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Low-Cycle Fatigue Strength of Fast Breeder Reactor Fuel Cladding Tube Material

(Primary Test)

November, 1971

CONSTRUCTION DESIGN COMMITTEE

F B R MATERIAL SPECIALISTS COMMITTEE

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1. Introduction

Here are arranged in order the results of tests made on the fatigue curves of cladding tube materials which form the foundation for analyzing fatigue of fuel cladding tubes for the experimental fast breeder reactor "JYOYO" being developed by the Power Reactor & Nuclear Fuel Development Corporation.

In actual uses, the cladding tubes will be put in a high-temperature atmosphere at a level of approx. 650°C and thermal stress will be produced as a result of the difference between the outside temperature and the inside temperature of the tubes. The high temperature and the thermal stress will be varied according as a breeder reactor goes or stops, or as its load varies, and the cladding tubes are thought to be put in a state of thermal fatigue.

For thermal fatigue under varying stress, strain and, in addition, temperature, the conventional ASME way of fatigue analysis treats it as a low-cycle fatigue at a fixed temperature neglecting the effect of the variation of temperature, but the past studies included a case which reported that thermal fatigue strength at temperature cycles of the upper limit temperature T_{max} and the lowest limit temperature T_{min} superposed was lower than that at a fixed temperature $T=T_{max}$.

In the present study, tests were made on the low-cycle fatigue strength at a constant temperature (hereinafter referred to as "high-temperature fatigue") and on the thermal fatigue strength at temperature cycles superposed(hereinafter referred to as "thermal fatigue") of cladding tube materials for the purpose of obtaining reasonable fatigue curves through the research of the relativity between the two types of the fatigue strength.

In the present study, portions of the fatigue test were assigned to and taken over by the Department of Technology of Tokyo University, Mitsubishi Atomic Power Industries Inc., and Kobe Technical Institute and Nagasaki Technical Institute of

Mitsubishi Heavy Industries Ltd. and the test material was manufactured by Kobe Steel Ltd. in accordance with the research program laid out by the Corporation.

All the assigned institutes' tests and studies were completed and their reports are filed already. The present report arranged those results in order and discusses them focussed on the following two points:

i) Significant differences among those test results presented by the assigned research institutes.

ii) To obtain fatigue curves that are considered resonable.

The present report does not mention of safety factor for it should desirably be established from a collective point of view, nor, therefore, this report shows design fatigue curves. The data used in this report are derived from the following sources; for further information, see these sources.

1) High Temperature Fatigue Test of Fuel Cladding Tube Material for Fast Breeder Reactor, November 1970. Mitsubishi Atomic Power Industries Inc.

2) Study on Low-Cycle Fatigue Strength of Fuel Cladding Material for Fast Breeder Reactor, May 10, 1971, Department of Technology, Tokyo University.

2. Outline of Testing Method

The testing methods employed by the assigned research institutes are as outlined below.

2.1 Specimens

SUS32 cold drawn hollow round bars (outside diameter: 18mm, inside diameter: 10mm) were used as the specimens. Although the dimensions of the specimen tubes are remarkably differed from those of actual-size cladding tubes (outside diameter: 6.3mm, inside diameter: 5.7mm) for convenience' sake, plasticizing processing and heat treatment are given to the specimens so that they have substantially the same mechanical properties and microstructure as those of actual cladding tubes.

The chemical composition of the specimens are shown in Table 1 and their static mechanical properties at different temperatures are shown in Table 2.

2.2 Assignments of Test and Test Conditions

Low-cycle fatigue test under a constant temperature and low-cycle fatigue test under temperature cycles superposed were performed at 5 different test temperature conditions respectively, at 10 such conditions altogether. The test temperature in the high-temperature fatigue test was set at the uppermost limit temperature of the thermal fatigue test, while the lowest limit temperature in the thermal fatigue test was set at 250°C. Other tests performed include the low-cycle fatigue test at R.T. for standard data, the thermal fatigue test at design temperature conditions (T_{max}=650°C, T_{min}=370°C), and other tests conducted by the 2 assigned research institutes at each test temperature condition for the purpose of comparing the obtained test results. The test conditions as related to the assigned research institutes are shown in Table 3.

2.3 Specimens and Testing Apparatuses

The specimen and the testing apparatus used by each assigned research institutes are shown in Table 4. The shapes of those specimens were not necessarily same because of difference in the testing apparatuses used.

2.4 Temperature and Strain Waveform

i) Frequency of Strain

The frequency of strain employed in each assigned research institute is shown in Table 3.

ii) Temperature Cycle

In the thermal fatigue test, Tokyo University employed a high-temperature compression process where compressive strain is loaded at the upper limit temperature, while Mitsubishi (Nagasaki) employed a high-temperature tension process where tensile strain is loaded at the upper limit temperature. It is noted from the preliminary test made by Mitsubishi (Nagasaki) using SUS 27, that thermal fatigue strength is reduced in the high-temperature tension process more than in the high-temperature compression process.

iii) Strain Waveform

In the high-temperature fatigue test, Mitsubishi (Kobe) used a triangular waveform while Tokyo University used a trapezoid waveform having a holding time of 5 to 15 sec. In the thermal fatigue test, both Mitsubishi (Nagasaki) and Tokyo University used a trapezoid waveform having a holding time of 5 to 15 sec.

iv) Separation of Plastic Strain

Every assigned research institute measured the range of plastic strain from the recorded stress strain hysteresis curves.

3. Test Results

The results of the high-temperature fatigue test and the thermal fatigue test are shown in Tables 5 through 10. These tests were performed under a complete by reversed tension-compression strain and a total strain control.

The specimens showed a repetition strain softening tendency because they were treated with an intensive cold work. All the figures of the plastic strain range, elastic strain range and stress range in these tables are representative values in the expression $n \doteq 1/2 N_f$.

Fatigue curves in the relations between the amplitudes of total strain, elastic strain and plastic strain, and life to rupture are shown in Fig. 1 through 6.

4. Discussions on Test Results

4.1 Difference in Data among Different Assigned Research Institutes

i) High-Temperature Fatigue

The following facts are pointed out from the Fig. 1 through 6. In the high-temperature fatigue test the fatigue curves of Tokyo University and Mitsubishi (Kobe) in the relation between the amplitude of total strain and life to rupture are conforming with each other with no marked difference between the data of the two institutes. However, in the relations between the amplitude of elastic strain vs. life to rupture and between the amplitude of plastic strain vs. life to rupture, a significant difference is found between them, that is, the data of Tokyo University indicate higher amplitude of elastic strain and lower amplitude of plastic strain than those of Mitsubishi (Kobe).

ii) Thermal Fatigue

Comparison between the data of Tokyo University and the data of Mitsubishi (Nagasaki) in connection with the relation between total strain amplitude and life to rupture reveals that although significant difference is not seen in the test temperature range of 500/250°C, the data of Tokyo University generally tend to show higher values than those of Mitsubishi (Nagasaki) at the other temperatures. This difference is especially remarkable at the temperatures 650/250°C. For the relations between elastic strain amplitude and life to rupture and between plastic strain amplitude and life to rupture, the elastic strain amplitude in higher and the plastic strain amplitude is lower in the data of Tokyo University than in those of Mitsubishi (Nagasaki).

iii) Repeated Stress Strain Curves

Repeated stress strain curves in the relation between stress range S_R and total strain range ε_{tR} are shown in Fig. 7 through 16. Usually, the comparison of this kind of figures shows a noticeable deviation, but the data of Tokyo University and Mitsubishi (Kobe) in the high-temperature fatigue test can be said well conforming with each other except at 600°C and 700°C. In the tests at 600°C and 700°C where the data of Tokyo University show lower values, deviation is remarkable indicative of difficulty of the tests.

In the thermal fatigue test, the data of Tokyo University show lower values at 500°C/250°C, the data of Mitsubishi (Nagasaki) show slightly lower values at 600°C/250°C, 650°C/250°C and 700°C/250°C, and the two data are in good conformity at 650°C/370°C.

The major differences in the above-mentioned test results are the differences of elastic strain elements and plastic strain elements, the difference in the thermal fatigue test results arranged by the total strain amplitude, and the difference of repeated stress strain curves. And the conceivable major causes of these differences are the difference in the strain waveforms employed by Tokyo University and Mitsubishi (Kobe) in the high-temperature fatigue test, and the difference in the strain and temperature phases used by Tokyo University and Mitsubishi (Nagasaki) (high-temperature compression and high-temperature tension) in the thermal fatigue test. In particular, the different in the fatigue curves of total strain amplitude vs. life to rupture shown in the thermal fatigue test may be attributable to the difference between the high-temperature tension and the high-temperature compression.

For the difference in thermal fatigue strength due to the high-temperature compression process and the high-temperature tension process, Mitsubishi (Nagasaki) made a supplementary test using SUS 27 and the resultant difference in the fatigue strength is generally in accordance with the difference in the fatigue strength of the present thermal fatigue test made at 650/250°C. Hence, the difference in the data of Tokyo University and Mitsubishi (Nagasaki) for fatigue strength as indicated under the relation between total strain amplitude and life to rupture is thought derived from the difference of the testing processes, the high-temperature tension process.

The reason for the non-conformity of repeated stress strain curves among the participant research institutes in the thermal fatigue test cannot be well explained from the difference between the high-temperature compression process and the high-temperature tension process. In the said supplementary test, there no difference was found between the repeated stress strain curves in the high-temperature compression process and those in the high-temperature tension process.

With respect to the question of different elastic strain elements and plastic strain elements in different research institutes, which is common to all the test results, one of the conceivable causes is the difference in the strain waveforms employed. In other words, it is conjectured that owing to the difference of strain rates in the loading and the unloading processes and to the difference of strain holding times, the stress relaxation was presumably made to differ during the maximum holding period, and that the treatment might have been varied according to the research institutes. However, considering that the variation of the plastic strain arising from the stress relaxation during such short period of 15 sec at the longest is only 5 to 10 per cent, it is difficult to believe that this alone fully explains the reason of the difference in question. Another conceivable cause in the high-temperature fatigue test is that heating was made in different methods: direct and indirect electric heating methods. But in direct electric heating, the strain increment even after compensated will be about 10% at most which is thought weak enough to claim the major cause.

Thus, considerable difference comes out when the data of the assigned research institutes are compared in detail. But when attention is paid only to the fatigue curves of total strain amplitude vs. life, the comparison of the data of the research institutes reveals little difference which, if any, is generally permissible. Therefore, the high-temperature fatigue and the thermal fatigue strength evaluated by the amplitude of total strain will be used in the following analytical discussions.

