TEMPERATURE AND STRAIN RATE EFFECTS IN SOLUTION ANNEALED CuCrZr –

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OBJECTIVE

The objective of this work is to investigate the strain rate and temperature dependence of the tensile properties of solution annealed CuCrZr.

SUMMARY

Previous reports presented the effects of strain rate and test temperature on the tensile properties of GlidCop™ Al25 and Hycon 3HP™ tested in air. The present report summarizes the results of a similar set of tests on solution annealed (SA) CuCrZr. The SA CuCrZr proved to have only a slight dependence on test temperature up to 350°C in comparison to the other alloys tested in this series. Tests conducted at 450°C, irrespective of the strain rate used, produced a low level of precipitate ageing in the solution annealed alloy that masked any potential effect of strain rate and test temperature. For a given strain rate the yield and ultimate strength decreased slightly up to 350°C, then increased significantly at 450°C as the ageing began. The uniform and total elongation both decreased steadily as the test temperature was increased to 450°C. The reduction in area was less sensitive to temperature up to 250°C, then decreased steadily up to 450°C. In general the tensile results showed little dependence on strain rate with the exception that the reduction in area was somewhat higher at the two highest strain rates (1.5×10^{-1} and $1.5\ s^{-1}$) when tested at 350 and 450°C, which may a consequence to the age hardening. Failure mode in the material appeared ductile throughout the range of strain rate and test temperatures.

PROGRESS AND STATUS

Introduction

As shown in previous reports (1-9), there is a growing recognition that the copper alloys currently considered as candidate materials for the first wall, divertor and limiter structures do not possess the required combination of properties to adequately meet the design criteria for future generation fusion reactors. One of the problems that has arisen is the sensitivity to strain rate, test temperature, and test atmosphere that is found to vary with each alloy and the different heat treatments that can be given to the respective alloys. The degradation in strength and ductility can be quite severe depending on the alloy and test conditions. Unfortunately the actual mechanism remains unclear and may be different for each alloy, particularly the oxide dispersion strengthened GlidCop™ and the precipitation strengthened CuNiBe alloy Hycon 3HP™. CuCrZr, another precipitation strengthened alloy, can be distinguished from the other two alloys for two reasons – namely the mechanical properties appear to be relatively unaffected by test temperature and strain rate in the unirradiated state [6], and the toughness remains higher after irradiation than the other two alloys despite suffering from a severe loss of ductility and work hardening capability when irradiated at temperatures less than 180°C.

An experiment to study the effects of strain rate and test temperature, as well as test environment has been initiated on these three alloys to compare their behavior. The range of strain rates and temperatures was also extended over work reported in the literature to

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encompass a broader range of behavior. This report concerns the results on tensile properties of the CuCrZr alloy in the solution annealed condition (no cold work or ageing treatment). Results on the GlidCop™ and Hycon alloy have been presented previously [7].

Experimental Procedure

The CuCrZr used in this experiment was manufactured by Zollern GmbH Laucherthal (Heat Z822). This material was used in a previous study on the effect of heat treatment on the tensile and electrical conductivity [5]. The composition of the material is reported as 0.85 wt% Cr, 0.09% Zr, and <0.001 wt% P. The bar was solution annealed at 970°C for 20 minutes and then water quenched.

The tensile tests were conducted in open air over a strain rate range of 3.9×10^{-4} to $1.5\ s^{-1}$ and covering the temperature range of 25 to 450°C. The testing was conducted on an MTS servo hydraulic frame. The specimens were taken to temperature and then held for 5 minutes to allow the temperature to equilibrate through the entire specimen. Since the tests were conducted in open air, thermal convection was sufficient to equilibrate the temperature in the short period of time. Oxidation of the specimens did occur during the testing, but from comparison with previously published data [5] the oxide scale does not appear to have affected the tests. The specimen geometry and orientation with respect to the original rolling or extrusion direction is the same as that reported earlier [7]. To aid in gripping and aligning the specimens 3.2 mm diameter pin holes were drilled in the center of the specimens grips at each end. The 0.2% offset yield, ultimate, uniform and total elongation, and the reduction in area (RA) were measured on 2 specimens each from computerized data for the two highest strain rates, and from chart recordings for the two lower strain rates. The reduction in area was measured in an optical comparator.

