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The Effect of Fire Damage on the Mechanical Properties of Structural Steels Assessed using Laboratory Heat Treatment Simulations

British Steel Corporation

Research Organisation

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BRITISH STEEL CORPORATION

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THE EFFECT OF FIRE DAMAGE ON THE MECHANICAL PROPERTIES OF STRUCTURAL STEELS ASSESSED USING LABORATORY HEAT TREATMENT SIMULATIONS

SUMMARY

A series of laboratory based heat treatments have been carried out to examine the effects of fire damage on the mechanical properties of two Grade 43A type steels, a Grade 50 type steel and a sample of wrought iron. Factors studied included temperature, and time at temperature as well as heating and cooling rates.

No decrease in strength or notch toughness occurred after heating to temperatures up to 600°C and cooling back to room temperature. After heating above 600°C, some deterioration in properties was observed but in all cases the strength levels were still well in excess of the maximum allowable design stresses given in BS449: Part 2. The lowest yield stress value obtained was only 40 N/mm² below the appropriate minimum specified requirement. Under these conditions, it is likely that the steelwork involved in a fire would be severely distorted or even have collapsed and hence be unsuitable for reuse.

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Author: D G Lapwood

Department: Rails and Sections

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CONTENTS

			Page
1	INTRODUCTION		1
2	LITERATURE REVIEW		1
3	FIRE SIMULATION HEAT TREATMENTS		2
	3.1	Material Sources	2
	3.2	Heat Treatment and Testing	2
	3.3	Heating and Cooling Rates	3
4	RESULTS		4
	4.1	Tensile Properties	4
	4.2	Impact Properties	5
	4.3	Microstructures	6
5	DISCUSSION		6
	5.1	Grade 43A Mild Steel	7
	5.2	Grade 50 Type Steel Microalloyed with Vanadium	7
	5.3	Wrought Iron	8
6	CONCLUSIONS		9
7	RECOMMENDATIONS FOR FUTURE WORK		10

THE EFFECT OF FIRE DAMAGE ON THE MECHANICAL PROPERTIES OF STRUCTURAL STEELS ASSESSED USING LABORATORY HEAT TREATMENT SIMULATIONS

1. INTRODUCTION

On many occasions the main structural steelwork remains undistorted after a building has been involved in a fire. Frequently, however, engineers are concerned that the steel may have suffered permanent metallurgical damage as a result of the fire. Much of this fear is based on folklore and very little information has been published to aid engineers in deciding which members could be safely used again and which will require replacement.

The Rails and Sections Department of Teesside Laboratories in conjunction with the Marketing Department of BSC Sections have recently prepared a paper (1) for publication in various journals with the principal aim of dispelling some of the misconceptions generally held concerning the effects of fire on structural steels. The paper examines the factors which can cause steelwork to distort and collapse during fires and presents some guidelines on the major factors to be considered when contemplating the reinstatement of a steel framework after a fire.

Part of the paper describes the results of some laboratory based experiments to examine the effects of fire damage on the mechanical properties of structural steels. This report presents these results in greater detail and includes additional test data not previously reported.

2. LITERATURE REVIEW

There are very few documented instances of detailed metallurgical examinations carried out on structural steelwork which has been subjected to fire. Only five such examinations have been found, all of which were carried out by BSC personnel during the period 1973-79 (2,3,4,5,6). In addition, a series of BS476: Part 8 fire tests on universal beams is being carried out by Teesside Laboratories at the Fire Research Centre, Warrington (7). The tensile properties of the steelwork used are assessed before and after each test and any deterioration in strength can be related to the steel temperature known to have been achieved during the test.

A detailed comparison of the results is given in the paper referred to above and shows that in the majority of cases the strength levels of the fire damaged steelwork were still above the minima specified by the appropriate material specifications and all in excess of the maximum allowable design stresses given in BS449: Part 2, the Use of Structural Steel in Building.

3. FIRE SIMULATION HEAT TREATMENTS

Since there was so little quantitative information available on fire damaged steelwork, a series of fire simulation heat treatments has been carried out in the laboratory to study, under carefully controlled conditions, the effects of temperature and time on the mechanical properties of various grades of structural steel and wrought iron.

3.1 Material Sources

Three steels and one sample of wrought iron were tested. The three steels consisted of two mild steels, a low and a high strength BS4360 Grade 43A steel, and a vanadium treated steel produced to ASTM A572 Grade 50 which has similar requirements to those of BS4360 Grade 50B.

The low strength mild steel was taken from 15mm thick flats, hot rolled in the laboratory from short lengths of a commercially produced 130 x 130mm Grade 43A billet which had been the subject of a separate investigation (8) and, in fact, failed the requirements of BS4360. The high strength mild steel was taken from the 11.6mm thick web of a 533 x 210 mm x 109 kg/m beam and the microalloyed steel from the 14.5mm thick web of a 686 x 254 mm x 170 kg/m beam. Both beams were commercially rolled at Teesside Works Lackenby No. 10 Mill. The wrought iron samples were short lengths of 120 x 100 mm tee section, (flange and web, both 10 mm thick) obtained during the demolition of Stockton Railway Station which was built c.1895.

3.2 Heat Treatment and Testing

The fire simulation heat treatment simply consisted of heating a steel or wrought iron sample in a furnace to one of twelve temperatures in the range 100-1000°C for either one hour or four hours and allowing the sample to cool in air. The samples taken from the two beams were each 420x75mm, from which one plate tensile test piece and six Charpy V notch impact test specimens were machined. The samples from the low strength mild steel flats were heat treated using an edge protection jig. Each 200x50mm sample was then machined to provide duplicate 5.65mm diameter tensile test pieces and six Charpy impact specimens. The wrought iron tee sections were heat treated as 200mm full section lengths. There was insufficient wrought iron to carry out the full range of heat treatments and therefore the 4 hour treatments were omitted entirely. Duplicate round tensile test pieces were machined from the flange/web junction of each tee section. No impact test specimens were taken from these samples.

The tensile test specimens were tested in accordance with BS18 : Part 2 to determine values of yield stress, tensile strength, % elongation and, when testing round specimens, % reduction in area. The Charpy V notch specimens were tested to determine full impact transition curves. Sub-size 10x7.5mm Charpy specimens were taken from the high strength mild steel samples, all other Charpy specimens were 10x10mm in cross section.

3.3 Heating and Cooling Rates

The heating and cooling rates of the samples were approximately 60C^{o}/min. and 36C^{o}/min. respectively. The heating rate of steelwork during a fire depends mainly on the fire load and the type of fire protection (if any) used, e.g. insulation boards, intumescent paints, etc. The cooling rate depends on the conditions during damping down. It is possible that the heating rate of unprotected steelwork during some fires would be faster and the cooling rate slower than the rates observed during the laboratory heat treatments. A simple experiment was therefore carried out to examine the effects of these differences.

This experiment consisted of heating a 420mm length of commercially produced 50x50x6mm Grade 43A angle to one of three temperatures in the range 800-920^{o}C, removing the sample from the furnace immediately on achieving temperature and cooling in vermiculite to 500^{o}C (transformation is complete at this temperature). Cooling was completed in air.

By setting the furnace at a temperature approximately 100C^{o} higher than the aim heat treatment temperature combined with the effect of heating material approximately half the thickness of the samples used in the earlier heat treatments, heating rates were achieved in the range 150-200C^{o}/min. These rates are very fast and probably exceed those which would be expected for unprotected steelwork under the worst fire conditions by a factor of at least two. The cooling rates in the vermiculite were around 20C^{o}/min. One plate tensile test specimen was machined from each leg of each heat treated angle.

4. RESULTS

Table 1 shows the chemical compositions (product analyses) of the four steels and the one wrought iron tested. The results of the tensile and Charpy V notch impact tests in both the as received and heat treated material are listed in Tables 2 and 3a-c respectively. The effect of fire simulation temperature on the yield stress and tensile strength of the low and high strength Grade 43A and the ASTM A572 steels and the wrought iron are presented graphically in Figures, 1, 2, 3, and 4 respectively. Similarly, the effect on the Charpy impact energy absorbed at 0°C and the 27 Joule impact transition temperature are shown in Figures 5, 6 and 7 (no impact tests were carried out on the wrought iron). The tensile test results on the 6mm thick Grade 43A steel subjected to heat treatments with modified heating and cooling rates are shown in Table 4.