4.2 Comparison between High-Temperature Fatigue Strength and Thermal Fatigue Strength

The high-temperature fatigue strength and the thermal fatigue strength were compared based on the fatigue curves for total strain amplitude vs. life. As a result, the following finding were obtained.

i) In the comparison between the high-temperature fatigue strength at T=500°C and the thermal fatigue strength at T_{max} = 500°C and T_{min} = 250°C, the high-temperature fatigue was higher.

ii) In the comparison between the high-temperature fatigue at T = 600°C and the thermal fatigue strength at T_{max} = 600°C, when the test temperature of the high-temperature fatigue was set at the uppermost limit temperature of the thermal fatigue, the strength of the high-temperature fatigue was higher.

iii) When the strength of the thermal fatigue was compared in two different temperature ranges of 650/250°C and 650/370°C, the strength was lower in the former range which was wider than the latter.

According to the above findings, a high-temperature fatigue test in a temperature range 600°C and higher is likely to being about a forecasting of danger for the life of cladding tubes, even if the test was performed at the uppermost limit temperature. On the other hand, the influence of the mean temperature (T_m=0.5 (T_{max} + T_{min})) affecting the thermal fatigue strength is smaller than the influence of a temperature range, and therefore use of the data of a thermal fatigue test made in a somewhat high temperature range will enable to estimate the life of safty side.

The above discussion are summarized in the ε_{ta}-N_f curves in Fig. 17.

5. Design Fatigue Curves

From the ε_{ta}-N_f curves, fatigue curves of equivalent elastic stress amplitude (Se) vs. life (N_f) were drawn up. The values of the longitudinal elastic coefficient used for the Se calculation are the full line in Fig. 18, which is formed with smaller values for safety purpose because values produced by Mitsubishi (Nagasaki) and Kobe Steel from the present specimens are differed considerably. For the thermal fatigue, values at the uppermost limit temperature are used.

The obtained Se-N_f curves are shown in Fig. 19. These fatigue curves for equivalent elastic stress amplitude vs. life are to serve as a basis for further analysis of fatigue, and design fatigue curves will be produced by multiplying them by a certain proper safety factor.

6. Summary

The results of the high-temperature fatigue test and the thermal fatigue test performed in the temperature range from R.T. up to 700°C using SUS 32 materials equivalent to the fuel cladding tube materials for the FBR experiment reactor were arranged in order, and the fatigue curves for equivalent elastic stress amplitude (Se) vs. life (N_f), which are to provide basis for preparation of design fatigue curves, were drawn up. In order to produce design fatigue curves from the said fatigue curves, the value of a proper safety factor must be established.

The findings in this operation are as summarized below.

i) Difference was not found among the high-temperature fatigue strengths obtained by all the assigned research institutes in case that such strengths were evaluated by the fatigue curves for total strain amplitude vs. life.

ii) Significant difference was found among the thermal fatigue strengths obtained by such research institutes even when such strengths were evaluated by the ε_{ta}-N_f curves. The difference is considered to be derived from the different testing methods, i.e., a high-temperature compression method and a high-temperature tension method.

ii) A considerable amount of difference was found in the fatigue curves for elastic strain vs. life and for plastic strain vs. life produced by such research institutes, and the cause of such difference could not be elucidated by the present data produced. Then, the ε_{ta}-N_f curves were chosen as most reliable for the purpose of the present analysis, and the analysis operation was conducted, based on them.

Table 1. Chemical composition

(From mill sheet)

	C	Si	Mn	P	S	Ni	Cr	Co	Mo	N
Spec.	0.06 ~0.08	≤0.75	≤2.00	≤0.03	≤0.03	11.0 ~14.0	16.0 ~18.0	≤0.10	2.00 ~3.00	≤0.035
Check	0.061	0.56	1.51	0.026	0.012	12.11	16.14	0.030	2.45	0.020

Table 2. Mechanical Properties

Data from	Test temp. (°C)	Tensile strength (kg/mm²)	0.2% Proof stress (kg/mm²)	Elongation (%)	Variation in diam. (%)	Young's modulus (kg/mm²)	Grain size ASTM No.	Hardness HRC
Spec.		≥60	≥40	≥25			≥6	
From mill sheet	R.T.	76.3	67.8	36.0			7.5	24 ~26.4
		75.8	66.7	34.0			7.5	23.2~24.7
Mitsubishi (Nagasaki)	R.T.	75.0	63.0	27.8	26.9	18.3 x 10^3		
		74.3	63.7	29.0	28.4	18.5 x 10^3		
	300	64.1	55.6	13.0	17.2	17.1 x 10^3		
		64.5	54.2	12.0	15.9	16.9 x 10^3		
	500	61.8	51.1	18.0	18.3	15.9 x 10^3		
		62.6	55.6	15.6	18.6	17.7 x 10^3		
Kobe Steel Ltd.	R.T.					20.5 x 10^3		
	600					15.6 x 10^3		
	650					14.9 x 10^3		
	700					14.4 x 10^3		

Table 3. Test temperature condition assigned to research institutes

	Test Temp. °C	Assigned research institute		
		Tokyo university	Mitsubishi (Kobe)	Mitsubishi (Nagasaki)
Constant Temperature	R.T.	1.2 - 5cpm	2 - 3cpm	
	500	1.2 - 5cpm	2 - 3cpm	
	600	1.2 - 5cpm	2 - 3cpm	
	650	1.2 - 5cpm	2 - 3cpm	
	700	1.2 - 5cpm	2 - 3cpm	
Thermal Cycle	500/250	1.2cpm		0.6 - 0.85cpm
	600/250	1.2cpm		0.6 - 0.85cpm
	650/250	1.2cpm		0.6 - 0.85cpm
	700/250	1.2cpm		0.6 - 0.85cpm
	650/370	1.2cpm		0.6 - 0.85cpm

Table 4. Specifications of eesting apparatus used in each research institute

	Tokyo University	Mitsubishi Kobe	Mitsubishi Nagasaki
Type of apparatus	Oil pressure servo type thermal fatigue tester	Oil pressure low-cycle fatigue tester	Oil pressure thermal fatigue tester
Load capacity	Static ± 15 ton, Dynamic ± 10 ton	± 10 ton	± 10 ton
Maximum displacement	Static ± 50 mm, Dynamic ± 2.5 mm		± 20 mm
Load detection	Differential transformer	Strain gauge type load cell	Strain gauge type load cell
Strain detection	Differential transformer	Strain gauge type non-adhesive detector	Differential transformer
Heating method	Direct electric heating	Heating in electric furnace	Direct electric heating
Maximum heating temperature	~ 1000°C	~800°C	~ 800°C
Control method		On-off control by an indicator having limit switch	Solenoid valve - on-off control
Specimen			

Table 5. Test results (R.T.)

Test temp. T(°C)	Data from	Strain amplitude ta(%)	Plastic strain amplitude pa(%)	Elastic strain amplitude ea(%)	Stress range R(kg/mm²)	No. of cycles to rupture N_f(cycles)
R.T.	Tokyo Univ.	1.024	0.692	0.332	117.8	547
		0.75	0.39	0.36	113.0	1048
		0.50	0.257	0.243	102.6	1628
		0.412	0.136	0.276	90.0	3034
		0.34	0.07	0.27	96.2	8756
	Mitsubishi (Kobe)	3.00				Buckled
		1.82	1.53	0.29	127.0	128
		1.30	0.92	0.38	-	269
		1.06	0.75	0.31	115.5	565
		0.67	0.42	0.25	109.0	1348
		0.47	0.27	0.20	97.5	2947
		0.39	0.19	0.20	99.3	2644
		0.40	0.21	0.19	94.0	5487
		0.34	0.139	0.201	90.8	8412

Table 6. Test results (500°C , 500/250°C).

Test temp. T (°C)	Data from	Strain amplitude ε_{ta} (%)	Plastic strain amplitude ε_{pa} (%)	Elastic strain amplitude ε_{ea} (%)	Stress range σ_R (kg/mm^2)	No. of cycles to rupture Nf (cycles)
500	Tokyo Univ.	1.036	0.664	0.372	105.1	106
		0.508	0.204	0.304	90.9	486
		0.436	0.15	0.286	86.4	1 091
		0.34	0.08	0.26	88.2	2 359
		0.285	0.05	0.235	81.0	3 022
		0.248	0.027	0.221	74.0	4 143
		0.226	0.01	0.216	50.5	19 017
	Mitsu -bishi (Kobe)	1.78	1.46	0.32	115.8	13
		1.56	1.28	0.28	—	6
		0.92	0.72	0.20	100.5	103
		0.77	0.48	0.29	—	127
		0.67	0.40	0.27	93.0	432
		0.64	0.33	0.31	100.0	245
		0.53	0.26	0.27	—	492
		0.39	0.119	0.271	89.0	1 552
		0.32	0.077	0.243	87.5	2 533
		0.27	0.044	0.226	85.0	6 670
500/250	Tokyo Univ.	1.008	0.70	0.308	114.0	100
		0.93	0.598	0.332	110.2	123
		0.81	0.424	0.386	110.0	239
		0.595	0.185	0.41	102.2	698
		0.48	0.16	0.32	98.7	694
	Mitsu -bishi (Naga -saki)	1.5	1.135	0.365	130.6	33
		1.1	0.765	0.335	119.8	111
		0.85	0.525	0.325	117.1	197
		0.7	0.385	0.315	113.0	243
		0.6	0.315	0.285	103.0	565
		0.5	0.215	0.285	101.7	1 180
		0.4	0.155	0.245	88.2	2 453
		0.3	0.07	0.23	82.8	5 790

Table 7. Test results (600°C, 600/250°C).