Results and Discussion

The tensile results for the solution annealed CuCrZr are presented in Table 1. The values represent an average of two tensile tests per condition, with the variation usually less than ±5% for the strength, elongation and reduction in area. Figures 1 through 3 show how the tensile properties vary as a function of test temperature. Only a small decrease occurs in the yield and ultimate strength up to 350°C, irrespective of the strain rate, and the elongation, though more variable, decreases steadily as the test temperature increases. The reduction in area appears to be slightly higher for the two highest strain rates as the test temperature is increased, with a difference of approximately 10-15% at 350 and 450°C. Unfortunately the tests conducted at 450°C result in limited age hardening that causes the yield and ultimate strengths to increase well above the values measured at 350°C. The decrease in elongation and reduction in area may therefore be due to the influence of the age hardening as well as the higher test temperature.

Unlike the GlidCop™ Al25 [3, 7], the tensile properties of the solution annealed CuCrZr are essentially independent of the strain rate, and no evidence of the embrittlement found in the case of the Hycon alloy is observed. The yield strength and elongation for the solution annealed CuCrZr are plotted as a function of strain rate in Figures 4 and 5. The strain rate sensitivity parameters for the yield are lower than those reported for the GlidCop™ and Hycon alloys by Zinkle and Eatherly [3] and separately by Edwards [7]. The elongation remains independent of strain rate at test temperatures up to 450°C despite the limited age hardening that occurred in the specimens tested at 450°C.

Table 1. Temperature and strain rate dependence for solution annealed CuCrZr (JET)

Alloy	Test Temp. (°C)	YS (MPa)	UTS (MPa)	e_u (%)	e_{tot} (%)	RA (%)
3.9×10^{-4} s^{-1}	25	112	240	44.2	56.1	62.7
	150	101	202	40.6	50.0	57.0
	250	91.5	193	37.3	46.5	63.0
	350	95	206	30.2	36.4	51.2
	450	169	222	19.1	35.6	43.3
1.5×10^{-3} s^{-1}	25	118	242	43.3	57.4	64.6
	150	102	212	40.4	55.2	59.9
	250	95	191	34.1	42	64.4
	350	91.4	196	30.1	36.3	55.5
	450	166	226	21.2	35.7	46.5
1.5×10^{-1} s^{-1}	25	104	255	46.0	60.7	64.0
	150	102	219	41.7	55.9	57.5
	250	98	196	37.2	48.1	66.1
	350	95	185	30.7	40.6	62.2
	450	165	240	20.0	32.6	53.2
1.5 s^{-1}	25	121	263	41.8	53.7	63.9
	150	108	227	40.0	52.1	64.8
	250	96	200	37.1	49.6	68.3
	350	94	182	33.7	43.2	65.0
	450	177	253	21.3	31.6	54.2

The tensile data for the solution annealed CuCrZr thus confirm previous experiments that found that the CuCrZr is apparently less susceptible to the effects of test temperature and strain rate compared to the other two high strength alloys. However, further testing is warranted since the solution annealed CuCrZr will not remain in the same condition under irradiation at low temperatures (25-200°C). Irradiation-induced precipitation and radiation hardening will both lead to dramatic increases in strength and loss of ductility, whereas irradiation at higher temperatures could easily promote hardening at low doses and softening at higher doses as precipitate overaging occurs. The CuCrZr must also be tested in the condition more representative of its actual in-service condition, most likely a solution annealed and aged condition. This condition has been investigated to a limited extent by Zinkle and Eatherly [5] for the same material tested in vacuum.

FUTURE WORK

Specimens from solution annealed and aged CuCrZr are also planned for testing to compare the results with those obtained in this study and the previously reported tests on the GlidCop™ and Hycon 3HP™. The fracture surfaces of the solution annealed CuCrZr specimens will be selectively examined and reported at a later date.