4.1 Tensile Properties

All the steels tested had one important feature in common; there was no deterioration in strength after heating to temperatures up to 600°C irrespective of time at temperature. Above 600°C, the materials showed differing behaviour depending on quality and, for the mild steels, original strength level.

Heat treatment at temperatures above 600°C had little effect on the yield stress and tensile strength of the low strength mild steel (Figure 1) although a slight drop, of approximately 15 N/mm^2, was observed after heating to 700°C. The difference in original yield stress between the low and high strength mild steels was around 100 N/mm^2. After heating to temperatures above 600°C, the high strength mild steel showed a steady deterioration in yield stress reaching a minimum of 245 N/mm^2 after heating to 900°C, a decrease of around 90 N/mm^2 from the original strength level (Figure 2). It should be noted that the yield stress after heating to 900°C for 4 hours was only 10 N/mm^2 below the minimum value specified in BS4360 for Grade 43A and that the original yield stress of this sample was typical for sections produced in Grade 43A.

The yield stress of the steel microalloyed with vanadium reached a minimum of 304 N/mm^2 after heating to 800°C, a decrease of over 100 N/mm^2 from the original yield stress and around 40 N/mm^2 below the minimum value allowed in ASTM A572 (Figure 3). Above 800°C, the strength levels increased and after heating to 1000°C, the yield stress had recovered to within 40 N/mm^2 of the original level.

The wrought iron showed no deterioration in strength properties with increasing temperature of heat treatment (Figure 4). In fact, there was an increase of around 20 N/mm^2 in strength levels after 1 hour heat treatments at temperatures greater than 600°C.

Table 2 also shows that the ductility of all the materials tested, as measured by the % elongation at failure and % reduction in area, was maintained irrespective of the temperature and duration of heat treatment.

The effect of modifying the heating and cooling rates of the 6mm thick mild steel angles was to decrease their yield stress and tensile strength levels by approximately 30 N/mm^2 (Table 4). These changes were in line with those observed in the mild steels subjected to heat treatment for much longer times at similar temperatures (800-900°C) under conventional laboratory conditions. The lowest yield stress measured after heat treatment was 17 N/mm^2 below the BS4360 minimum value of 255 N/mm^2.

4.2 Impact Properties

It should be noted initially that neither BS 4360 Grade 43A nor ASTM A572 Grade 50 (nor BS 4360 Grade 50B) are offered with guaranteed impact properties. Nevertheless, the values obtained on the as-received material were excellent (Tables 3a-c). An energy absorption of 27 Joules minimum at the Charpy test temperature is normally regarded as a measure of adequate notch toughness in a steel. The temperature at which 27 Joules was absorbed, the 27 Joule impact transition temperature (27J ITT), was on average as follows for each of the steels tested.

Low strength Grade 43A	- 5°C
High strength Grade 43A	-35°C
ASTM A572 Grade 50	-15°C

The notch toughness of the three steels after heat treatment followed similar trends to those of the strength properties (Figure 5, 6 and 7) in that the impact transition temperatures and the number of Joules absorbed at 0°C remained constant up to 600°C. The transition temperatures of the low strength mild steel were, in fact, decreased to lower temperatures by about 10-20C°. This improvement in impact properties was maintained after heat treatment at temperatures up to 750°C.

Heat treating the mild steels at higher temperatures resulted in a deterioration in impact properties, the transition temperatures increasing by 10C° for the low strength mild steel (Figure 5) and 20C° for the higher strength material (Figure 6). The number of Joules absorbed at 0°C showed a corresponding decrease. It is worth noting that in both cases the worst transition temperatures observed, +5 and -10°C respectively, were still within the range which can be expected for mild steels in the hot rolled condition.

The heat treated samples of ASTM A572 Grade 50 showed a deterioration in impact transition temperature after treatment in the range 600-700°C, the maximum ITT observed being +10°C after heating for 4 hours at 650°C. At 750°C, the transition temperature decreased markedly to -30°C, around 15C° lower than the original levels. Above 750°C, the transition temperatures increased and after heating to 1000°C, they were at a similar level, -10°C, to the values in the hot rolled condition.

4.3 Microstructures

The microstructural changes, if any, that had occurred as a result of the fire simulation heat treatments were assessed. The mean ferrite grain size and the percentage of phases other than ferrite were measured on selected samples using standard metallographic techniques (Tables 5 and 6). Typical examples of the microstructural changes are shown in Figure 8.

5 DISCUSSION

The factors which control the properties of mild and micro-alloyed steels are well understood and a detailed discussion of this topic is beyond the scope of this report. The main factors are alloy content, ferrite grain size and, in the case of a steel microalloyed with vanadium (or niobium), the amount, size and distribution of the carbide and nitride (or carbonitride) precipitates within the ferrite grains. In general terms, the effects of these factors on properties can be summarised as follows:

Decreasing ferrite grain size, increases strength and improves notch toughness.

Increasing precipitation hardening, increases strength but has an adverse effect on notch toughness.

Bearing these effects in mind, the changes in mechanical properties of the Grade 43A type mild steels, the Grade 50 type microalloyed steel and the wrought iron as a result of the fire simulation heat treatments (ie. exposures to temperatures up to 1000°C) can be explained using well established metallurgical principles.

5.1 Grade 43A Mild Steels

In the as received, hot rolled condition, the two mild steels had similar microstructures consisting of ferrite and pearlite. After heating to temperatures up to 600°C, there was no change in strength or notch toughness nor were there any changes in microstructure (Table 5).

For temperatures above 600°C up to the A_1 temperature of 723°C some initial loss of strength was observed. This was due to the microstructural change known as spheroidisation. Although no phase changes occur in this temperature range, heating for periods of one hour or longer causes the cementite (Fe_3C) in the lamellar pearlite to coalesce within the ferrite into spheroidal particles which coarsen with time.

At temperatures above 723°C, the pearlite transformed to austenite and any remaining ferrite grains would coarsen usually in an irregular manner. On air cooling, the austenite transformed to ferrite and pearlite but the coarser ferrite structure was retained.

On heating the samples above the A_3 temperatures, the steels transformed to relatively coarse grained austenite which continued to coarsen with increasing time and temperature and resulted on cooling in a coarse grained ferrite(and Widmanstatten ferrite) and pearlite microstructure. The loss of strength and deterioration in impact properties were maintained.

As rolled, the high strength Grade 43A mild steel had a finer ferrite grain size than the low strength steel which together with the differences in carbon (hence pearlite) and manganese accounted for the higher strength. However, this grain size difference meant that the grain coarsening in the two mild steels after heating at temperatures in excess of 700°C had a consequently greater deleterious effect on the properties of the higher strength steel.

5.2 Grade 50 Type Steel Microalloyed with Vanadium

In the as received, hot rolled condition, the steel microalloyed with vanadium had a ferrite/pearlite microstructure with a similar ferrite grain size to the Grade 43A steel. In common with the mild steels no changes in the mechanical properties or microstructure were observed after the heat treatments at temperatures up to 600°C. For temperatures above 600°C up to 723°C, the loss in strength was due to spheroidisation and some initial coarsening of the vanadium carbide and nitride precipitates.

In the austenite plus ferrite region above 723°C, the precipitates would continue to coarsen within the ferrite grains which themselves would coarsen in an irregular manner, the precipitates providing some pinning of the grain boundaries. The carbides within the austenite would then begin to dissolve. On cooling, the austenite transformed to ferrite and pearlite and the relatively coarse grained ferrite was retained. The precipitation hardening effects were minimal with a two-fold result, a marked loss in strength together with a significant improvement in impact properties. In this case, the minimum strength and impact transition temperatures were observed after heating at 800°C.