Test temp T (°C)	Data from	Strain emplitude ε_{ta} (%)	Plastic strain emplitude ε_{pa} (%)	Elastic strain emplitude ε_{ea} (%)	Stress range σ_R (kg/mm^2)	No. of cycles to rupture Nf (cycles)
600	Tokyo Univ.	1.046	0.789	0.257	72.7	65
600	Tokyo Univ.	0.62	0.33	0.29	73.7	195
600	Tokyo Univ.	0.42	0.20	0.22	65.0	290
600	Tokyo Univ.	0.33	0.164	0.166	59.1	619
600	Tokyo Univ.	0.285	0.055	0.23	52.1	2 274
600	Tokyo Univ.	0.204	0.035	0.169	45.0	4 086
600	Mitsu-bishi (Kobe)	1.74	1.50	0.24	87.7	14
600	Mitsu-bishi (Kobe)	1.58	1.21	0.37	96.2	25
600	Mitsu-bishi (Kobe)	0.92	0.74	0.18	97.5	92
600	Mitsu-bishi (Kobe)	0.67	0.42	0.25	78.5	260
600	Mitsu-bishi (Kobe)	0.43	0.26	0.17	71.5	566
600	Mitsu-bishi (Kobe)	0.38	0.155	0.225	79.0	865
600	Mitsu-bishi (Kobe)	0.30	0.08	0.22	69.2	1 774
600	Mitsu-bishi (Kobe)	0.26	0.069	0.191	76.0	1 248
600	Mitsu-bishi (Kobe)	0.26	0.08	0.18	—	3 026
600	Mitsu-bishi (Kobe)	0.21	0.054	0.156	64.0	6 245
600/250	Tokyo Univ.	1.23	0.86	0.37	121.96	41
600/250	Tokyo Univ.	0.835	0.491	0.344	107.4	133
600/250	Tokyo Univ.	0.71	0.38	0.33	103.2	181
600/250	Tokyo Univ.	0.521	0.24	0.281	94.4	333
600/250	Tokyo Univ.	0.38	0.094	0.286	86.8	920
600/250	Mitsu-bishi (Naga-saki)	1.5	1.175	0.325	111.1	17
600/250	Mitsu-bishi (Naga-saki)	1.1	0.78	0.33	108.4	47
600/250	Mitsu-bishi (Naga-saki)	0.85	0.545	0.305	103.0	98
600/250	Mitsu-bishi (Naga-saki)	0.7	0.42	0.28	94.9	109
600/250	Mitsu-bishi (Naga-saki)	0.5	0.215	0.285	96.5	305
600/250	Mitsu-bishi (Naga-saki)	0.4	0.15	0.25	85.6	480
600/250	Mitsu-bishi (Naga-saki)	0.3	0.105	0.195	66.4	1 010
600/250	Mitsu-bishi (Naga-saki)	0.22	0.07	0.15	50.2	2 520

Table. 8. Test results (650° C , 650/250°C).

Test temp T (°C)	Data from	Strain amplitude ε_{ta} (%)	Plastic strain emplitude ε_{pa} (%)	Elastic strain emplitude ε_{ea} (%)	Stress range σ_R (kg/mm²)	No. of cycles to rupture Nf (cycles)
650	Tokyo Univ.	1.028	0.744	0.284	72.4	58
		0.59	0.388	0.202	68.8	176
		0.408	0.224	0.184	54.1	360
		0.366	0.164	0.202	53.7	559
		0.24	0.063	0.177	48.9	1 526
		0.21	0.05	0.16	46.3	1 856
		0.18	0.028	0.152	48.5	6 038
	Mitsu-bishi (kobe)	1.90	1.73	0.17	76.5	21
		1.44	1.16	0.28	76.5	72
		1.00	0.77	0.23	75.1	94
		0.67	0.53	0.14	65.0	220
		0.50	0.36	0.14	62.6	435
		0.38	0.165	0.215	66.5	749
		0.24	0.098	0.142	50.0	4 035
		0.24	0.087	0.153	—	2 129
		0.24	0.070	0.17	—	2 330
		0.21	0.051	0.159	48.9	11 300
650/250	Tokyo Univ.	1.055	0.725	0.33	105.0	56
		0.778	0.496	0.282	79.5	137
		0.60	0.34	0.24	77.2	251
		0.401	0.154	0.247	80.3	430
		0.30	0.072	0.228	70.4	1 167
	Mitsu-bishi (Naga-saki)	1.5	1.205	0.295	98.1	12
		1.1	0.83	0.27	88.3	32
		0.85	0.60	0.25	82.6	66
		0.7	0.47	0.23	76.4	95
		0.6	—	—	—	—
		0.5	0.285	0.215	71.0	249
		0.4	0.20	0.20	66.7	442
		0.3	0.125	0.175	57.8	745
		0.22	0.07	0.15	42.8	1 793

Table 9. Test results (700 °C 700/250°C).

Test temp. T (°C)	Data from	Strain emplitude ε_{ta} (%)	Plastic strain emplitude ε_{pa} (%)	Elastic strain emplitude ε_{ea} (%)	Stress range σ_R (kg/mm²)	No. of cycles to rupture Nf (cycles)
700	Tokyo Univ.	0.60	0.48	0.12	42.1	130
		0.40	0.248	0.152	42.8	166
		0.395	0.20	0.195	44.6	424
		0.325	0.155	0.17	42.2	786
		0.295	0.169	0.126	42.9	1 351
		0.18	0.055	0.125	48.5	6 060
	Mitsu-bishi (Kobe)	2.00	1.80	0.20	67.0	16
		1.45	1.28	0.17	61.2	40
		0.98	0.82	0.16	—	165
		0.68	0.48	0.20	54.8	165
		0.50	0.26	0.24	55.0	288
		0.39	0.192	0.198	54.5	746
		0.30	0.125	0.175	56.5	1 253
		0.25	0.134	0.116	47.0	1 920
		0.21	0.087	0.123	43.1	6 176
		0.20	0.088	0.112	44.5	2 989
		0.17	0.049	0.121	—	9 381
700/250	Tokyo Univ.	1.03	0.735	0.295	95.5	64
		0.712	0.423	0.299	79.6	183
		0.495	0.232	0.263	78.5	333
		0.40	0.17	0.23	70.4	487
		0.265	0.08	0.185	57.7	1 778
	Mitsu-bishi (Naga-saki)	1.5	1.25	0.25	80.2	15
		1.1	—	—	—	—
		1.1	0.86	0.24	77.5	46
		0.85	0.615	0.235	75.8	75
		0.7	0.475	0.225	72.1	128
		0.5	0.29	0.21	67.3	273
		0.4	0.19	0.21	68.1	488
		0.3	0.125	0.175	56.9	917
		0.22	0.06	0.16	51.8	2 245

Table 10. Test results (650/370°C).

Test temp T (°C)	Data from	Strain emplitude ε_{ta} (%)	Plastic strain emplitude ε_{pa} (%)	Elastic strain emplitude ε_{ea} (%)	Stress range σ_R (kg/mm²)	No. of cycles to rupture Nf (cycles)
650/370	Tokyo Univ.	1.0	0.615	0.385	90.3	85
		0.8	0.463	0.337	83.2	161
		0.6	0.332	0.268	76.1	266
		0.4	0.128	0.272	65.3	361
		0.305	0.083	0.222	60.7	1 170
	Mitsu-bishi (Naga-saki)	1.3	1.03	0.27	84.0	32
		1.0	0.725	0.275	86.7	62
		0.85	0.555	0.295	92.1	82
		0.6	0.36	0.24	74.8	156
		0.5	0.26	0.24	75.4	258
		0.4	0.195	0.205	65.0	502
		0.3	0.10	0.20	62.8	1 080
		0.22	0.075	0.145	45.6	2 040

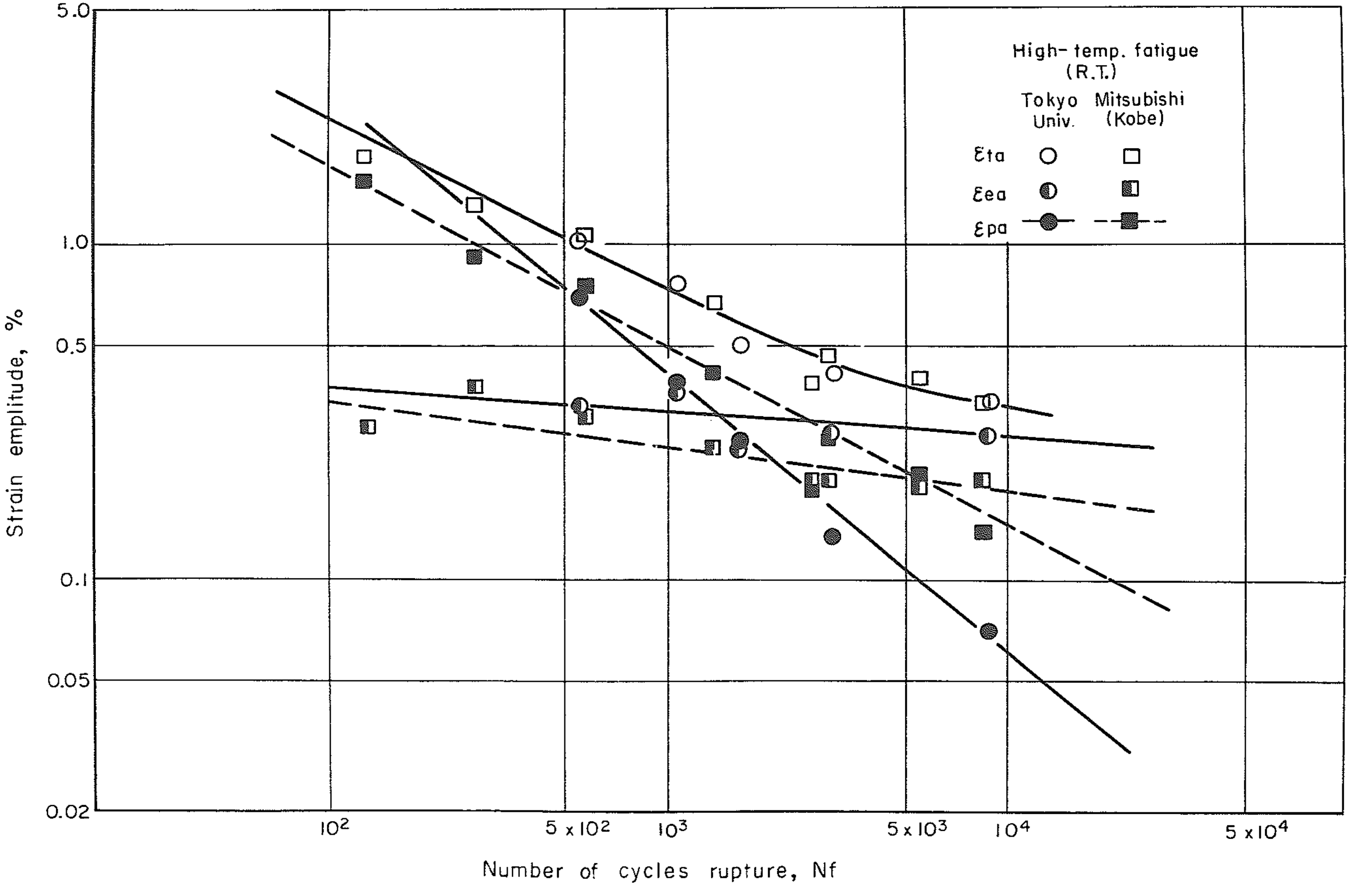

Fig. 1. S/N diagram.