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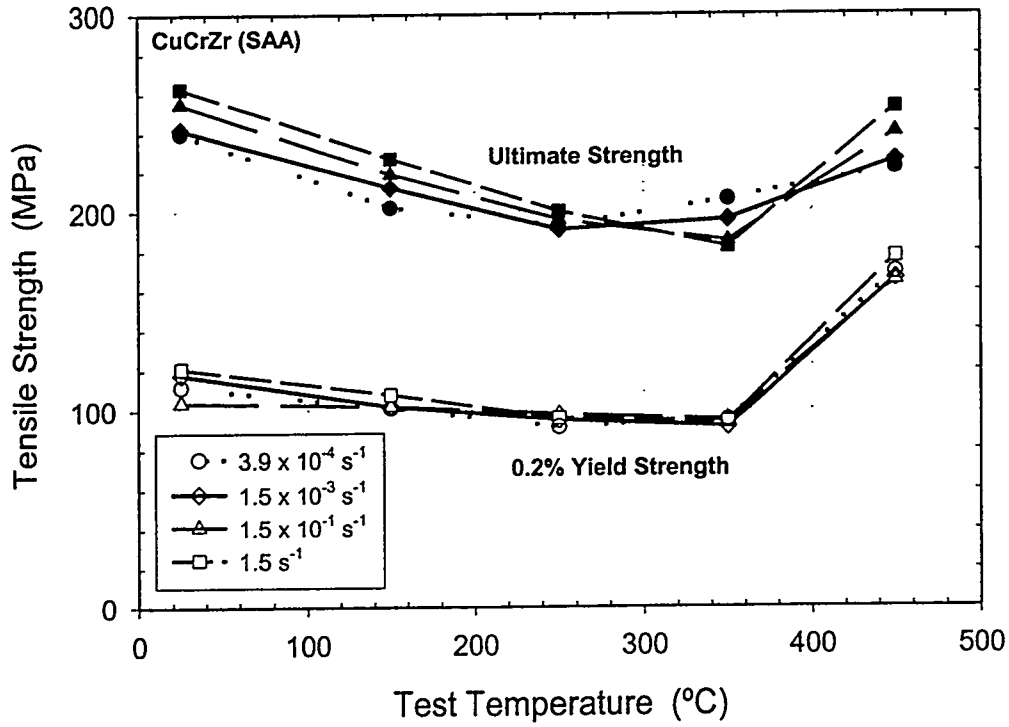

Figure 1. The temperature dependence of the yield and ultimate strength of the solution annealed CuCrZr shows that the strength decreases somewhat up to 450°C, where a limited degree of age hardening is thought to be responsible for the sudden increase in strength.