At 900°C, the steel was above its A_3 temperature and fully austenitic. All the vanadium carbide would be taken into solid solution and some vanadium nitride might begin to dissolve. The austenite grain boundaries, pinned by the nitrides, remained relatively fine grained. On cooling, the vanadium carbide reprecipitated in the ferrite grains which together with the relatively fine grain size resulted in the increase in strength. The impact properties showed only a slight deterioration since the increased precipitation hardening was offset by the decrease in grain size.

A further increase in strength due to precipitation hardening was observed after heating to 1000°C since at this temperature all the vanadium carbide and nitride precipitates would dissolve in the austenite and then reprecipitate on cooling as vanadium carbonitride which would offset the effect of austenite grain growth. The increased precipitation hardening and increase in grain size resulted in an increase in impact transition temperatures which, in this case, returned to the levels observed in the as-received sample.

5.3 <u>Wrought Iron</u>

In the as received condition, the microstructure of the wrought iron consisted entirely of ferrite of mixed grain size. Large amounts of slag and other inclusions were also present. Heating at temperatures up to 900°C resulted in an increase in ferrite grain size which was retained on cooling and would be expected to result in a loss of strength. However, the samples tested showed a slight increase in strength even though the grain size had increased. This strength increase might be attributable to the variation from sample to sample in the size and distribution of the slag and inclusions or some feature associated with the high phosphorus level. A secondary hardening effect due to phosphorus has been observed in normalised and tempered ferrite-pearlite steels with much lower phosphorus contents (up to 0.07%).

6 CONCLUSIONS

A series of laboratory based heat treatments have been carried out to examine the effects of fire damage on the mechanical properties of structural steels. The effects of temperature and time at temperature on strength and notch toughness after cooling back to room temperature have been studied for two BS4360 Grade 43A type mild steels, a Grade 50 type steel microalloyed with vanadium and a wrought iron. Heat treatments were also carried out on a Grade 43A steel using fast heating rates (up to 200C^{o}/min). and slower cooling rates (around 20C^{o}/min). The microstructural changes, if any, as a result of the fire simulation heat treatments were also assessed.

1) No deterioration in strength or notch toughness occurred after heating to temperatures up to 600^{o}C.

2) Above 600^{o}C, the materials showed differing behaviour depending on quality and for the Grade 43A type steels, original strength level. A drop in strength was observed after heating to these temperatures but in the worst case this was only 40 N/mm^2 below the minimum specified yield stress requirement. All values were still well in excess of the maximum allowable design stresses given in BS449:Part 2. However, under these conditions, it is likely that the steelwork would be severely distorted or have collapsed.

3) The Grade 43A steel heat treated at 800-900^{o}C using fast heating rates and slower cooling rates showed similar behaviour to the mild steels heat treated at similar temperatures under conventional laboratory conditions.

4) The changes in mechanical properties as a result of the fire simulation heat treatments have been explained using established metallurgical principles.

7 RECOMMENDATIONS FOR FUTURE WORK

Similar heat treatment programmes should be carried out on the two remaining steel types which are widely used in the construction industry. These are BS4360 Grade 50B micro-alloyed with niobium and the high strength weather resistant proprietry grade, COR-TEN, which contains additions of chromium, copper, vanadium and aluminium.

Research Manager:

J Lessells
Product Applications Group
Teesside Laboratories
P O Box 74
Ladgate Lane
MIDDLESBROUGH
Cleveland
TS8 9EG

Author: D G Lapwood

Rails and Sections

Manager: R R Preston

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QUALITY	%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Ni	%V	%Ti	%Cu	%Sn	%Nb	%Zr	%B	Sol %Al	Tot %Al	$\%N_2$	$\%O_2$
BS4360 Grade 43A- Low Strength	.17	.05	.63	.011	.037	<.005	<.005	.014	<.005	<.005	.019	.002	<.005	<.005	<.0005	<.002	<.002	.0060	.013
High Strength 50x50x6mm Angle	.19	.02	.97	.016	.019	.030	.005	.035	<.005	<.005	.043	.006	<.005	<.005	<.0005	<.002	.006	.0030	.035
	.16	.0 46	.624	.011	.037	<.005	<.005	.015	<.005	<.005	.019	.002	<.005	<.005	<.0005	<.002	<.002	.0059	.013
Specification (1979)	0.30 max	0.55 max	1.70 max	0.060 max	0.060 max	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ASTM A572 Grade 50	.19	.013	1.29	.010	.014	.012	<.005	.034	.080	<.005	.024	<.005	<.005	<.005	<.0005	<.003	.005	.0035	.026
Specification• (1978)	.23 max	0.40 max	1.35 max	.04 max	.05 max	-	-	-	0.01/ 0.15	-	-	-	-	-	-	-	-	0.015 max	-
Wrought Iron	.014	<.01	<.01	~.25	.023	<.005	<.005	.04	<.005	<.005	.03	<.002	<.005	<.005	<.0005	.011	.014	.0077	N/D
Specification	None available. Sample was taken from Stockton Railway Station which was completed in 1895.																		

• ASTM A572 also allows the use of niobium either singly or in combination with vanadium.

CHEMICAL COMPOSITIONS OF VARIOUS STEELS AND WROUGHT IRON SUBJECTED TO LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

TABLE

CONDITION	TIME h	TEMP. °C	BS4360 GRADE 43A LOW STRENGTH YS N/mm^2	TS N/mm^2	%El $5.65\sqrt{S_o}$	%R of A	HIGH STRENGTH YS N/mm^2	TS N/mm^2	%El 200mm	ASTM A572 GRADE 50 YS N/mm^2	TS N/mm^2	%El 200mm	WROUGHT IRON YS N/mm^2	TS N/mm^2	%El $5.65\sqrt{S_o}$	%R of A
As Received	-	-	239	396	40	70	344	475	25	417	545	23	242	368	30	48
	-	-	235	396	37	66	329	470	26	402	542	25	234	376	20	43
	-	-	247	404	39	70	341	472	26	408	531	22	-	-	-	-
	-	-	231	402	34	68	325	471	26	436	560	21	-	-	-	-
Heat treated	1	100	-	-	-	-	343	473	25	-	-	-	-	-	-	-
		200	-	-	-	-	329	479	26	-	-	-	-	-	-	-
		300	-	-	-	-	314	459	27	419	543	21	-	-	-	-
		400	-	-	-	-	320	461	29	412	539	21	-	-	-	-
		500	243	417	32	66	345	473	25	409	537	23	238	378	23	38
		600	262	419	33	69	333	464	26	402	531	23	265	395	21	49
		650	254	408	32	68	-	-	-	381	506	25	-	-	-	-
		700	240	393	33	70	306	428	28	366	493	28	258	396	24	48
		750	233	399	30	69	-	-	-	353	500	25	-	-	-	-
		800	253	399	29	70	289	445	29	312	472	28	259	399	25	46
		900	222	391	30	68	249	428	29	345	498	27	262	400	21	51
		1000	-	-	-	-	249	436	30	364	543	21	-	-	-	-
	4	100	-	-	-	-	331	467	25	-	-	-	-	-	-	-
		200	-	-	-	-	331	468	28	-	-	-	-	-	-	-
		300	-	-	-	-	338	480	26	404	538	22	-	-	-	-
		400	-	-	-	-	338	480	27	413	544	21	-	-	-	-
		500	239	411	34	69	336	473	26	401	537	23	-	-	-	-
		600	256	400	27	72	333	464	26	434	550	20	-	-	-	-
		650	251	400	35	69	-	-	-	421	543	19	-	-	-	-
		700	223	373	36	70	283	407	28	335	459	24	-	-	-	-
		750	233	400	32	70	-	-	-	327	490	27	-	-	-	-
		800	241	398	33	69	270	435	29	304	415	33	-	-	-	-
		900	230	405	33	67	243	421	29	356	511	24	-	-	-	-
		1000	-	-	-	-	243	431	30	373	559	21	-	-	-	-
SPECIFICATION			255 min	430/510	22 min	-	255 min	430/510	20 min	345 min	450 min	18 min	NONE AVAILABLE			

LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

TABLE 2

CONDITION	TIME h	TEMP. °C	JOULES ABSORBED AT (°C)									27J ITT °C
			+75	+40	+20	+15	+10	0	-10	-20	-30	
As rolled	-	-	-	133	86	-	53	34	20	11	-	-5
			-	133	88	-	55	33	19	14	-	-5
Heat treated	1	600	145	-	144	-	-	38	-	31	21	-25
										36		
		800	135	141	60	-	34	20	-	17	-	+5
		900	119	-	124	48	47	24	-	11	-	+5
	4	600	150	-	142	-	-	71	-	28	12	-20
		750	145	-	132	116	-	76	32	20	-	-15
		800	155	146	105	-	60	25	-	13	-	+5
		900	148	105	61	-	32	19	-	13	-	+5

CHARPY V-NOTCH IMPACT PROPERTIES OF LOW STRENGTH MILD STEEL SUBJECTED TO LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

TABLE 3a

CONDITION	TIME h	TEMP. °C	JOULES ABSORBED AT (°C)										27J ITT °C
			+20	0	-10	-20	-30	-35	-40	-50	-60	-70	
As rolled	-	-	53	50	-	48	37	-	14	-	4	-	-37
			58	58	-	54	32	-	8	-	4	-	-35
			50	52	-	48	38	-	26	-	5	-	-40
			58	60	-	51	25	-	9	-	5	-	-30
Heat treated	1	100	53	54	-	53	-	-	10	6	4	-	-35
		200	58	59	-	48	22	-	11	-	-	3	-30
		300	54	51	-	50	36	-	8	-	-	3	-35
		400	57	54	-	42	22	-	9	-	-	3	-30
		500	52	50	-	42	-	-	26	7	4	-	-42
		600	54	57	-	45	30	-	9	5	-	-	-37
		700	57	55	-	31	10	-	6	-	3	-	-25
		800	57	55	-	28	18	-	10	-	-	-	-25
		900	70	60	-	34	12	-	8	-	4	-	-25
		1000	64	55	24	13	9	-	7	-	-	7	-10
	4	100	57	51	-	46	25	-	8	-	4	-	-30
		200	53	52	-	48	36	-	11	-	-	3	-35
		300	50	54	-	51	34	-	14	-	-	3	-35
		400	58	53	-	48	36	-	12	-	-	3	-35
		500	50	51	-	46	42	16	13	-	-	-	-32
		600	53	54	-	45	16	-	7	-	-	-	-27
		700	55	45	39	15	6	-	-	-	3	-	-15
		800	59	55	-	44	41	17	12	-	-	-	-32
		900	71	56	39	13	10	-	-	-	4	-	-15
		1000	69	44	29	16	11	-	6	-	-	-	-15

• 10x7.5mm specimens

CHARPY• V-NOTCH IMPACT PROPERTIES OF HIGH STRENGTH MILD STEEL SUBJECTED TO LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

TABLE 3b

CONDITION	TIME h	TEMP. °C	JOULES ABSORBED AT (°C)								27J ITT °C
			+60	+40	+15	0	-10	-20	-30	-40	
As rolled	-	-	94	-	94	42	37	27	23	-	-20
			-	-	96	48	41	28	18	-	-20
			101	-	85	-	35	25	-	-	-15
			98	-	84	46	29	23	-	-	-10
Heat treated	1	300	98	-	60	-	26	28	-	-	-10
							31				
		400	100	-	97	49	35	22	-	-	-15
		500	100	-	95	39	36	20	-	-	-15
		600	96	-	56	31	31	22	-	-	-15
		650	100	106	48	35	27	18	-	-	-10
		700	112	113	53	35	25	17	-	-	-5
		750	109	-	104	46	41	29	23	-	-25
		800	125	-	103	114	-	44	34	22	-35
		900	-	-	105	91	-	46	21	-	-25
		1000	116	-	71	39	28	23	-	-	-10
	4	300	104	-	86	-	53	23	16	-	-15
								33			
		400	102	-	90	46	-	30	15	-	-20
		500	99	-	93	41	44	23	-	-	-15
								29			
		600	102	-	67	24	23	15	-	-	+5
		650	96	100	30	25	-	9	-	-	+10
		700	128	122	48	34	24	15	-	-	-5
		750	120	-	112	90	-	41	28	23	-30
		800	-	-	107	55	-	41	14	-	-25
		900	-	-	114	102	-	32	39	16	-25
									25		
		1000	192	-	74	-	57	18	-	-	-10
							25	18			

CHARPY V-NOTCH IMPACT PROPERTIES OF ASTM A572 GRADE 50 STEEL SUBJECTED TO LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

TABLE 3c

RS No.	YS N/mm^2	TS N/mm^2	%El 200mm	HEAT TREATMENT*
783D (1)	281	431	26	None. Tests on as-rolled angle
(2)	274	430	26	
783A (1)	246	403	24	Heated to 906°C @ 150C°/min., removed at once and cooled in vermiculite @ 17C°/min. in range 906-650°C
(2)	250	405	25	
783B (1)	241	405	24	Heated to 920°C @ 240C°/min., removed at once and cooled in vermiculite @ 20C°/min. in range 920-650°C
(2)	238	406	24	
783C (1)	254	403	26	Heated to 806°C @ 154C°/min., removed at once and cooled in vermiculite @ 20C°/min. in range 806-650°C
(2)	261	412	26	

* Heat treated samples removed from vermiculite at ~500°C

50x50x6mm GRADE 43A ANGLES - FIRE SIMULATION HEAT TREATMENTS WITH MODIFIED HEATING AND COOLING RATES - TENSILE RESULTS

TABLE 4

QUALITY	CONDITION	TIME h	TEMP. °C	FERRITE GRAIN SIZE d(μm)	$d^{-\frac{1}{2}}$ ($mm^{-\frac{1}{2}}$)	% PEARLITE	% WIDMANSTATTEN
Low Strength Mild Steel	As Received	-	-	18.7	7.3	14	-
	Heat Treated	1	500	19.6	7.1	12	-
			700	18.3	7.4	16[(1)]	-
			900	23.3	6.5	11	-
		4	500	19.4	7.2	12	-
			700	20.9	6.9	13[(1)]	-
			900	23.4	6.5	16	-
High Strength Mild Steel - BS4360 Grade 43A	As Received	-	-	11.0	9.5	23	-
	Heat Treated	1	500	12.7	8.9	17	-
			600	13.0	8.8	16	-
			700	13.1	8.7	15[(1)]	-
			800	13.0	8.8	12	-
			900	17.2	7.6	22	2
		4	500	12.0	9.1	16	-
			600	12.0	9.1	18	-
			700	15.1	8.1	16[(1)]	-
			800	15.2	8.1	15	-
			1000	19.1	7.2	18	8
Microalloyed Steel - ASTM A572 Grade 50	As Received	-	-	11.9	9.2	23	-
	Heat Treated	1	600	11.3	9.4	23	-
			700	9.3	10.4	22[(1)]	-
			900	10.8	9.6	16	-
		4	600	10.2	9.9	23	-
			700	12.0	9.1	21[(1)]	-
			900	13.1	8.7	20	11
Wrought Iron	As Received	-	-	-[(2)]	-	Nil	-
	Heat Treated	1	500	34.27	5.4	Nil	-
			700	-	-	Nil	-
			900	46.02	4.7	Nil	-

Notes: (1) Spheroidised pearlite

(2) All the wrought iron samples had mixed ferrite grain sizes. In only two cases was it possible to obtain approximate values.