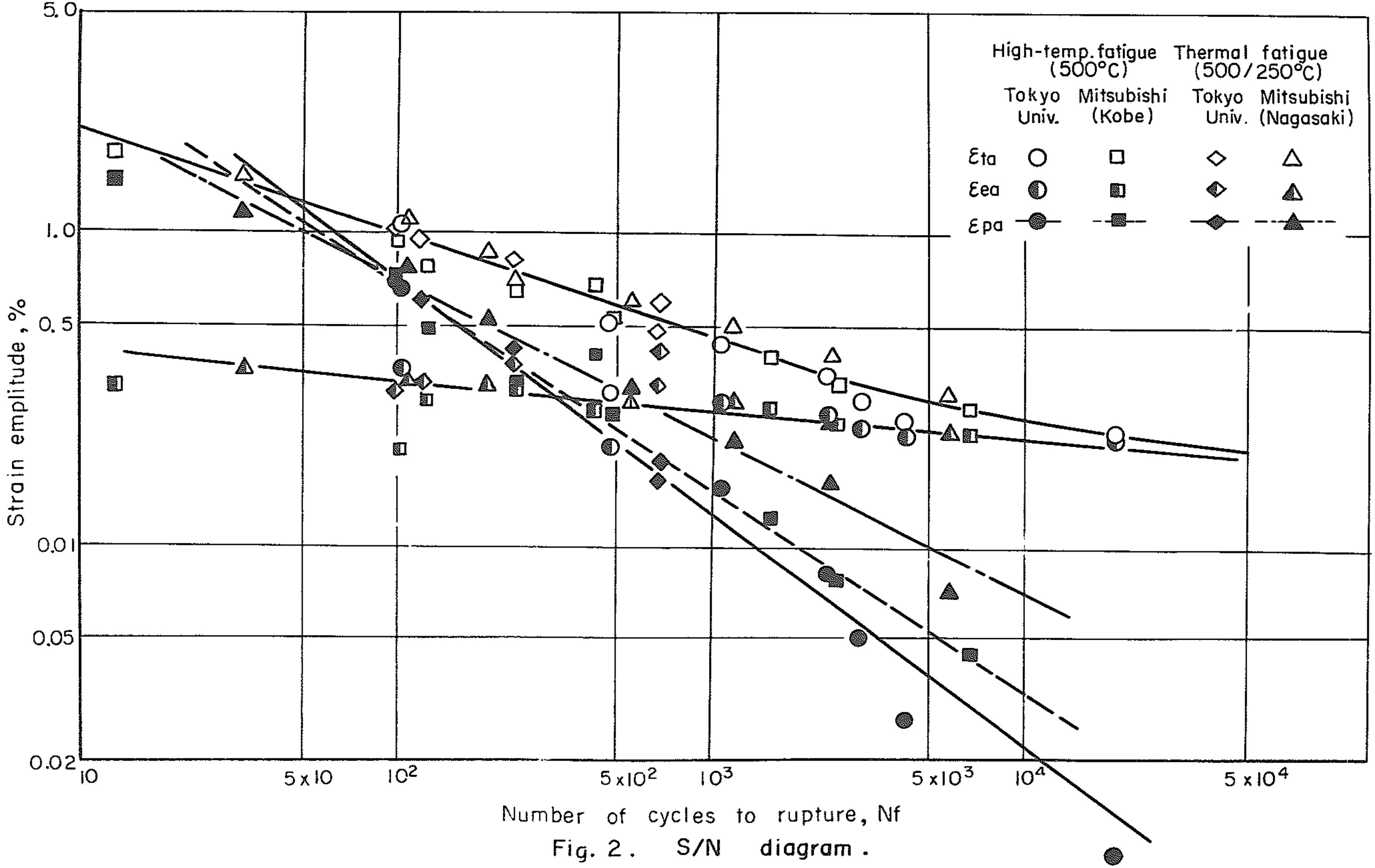

Fig. 2. S/N diagram.

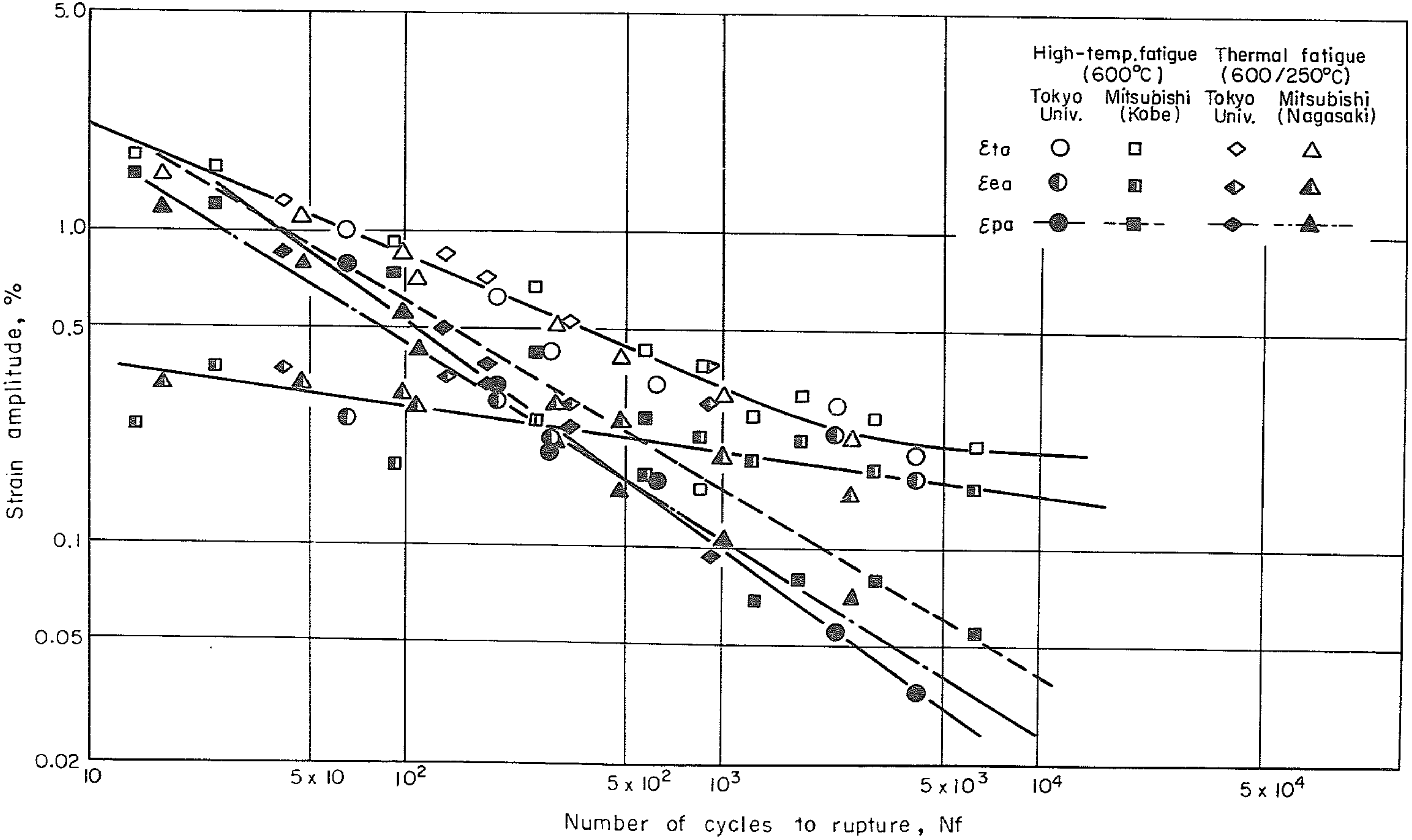

Fig. 3. S/N diagram.

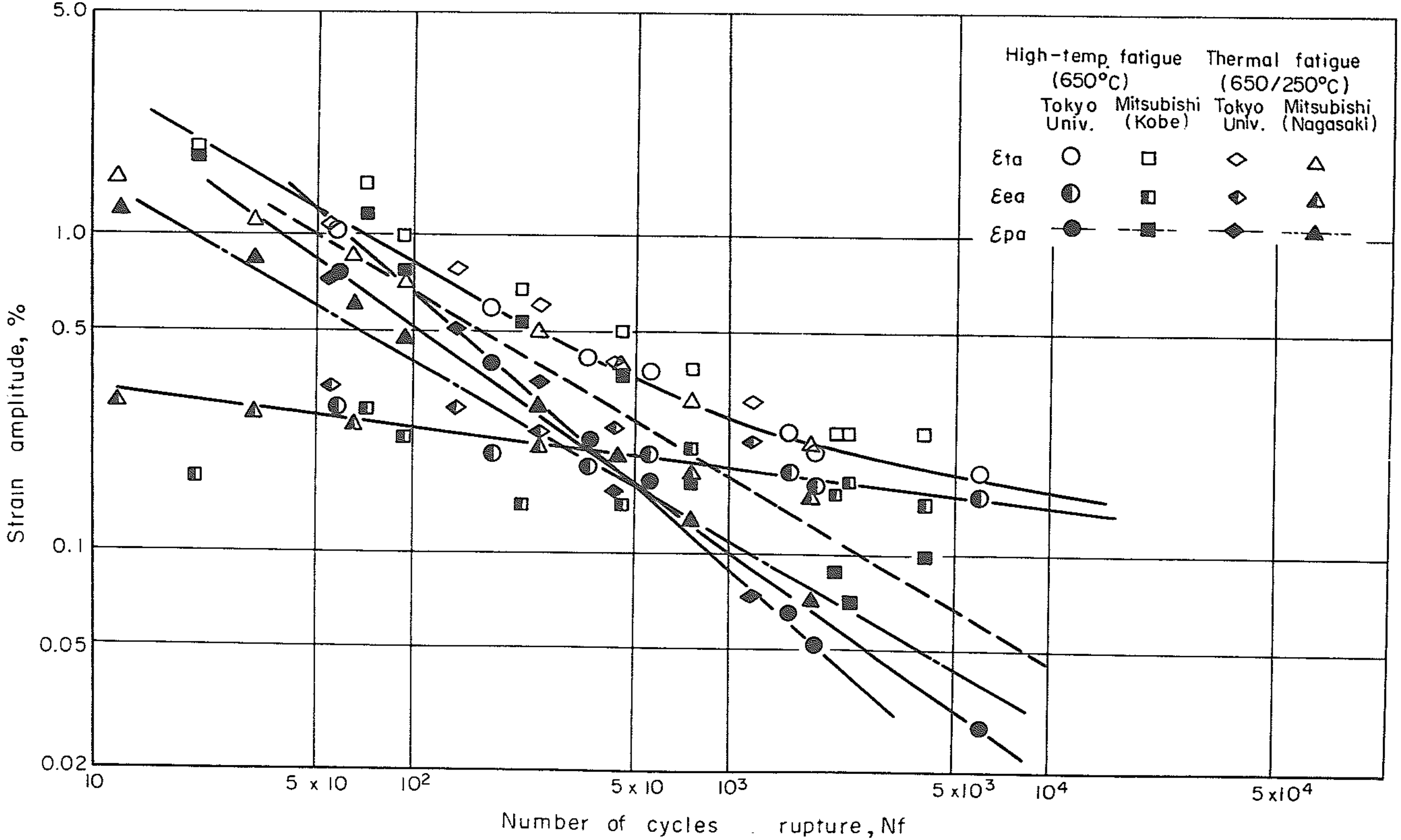

Fig. 4. S/N diagram.

