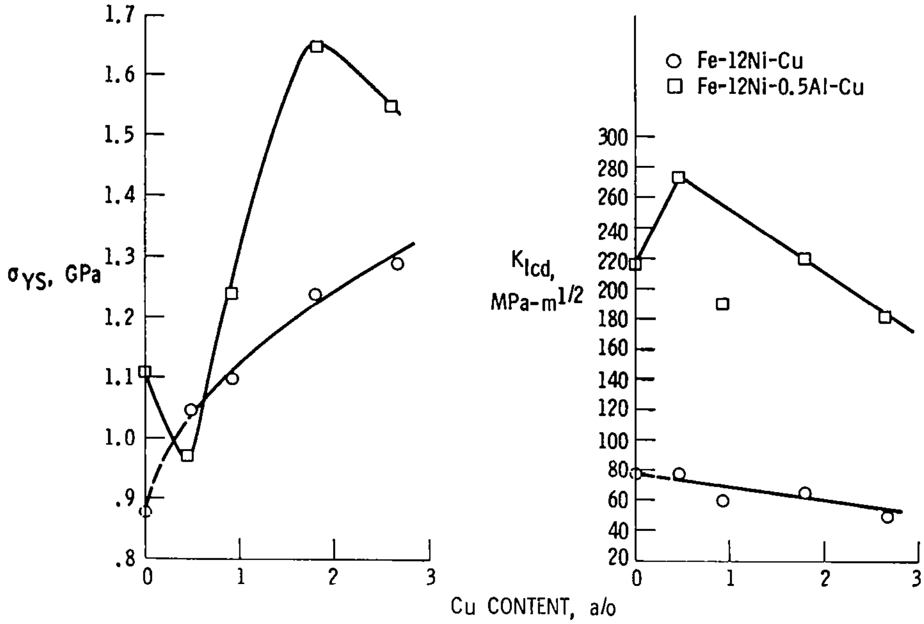
≈$4.00/LB

EFFECTS OF THERMOMECHANICAL PROCESSING ON STRENGTH AND TOUGHNESS OF Fe-12Ni-0.5Al ALLOYS AT -196° C



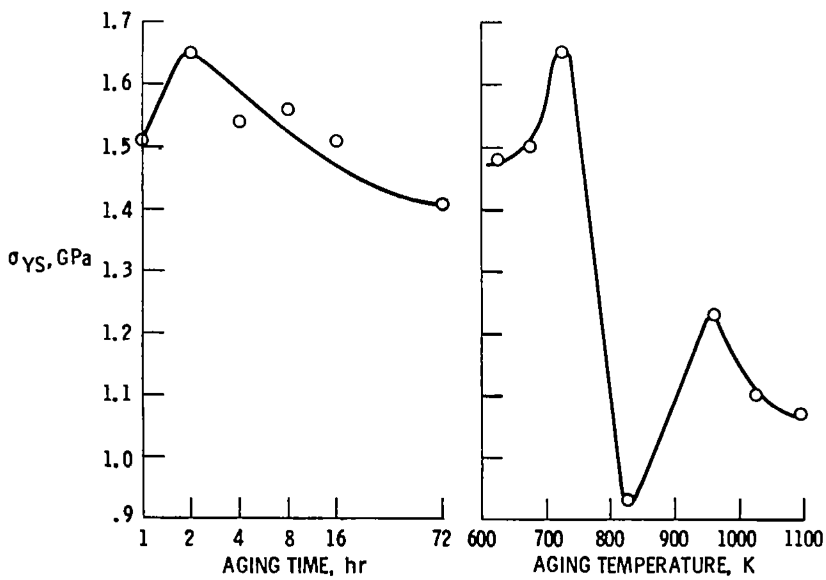
TOUGHNESS

STRENGTH AND TOUGHNESS OF Fe-12Ni-Cu AND Fe-12Ni-0.5Al-Cu ALLOYS AT 77 K



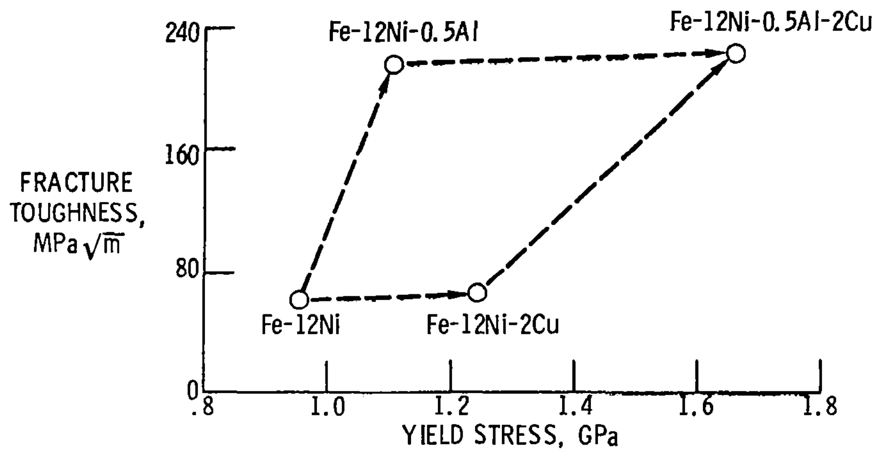
AGED 2 h - 725 K a - YIELD STRENGTH; b - FRACTURE TOUGHNESS

EFFECTS OF AGING CONDITIONS ON 0.2% YIELD STRENGTH OF Fe-12Ni-0.5Al-Cu ALLOY AT 77 K



a - AGING TIME AT 725 K; b - AGING TEMPERATURE FOR 2 h

CONTRIBUTIONS OF Al AND Cu TO TOUGHNESS AND STRENGTH OF Fe-12Ni ALLOY ANNEALED AT 450° C AND TESTED AT -196° C



THREADING OF Cu-RICH PARTICLES BY DISLOCATIONS IN Fe-12Ni-0.5Al-2Cu ALLOY

COMPARISON OF FRACTURE TOUGHNESS AND YIELD STRESS OF Fe-12Ni EXPERIMENTAL ALLOYS WITH COMMERCIAL STEELS AT -196° C