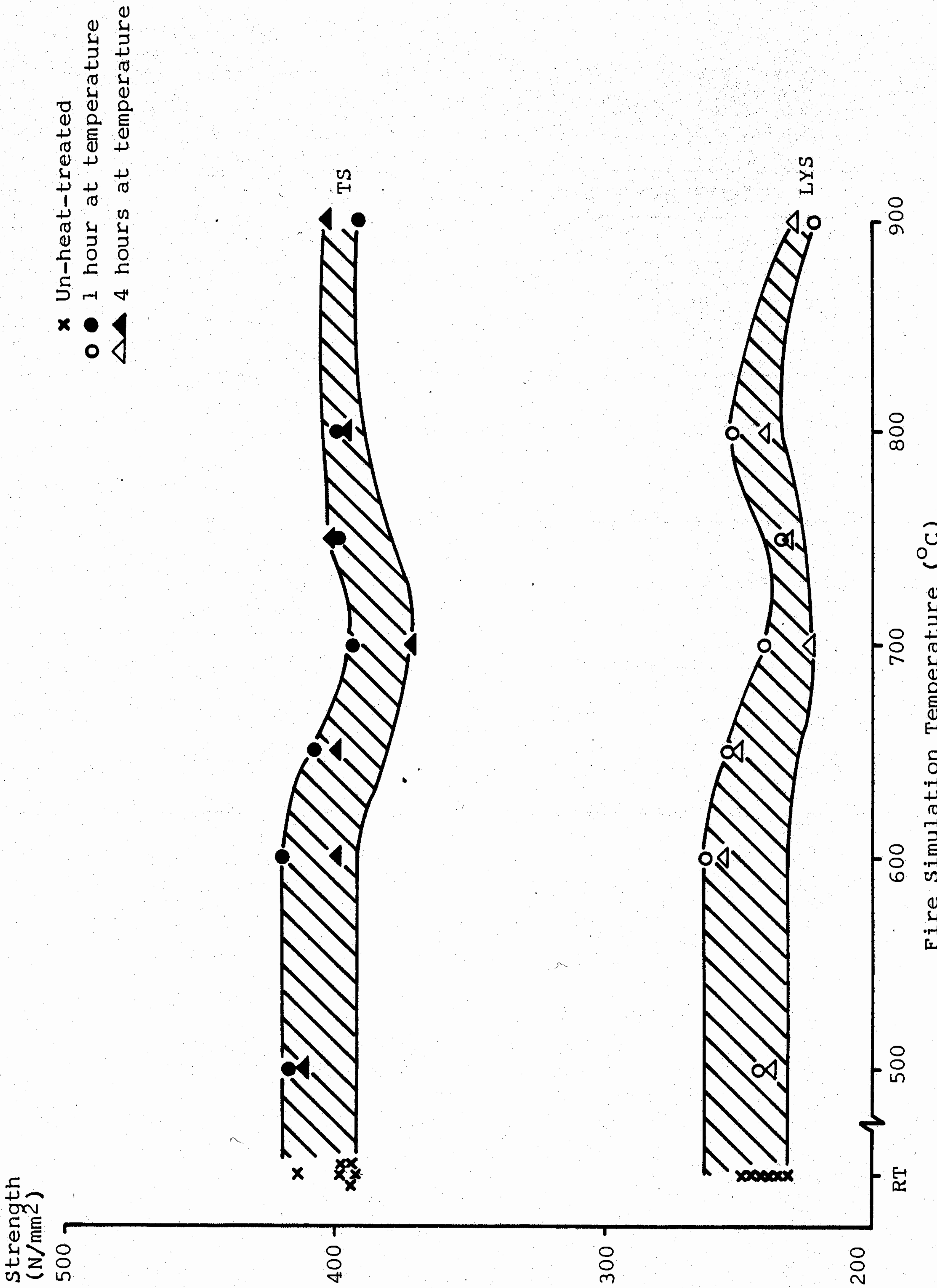
RESULTS OF METALLOGRAPHIC ASSESSMENT OF SELECTED HEAT TREATED SAMPLES

TABLE 5

RS No.	FERRITE GRAIN SIZE		% PEARLITE	HEAT TREATMENT
	$d(\mu m)$	$d^{-\frac{1}{2}}(mm^{-\frac{1}{2}})$		
783D (1)	13.6	8.6	16	None. As rolled
783A (2)	19.1	7.2	13	Heated to 906°C @ 150C°/min., cooled @ 17C°/min.
783B (1)	20.7	7.0	15	Heated to 920°C @ 204C°/min., cooled @ 20C°/min.
783C (1)	15.8	8.0	11	Heated to 806°C @ 154C°/min., cooled @ 20C°Cmin.

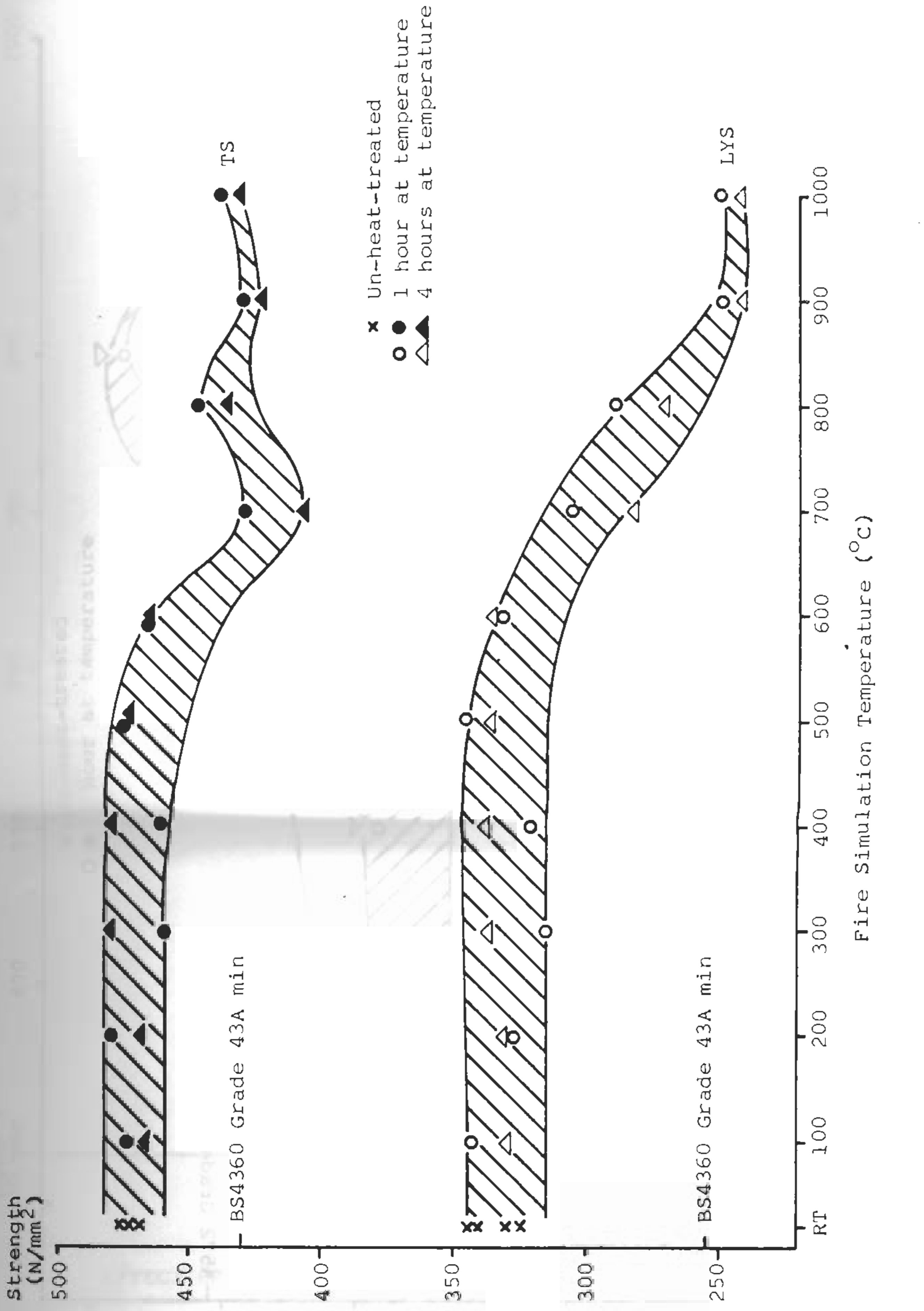
RESULTS OF METALLOGRAPHIC ASSESSMENT OF GRADE 43A ANGLES SUBJECTED TO HEAT TREATMENTS WITH MODIFIED HEATING AND COOLING RATES