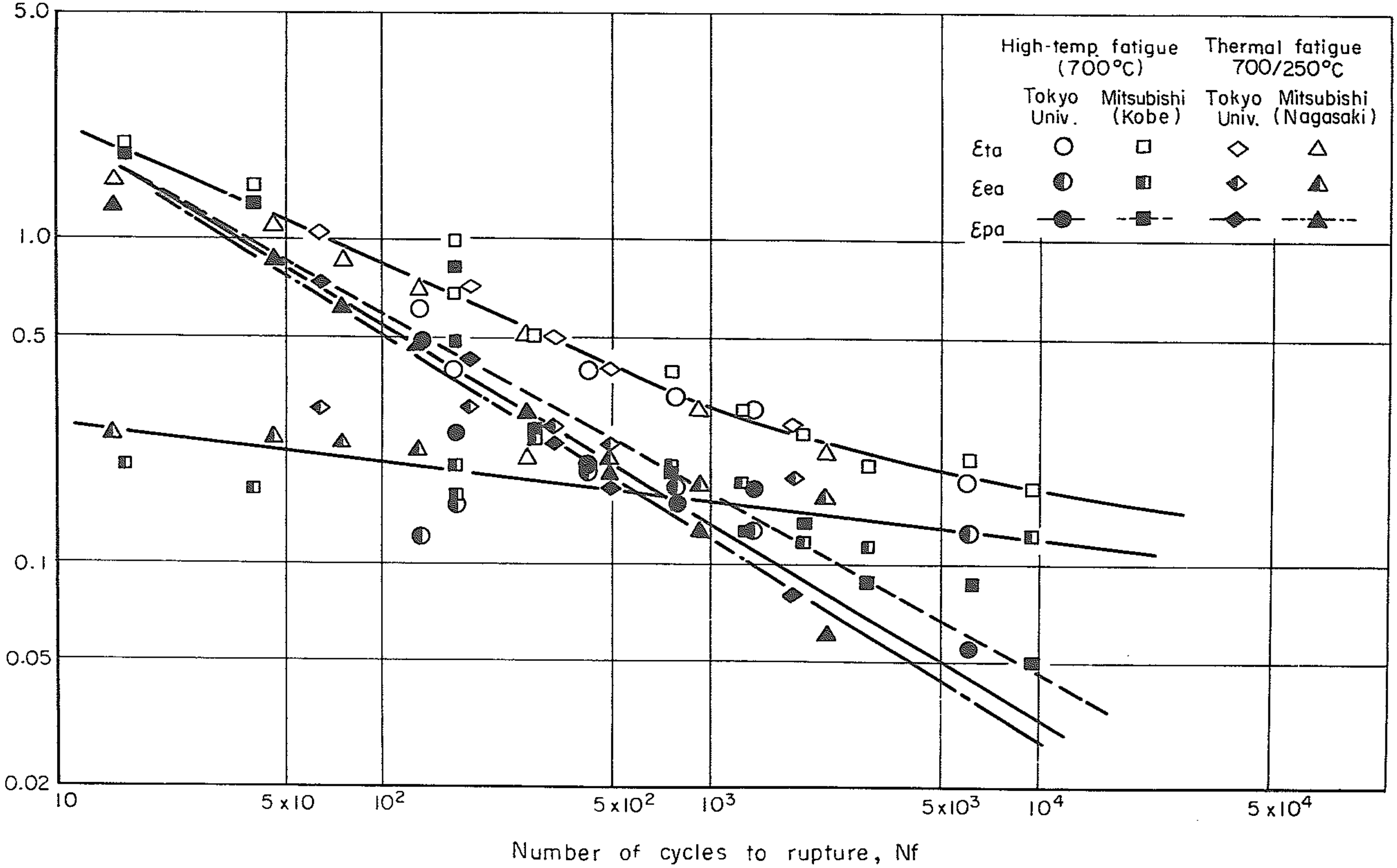

Fig. 5. S/N diagram.

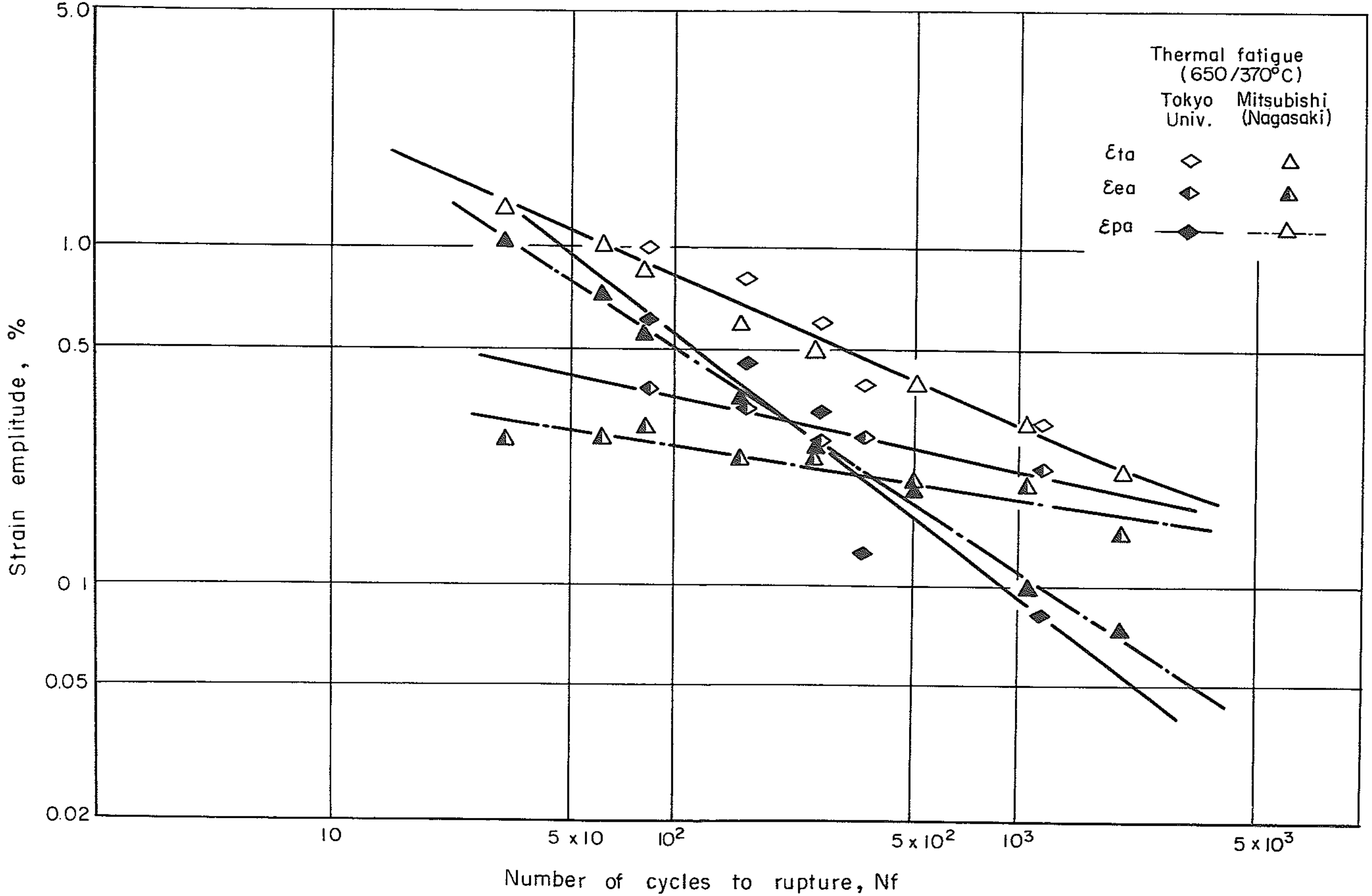

Fig. 6. S/N diagram.

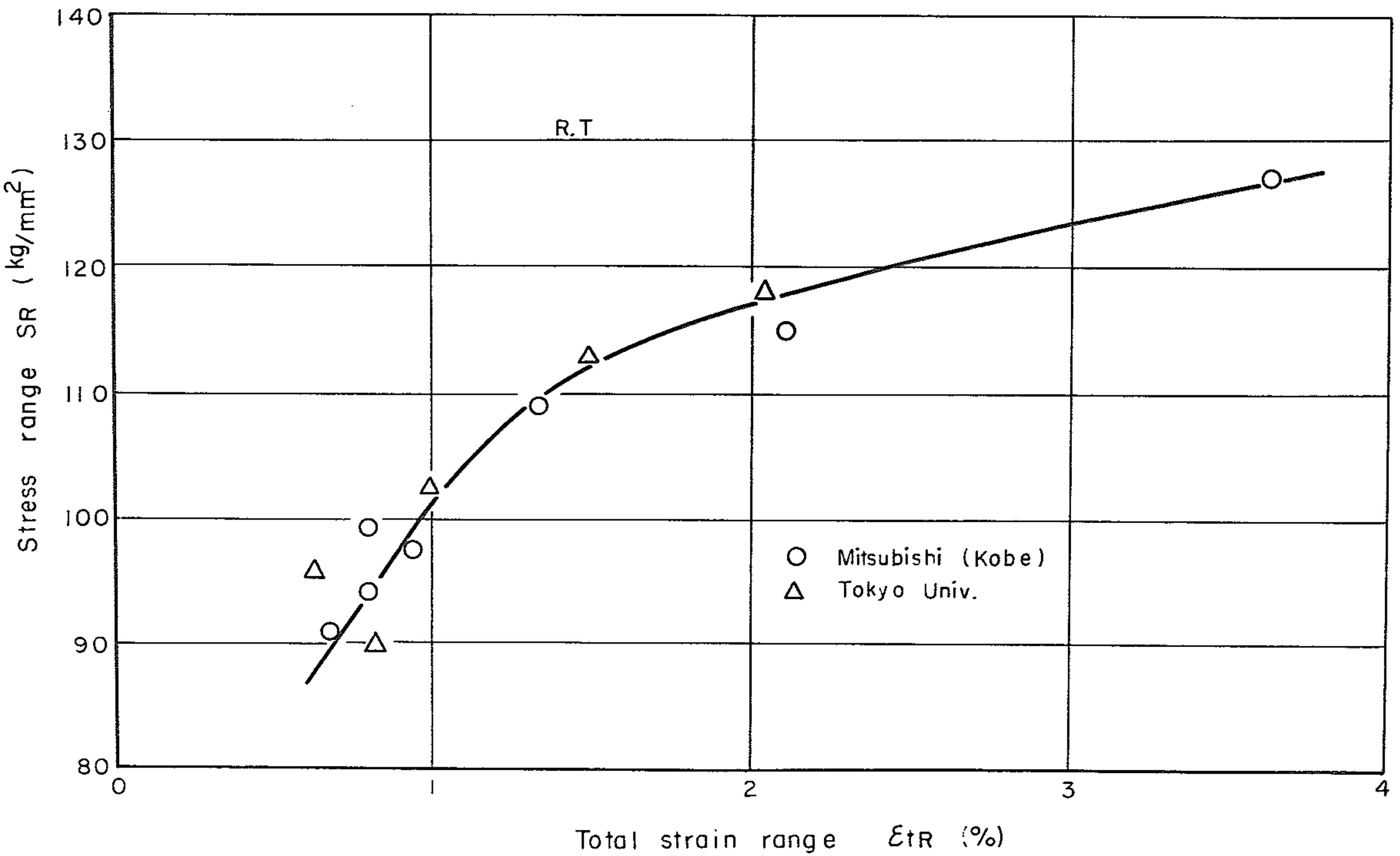

Fig. 7. Stress range vs. total strain range (R.T.).