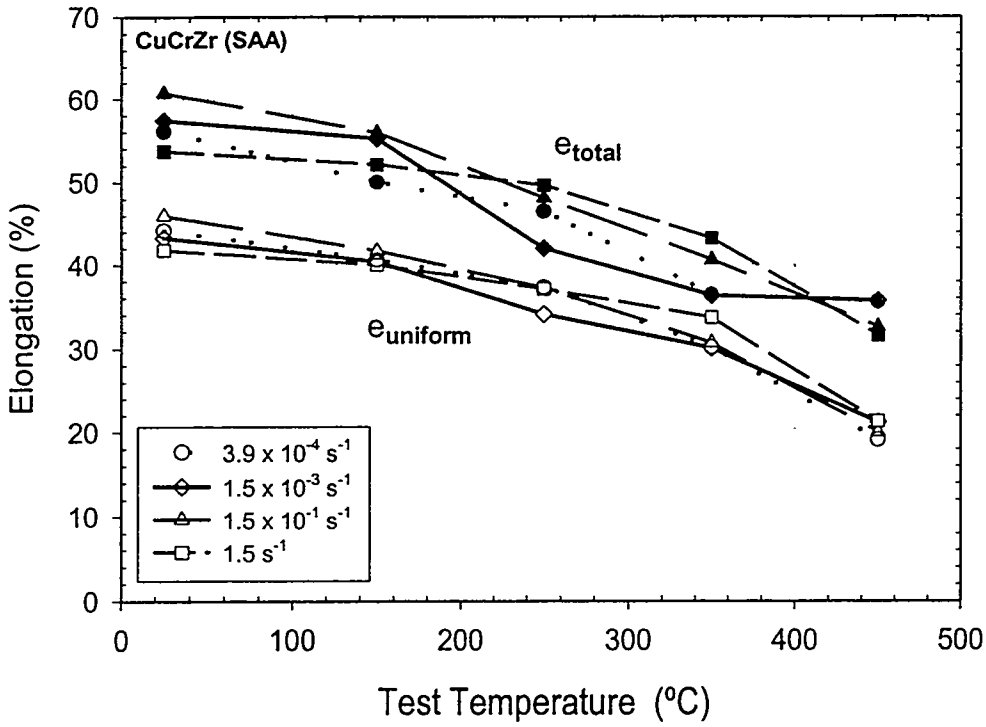

Figure 2. Shown is the temperature dependence of the uniform and total elongation of the solution annealed CuCrZr. Elongation decreases steadily as the test temperature is increased, though the 450°C tests are influenced both by the age hardening and the high test temperature.

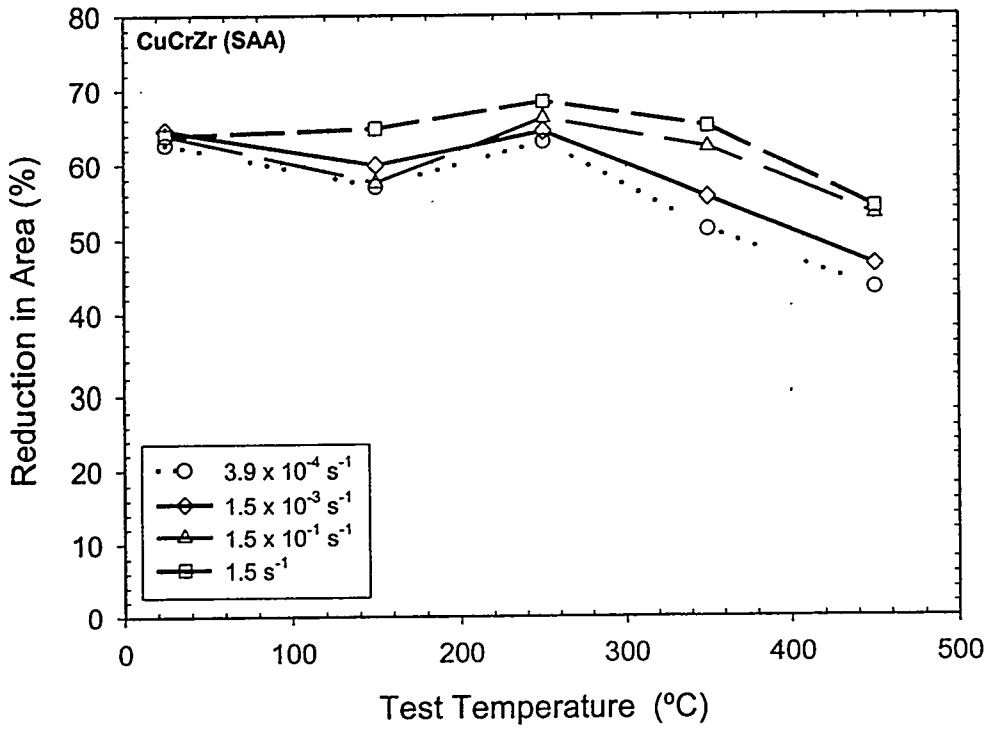

Figure 3. Changes in the reduction in area as a function of test temperature were found to be variable, however, even at 450°C the reduction in area remained above 40%. The two lower strain rates produced a noticeably smaller reduced area at 350°C and above, which might be a consequence of the age hardening.