TABLE 6



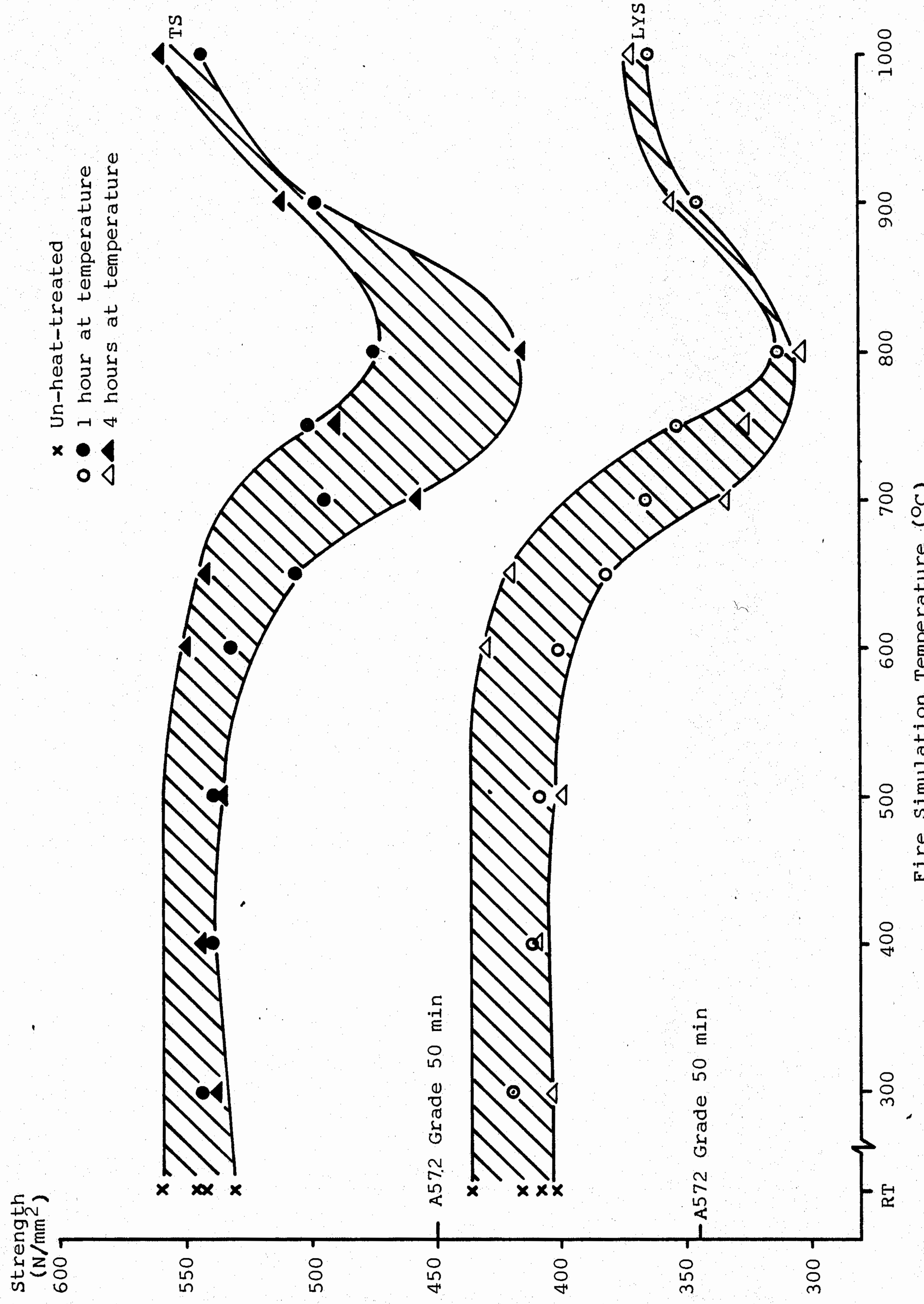
EFFECT OF LABORATORY HEAT TREATMENTS ON STRENGTH PROPERTIES OF A LOW STRENGTH MILD STEEL

FIGUR



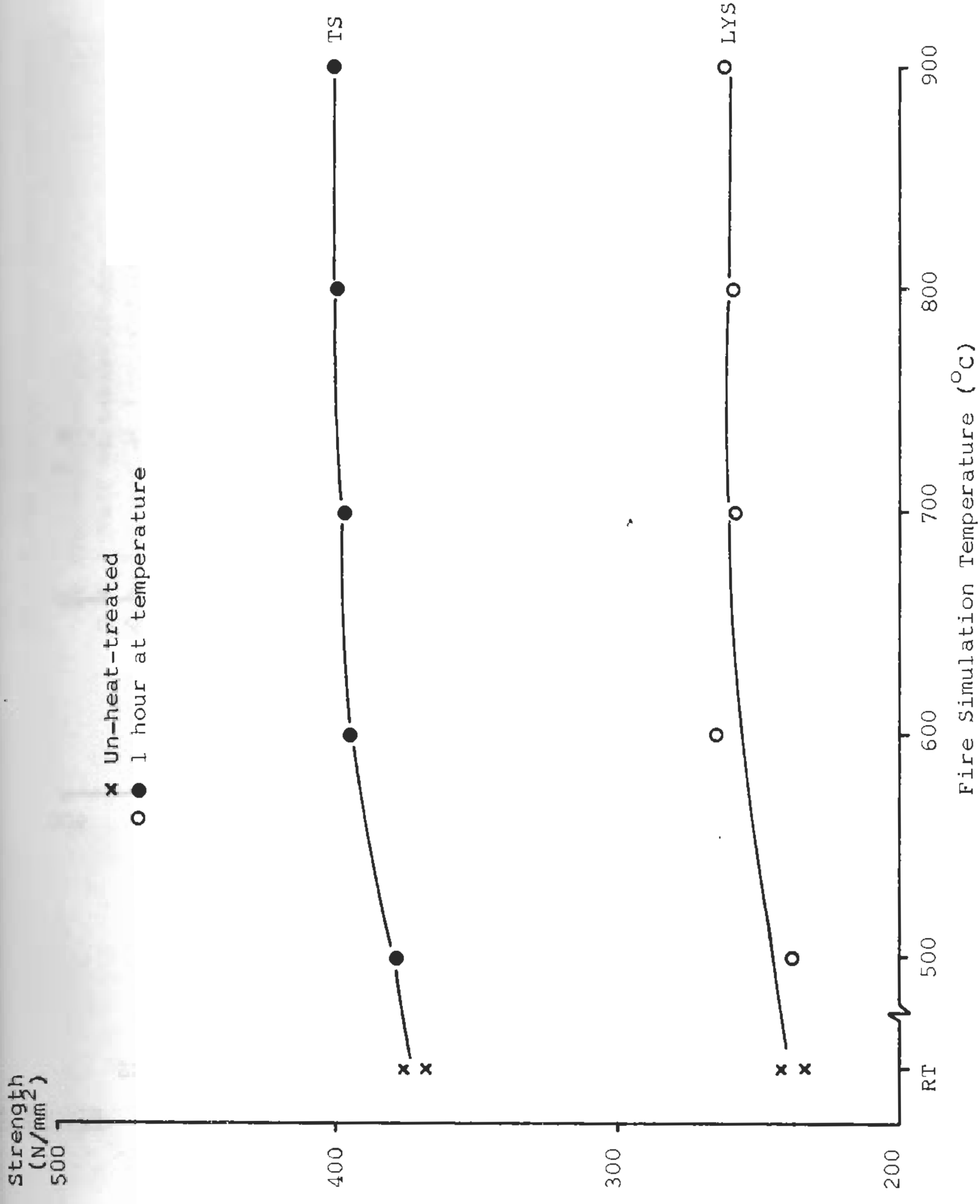
EFFECT OF LABORATORY HEAT TREATMENTS ON STRENGTH PROPERTIES OF A HIGH STRENGTH BS4360 GRADE 43A STEEL