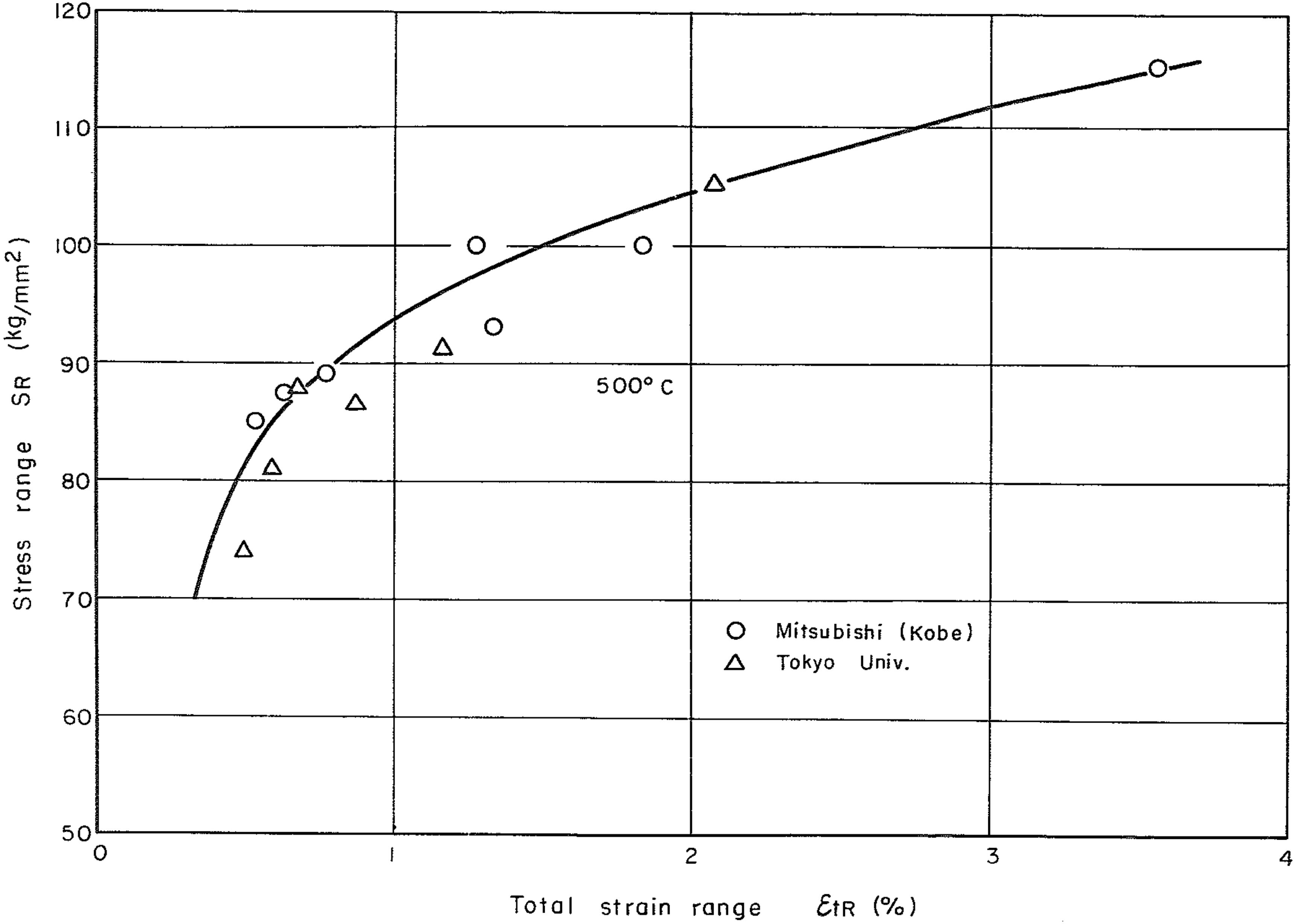

Fig. 8. Stress range vs. total strain range (500°C).

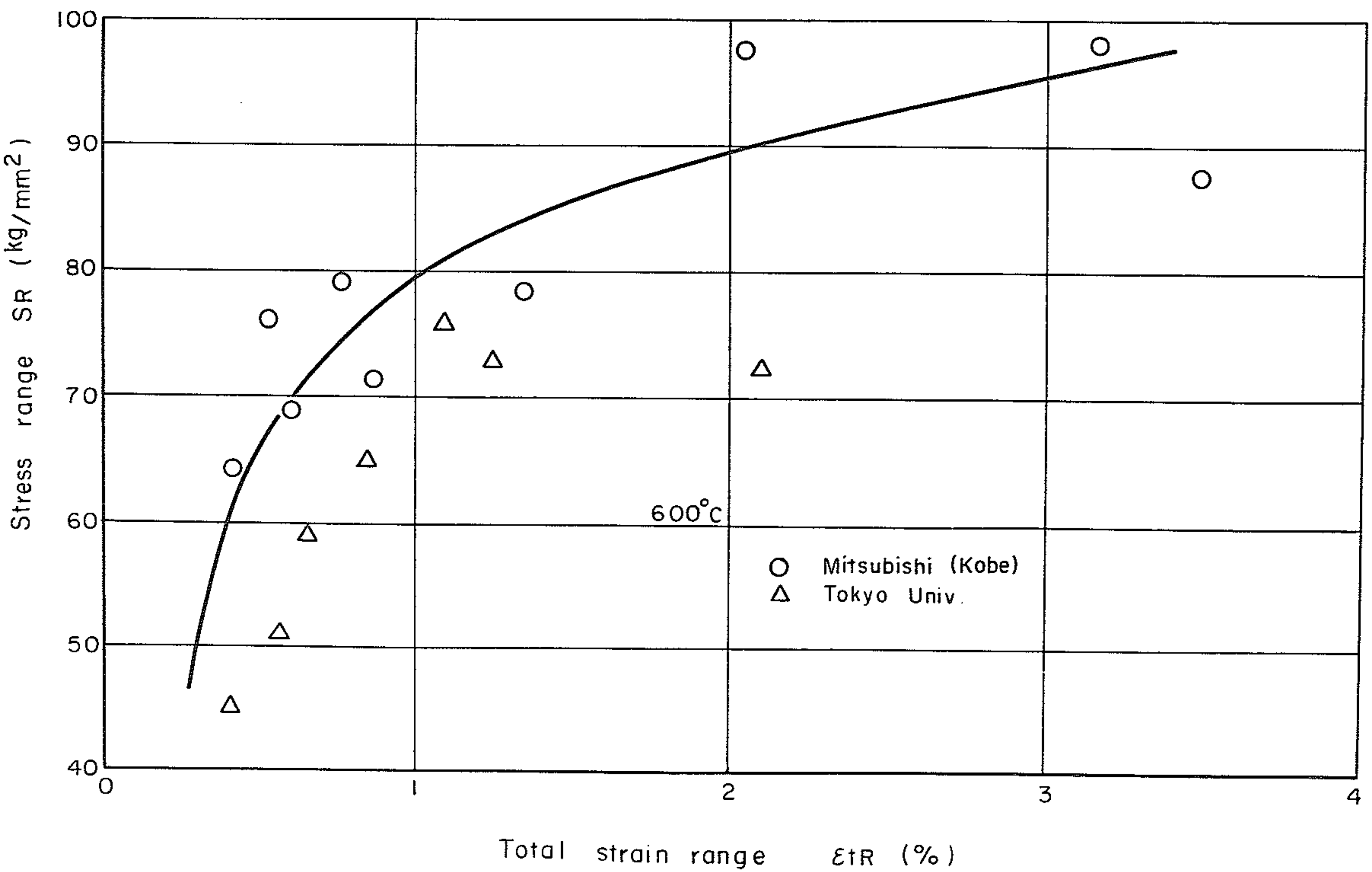

Fig. 9. Stress range vs. total strain range (600°C).