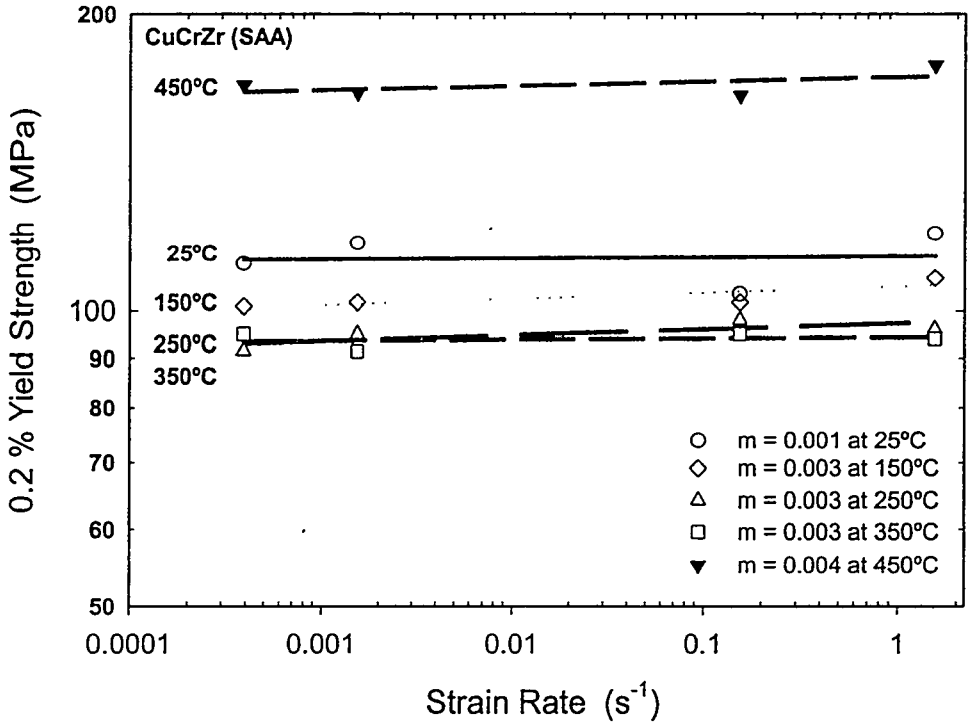

Figure 4. The yield strength of the solution annealed CuCrZr proved to be rather insensitive to the strain rates used in this experiment. The strain rate sensitivity was lower in general than those measured for the GlidCop™ Al25 and Hycon 3HP™.

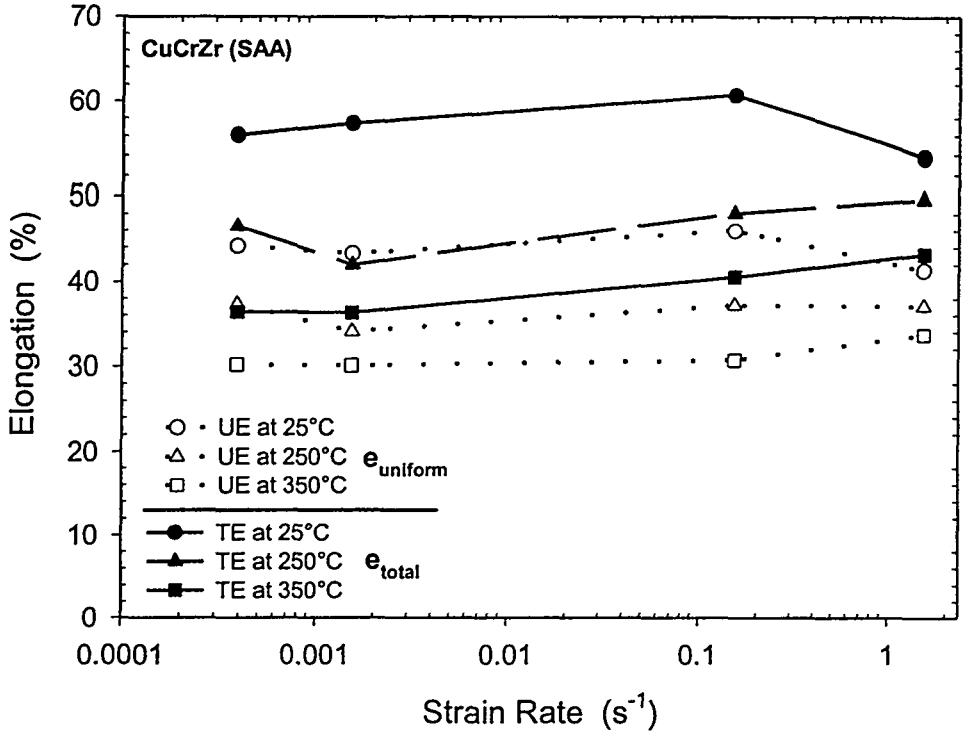

Figure 5. As in the case of the yield strength, the uniform and total elongation were not sensitive to the variation in strain rates used in this experiment. The curves for the tests conducted at 450°C are not shown for simplicity, but they show the same trend.