FIGURE 2



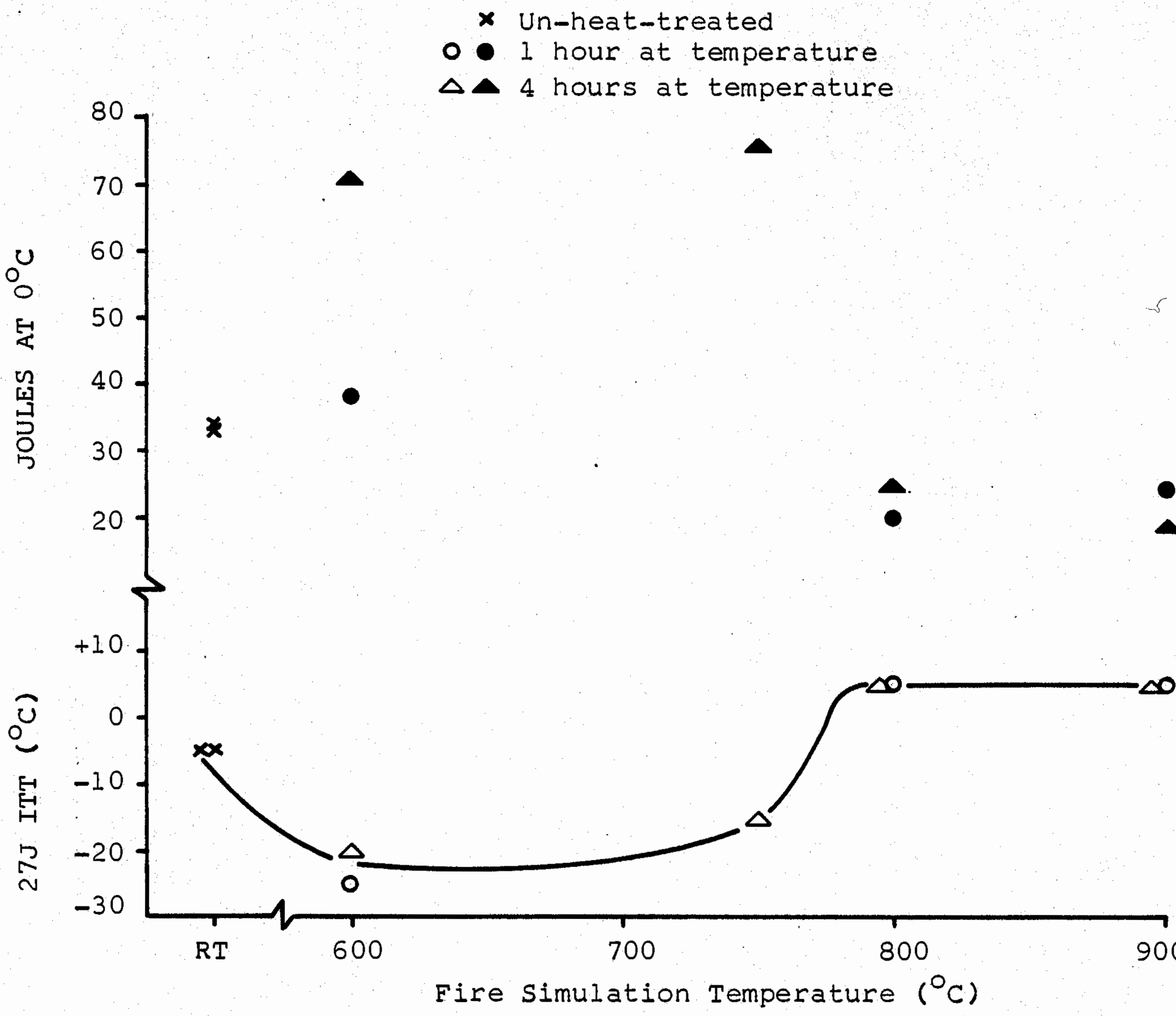
EFFECT OF LABORATORY HEAT TREATMENTS ON STRENGTH PROPERTIES OF AN ASTM A572 GRADE 50 STEEL