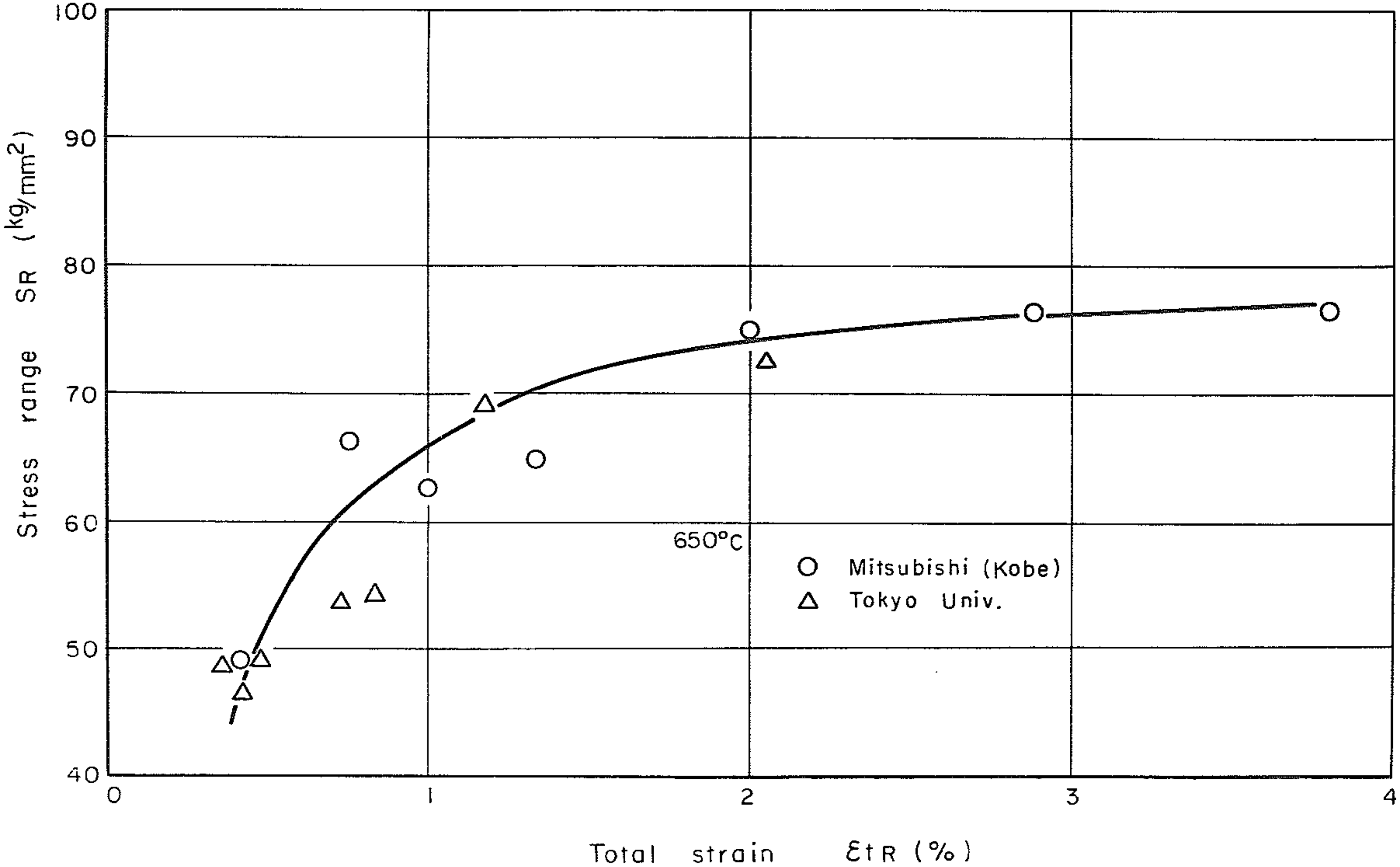

Fig. 10. Stress range vs. total strain range (700°C).

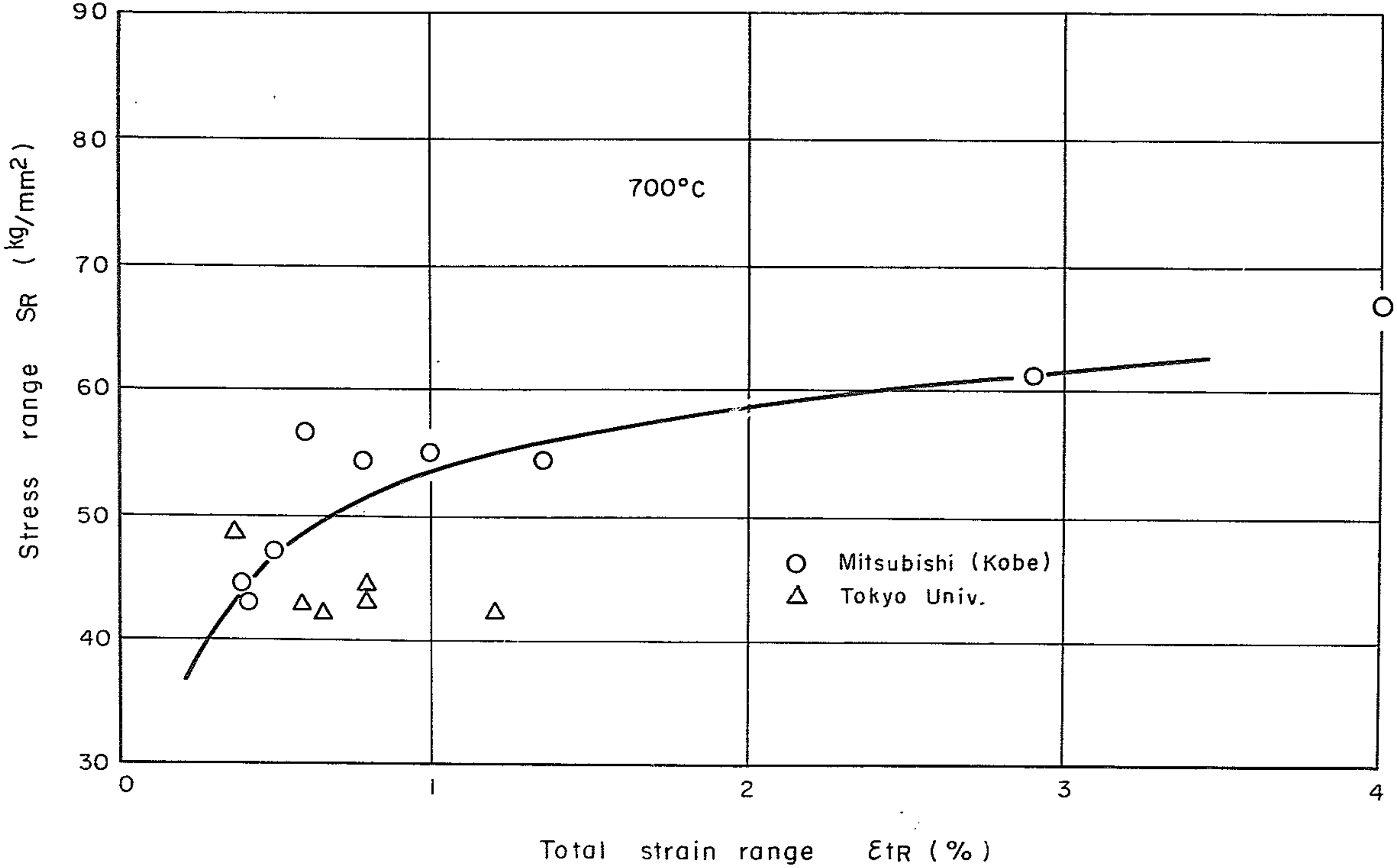

Fig. 11. Stress range vs. total strain range (700°C).

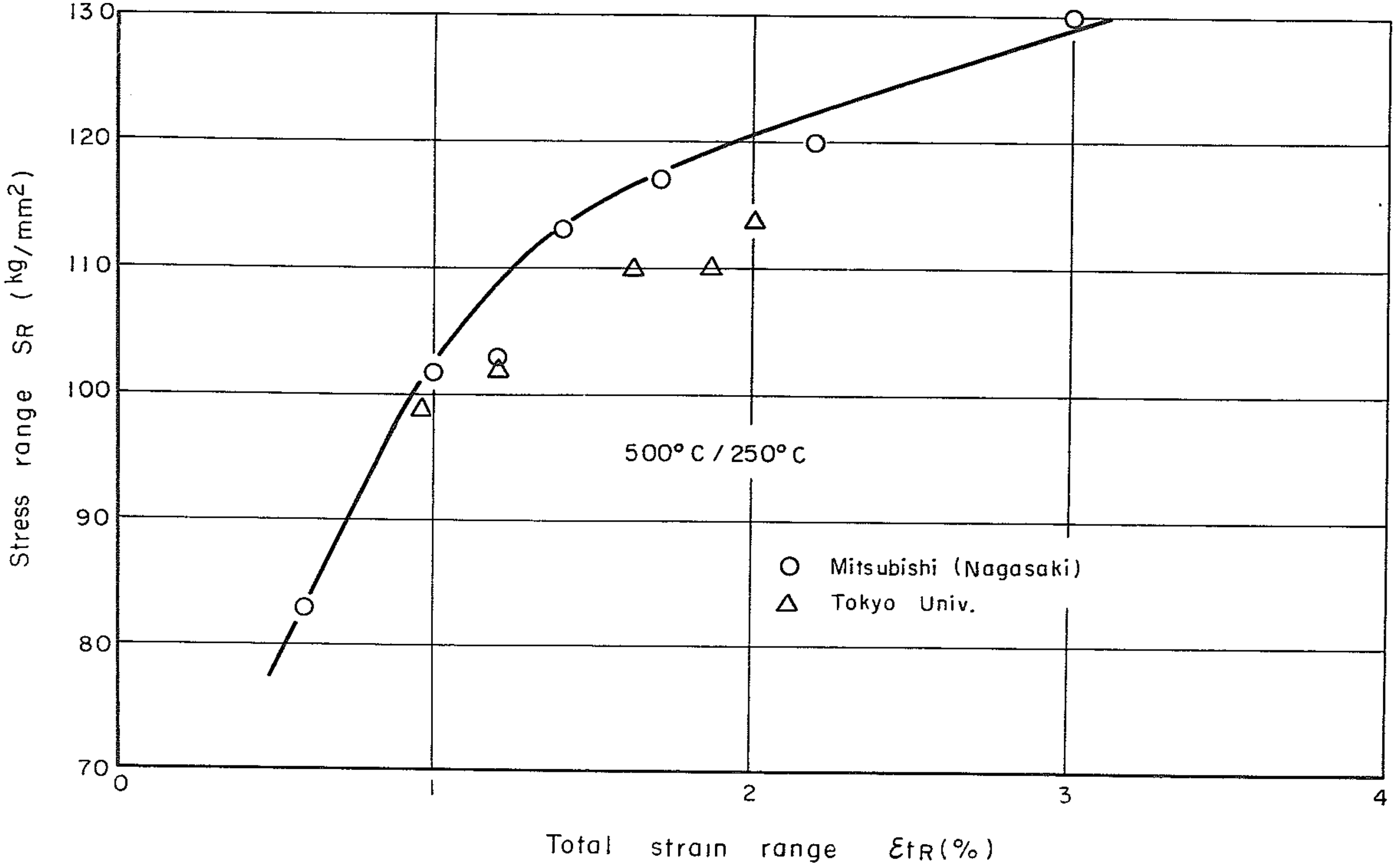

Fig. 12. Stress range vs. total Strain range (500/250°C).