FIGURE



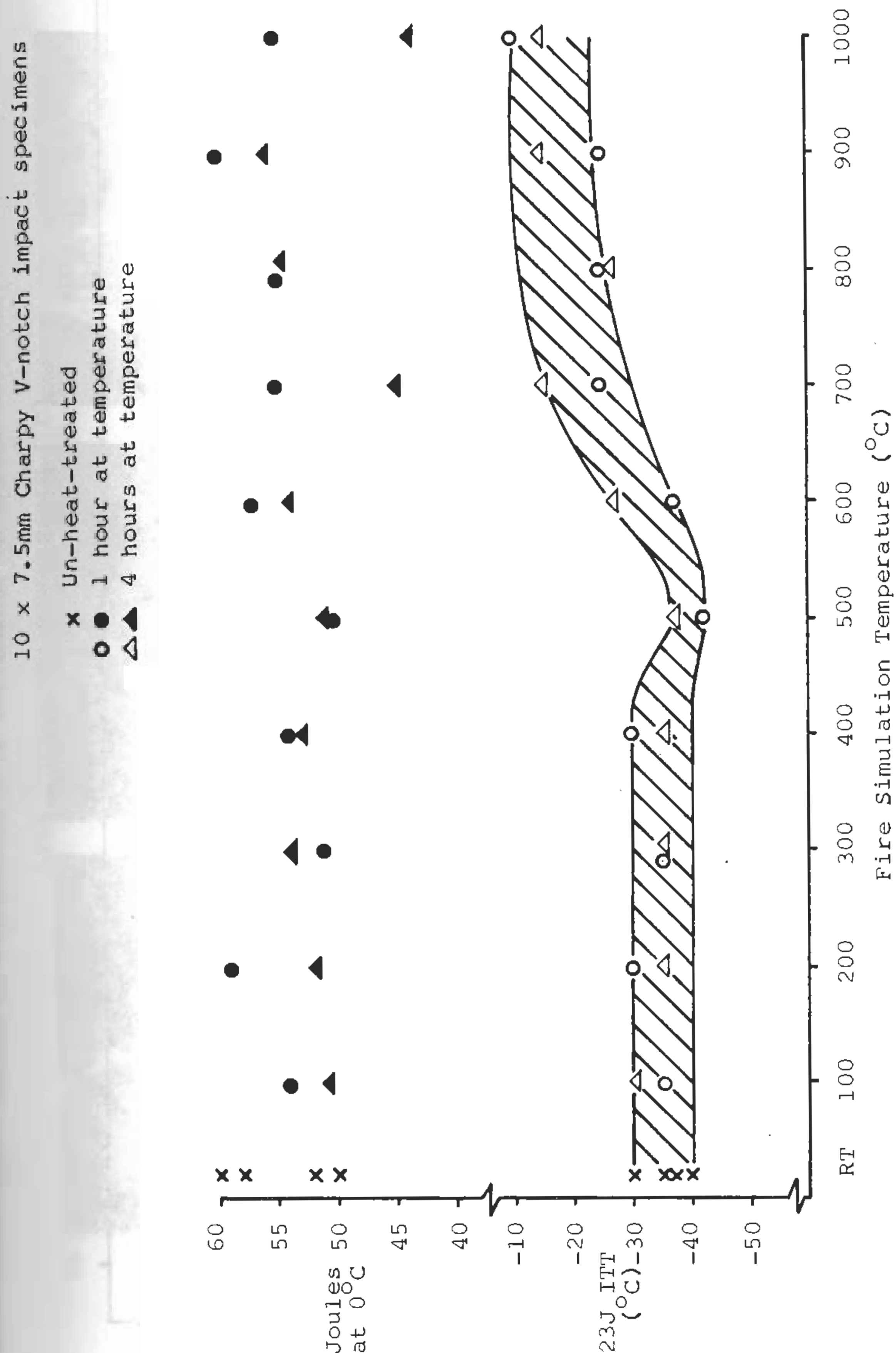
EFFECT OF LABORATORY HEAT TREATMENTS ON STRENGTH PROPERTIES OF A WROUGHT IRON

FIGURE 4



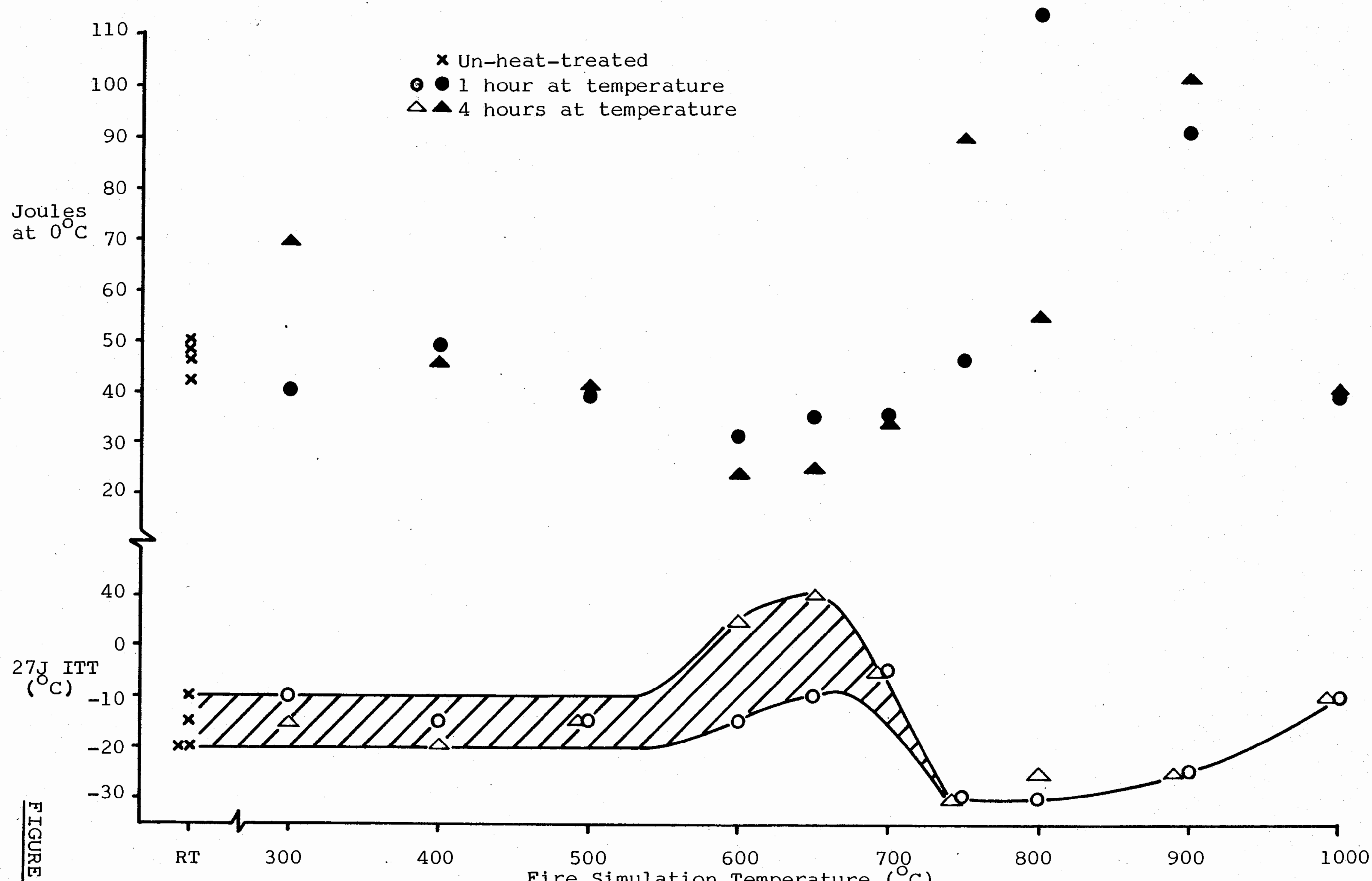
EFFECT OF LABORATORY HEAT TREATMENTS ON IMPACT PROPERTIES
OF A LOW STRENGTH MILD STEEL

FIGU



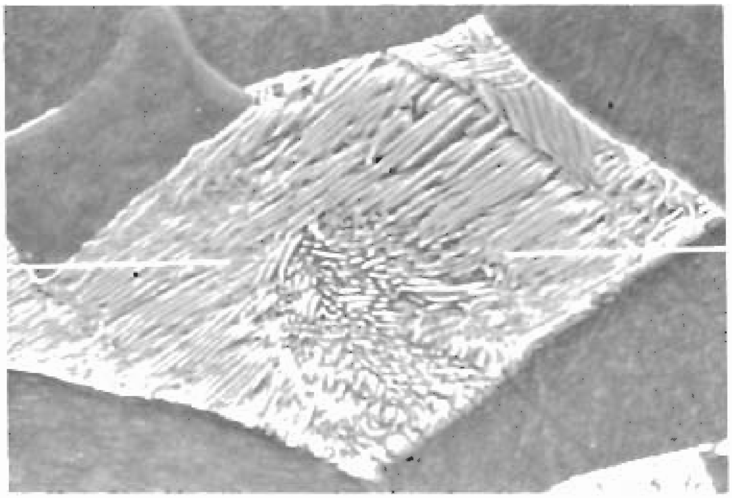
EFFECT OF LABORATORY HEAT TREATMENTS ON IMPACT PROPERTIES OF A HIGH STRENGTH BS4360 GRADE 43A STEEL

FIGURE 6

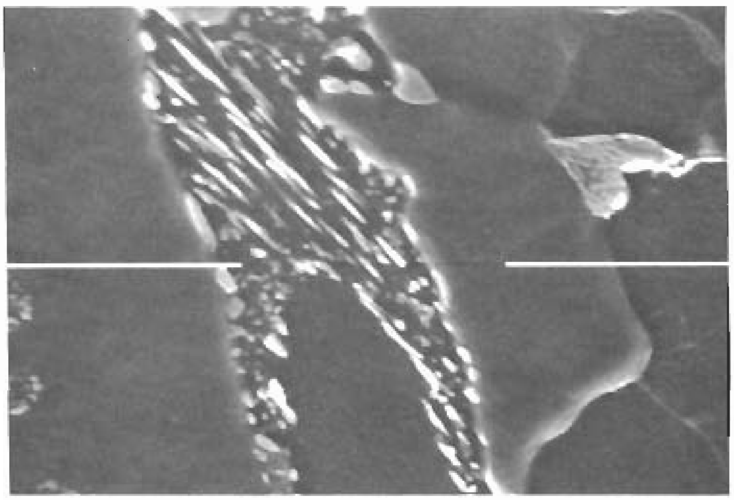


EFFECT OF LABORATORY HEAT TREATMENTS ON IMPACT PROPERTIES

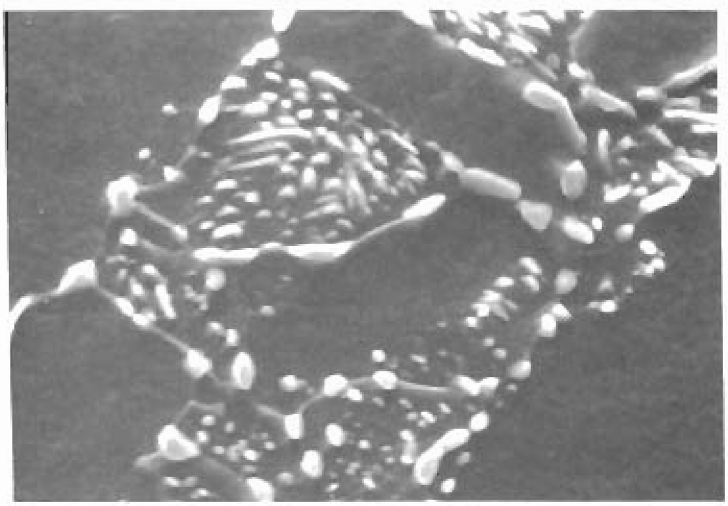
FIGURE 7



Hot rolled condition - showing lamellar pearlite



After 1 hour at $700^{o}C$ - showing partially spheroidised pearlite



After 4 hours at $700^{o}C$ - showing completely spheroidised pearlite

EXAMPLES OF MICROSTRUCTURAL CHANGES WHICH OCCURRED AS A RESULT OF LABORATORY HEAT TREATMENTS SIMULATING FIRE DAMAGE

x4K

FIGURE 8