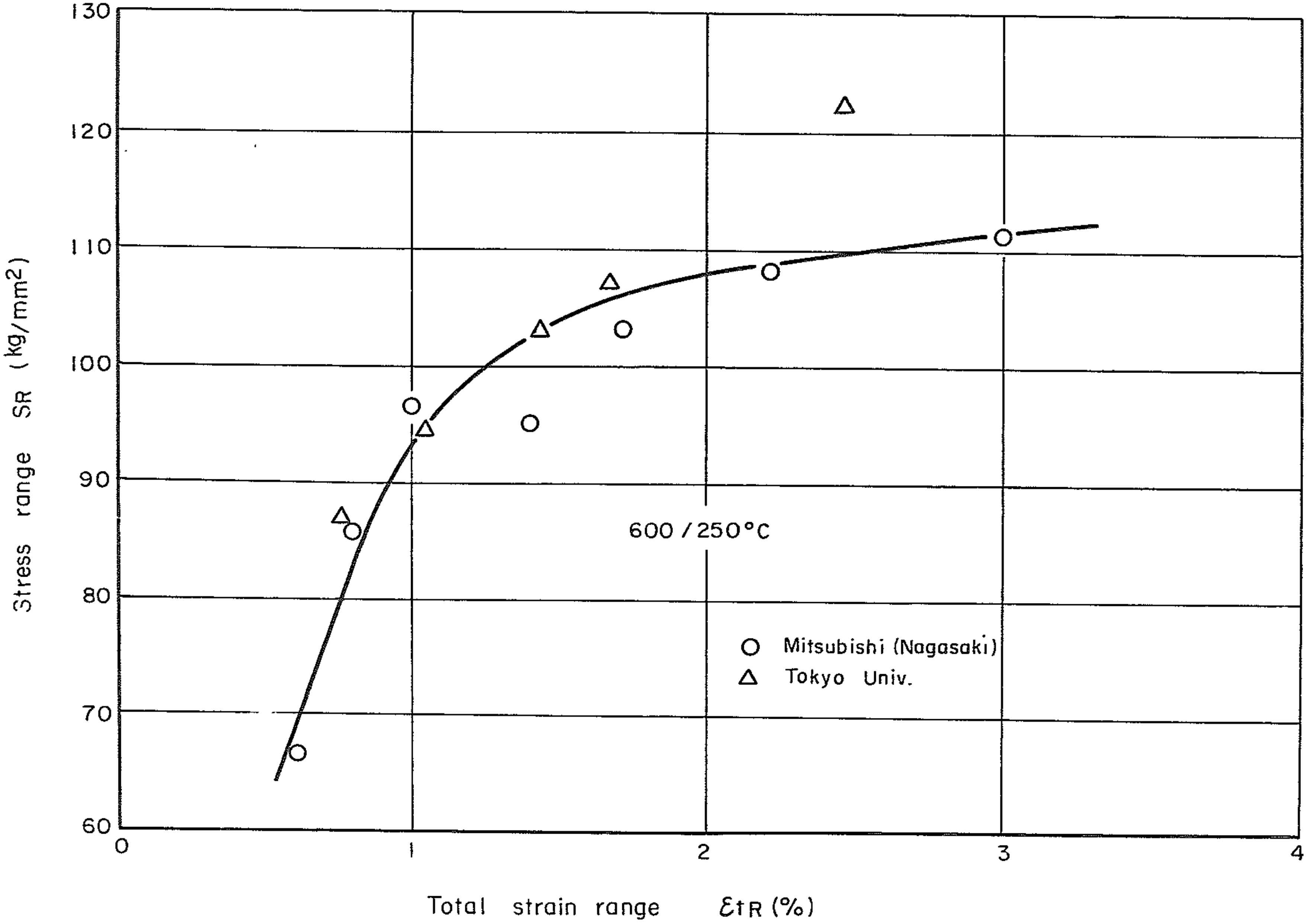

Fig. 13. Stress range vs. total strain range (600/250°C).

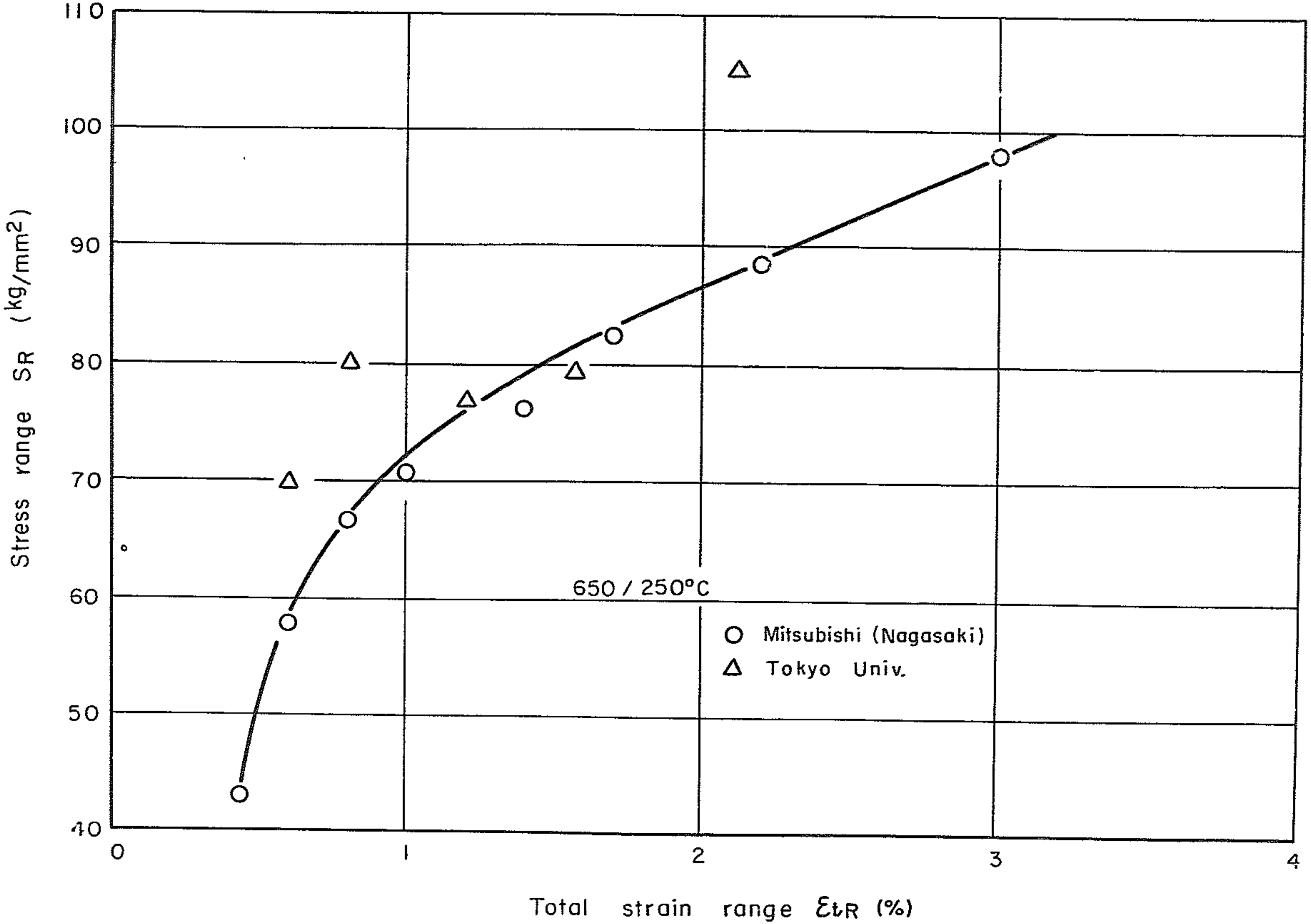

Fig. 14. Stress range vs. total strain range (650/250°C).

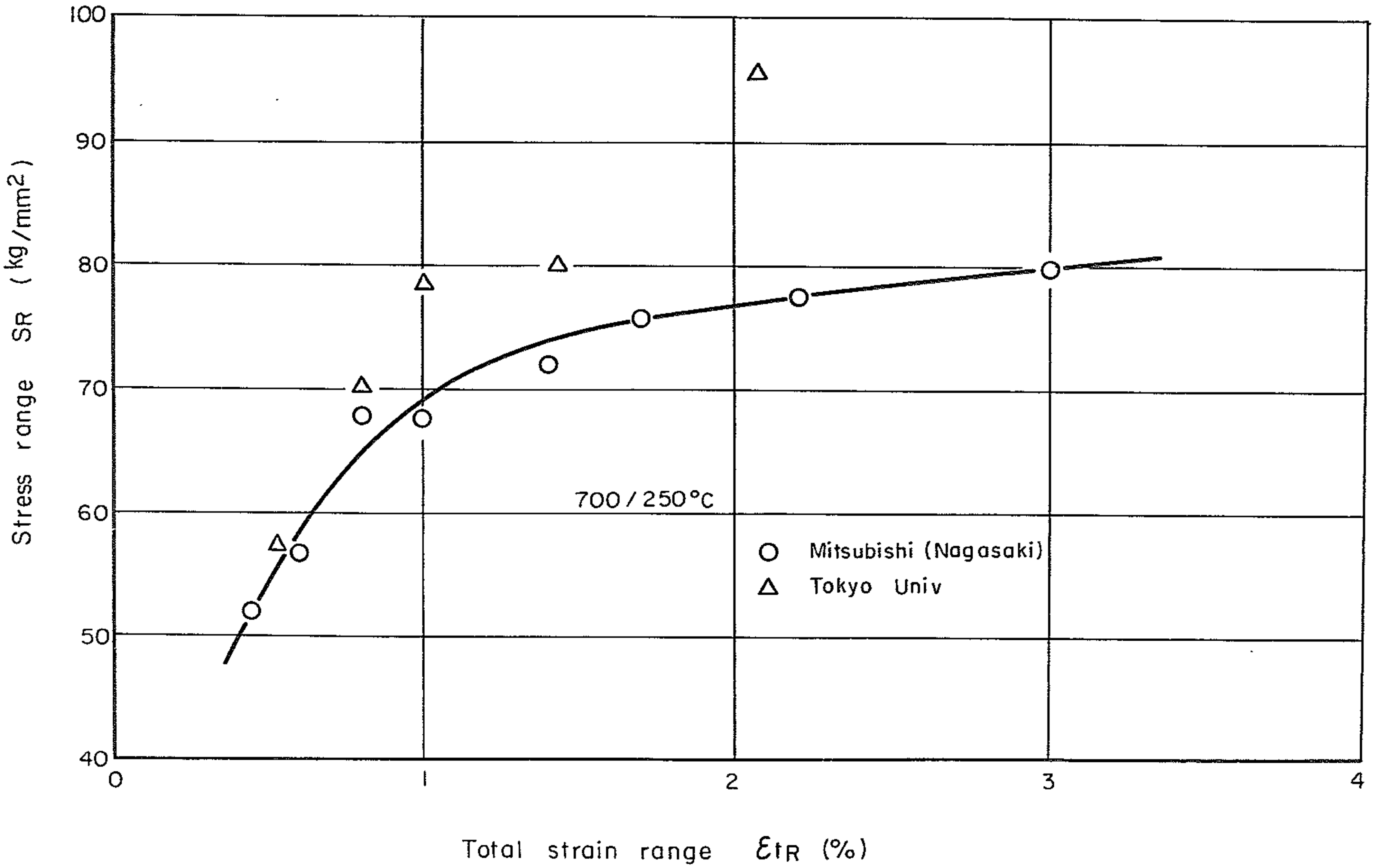

Fig. 15. Stress range vs. total strain range (700/250°C).

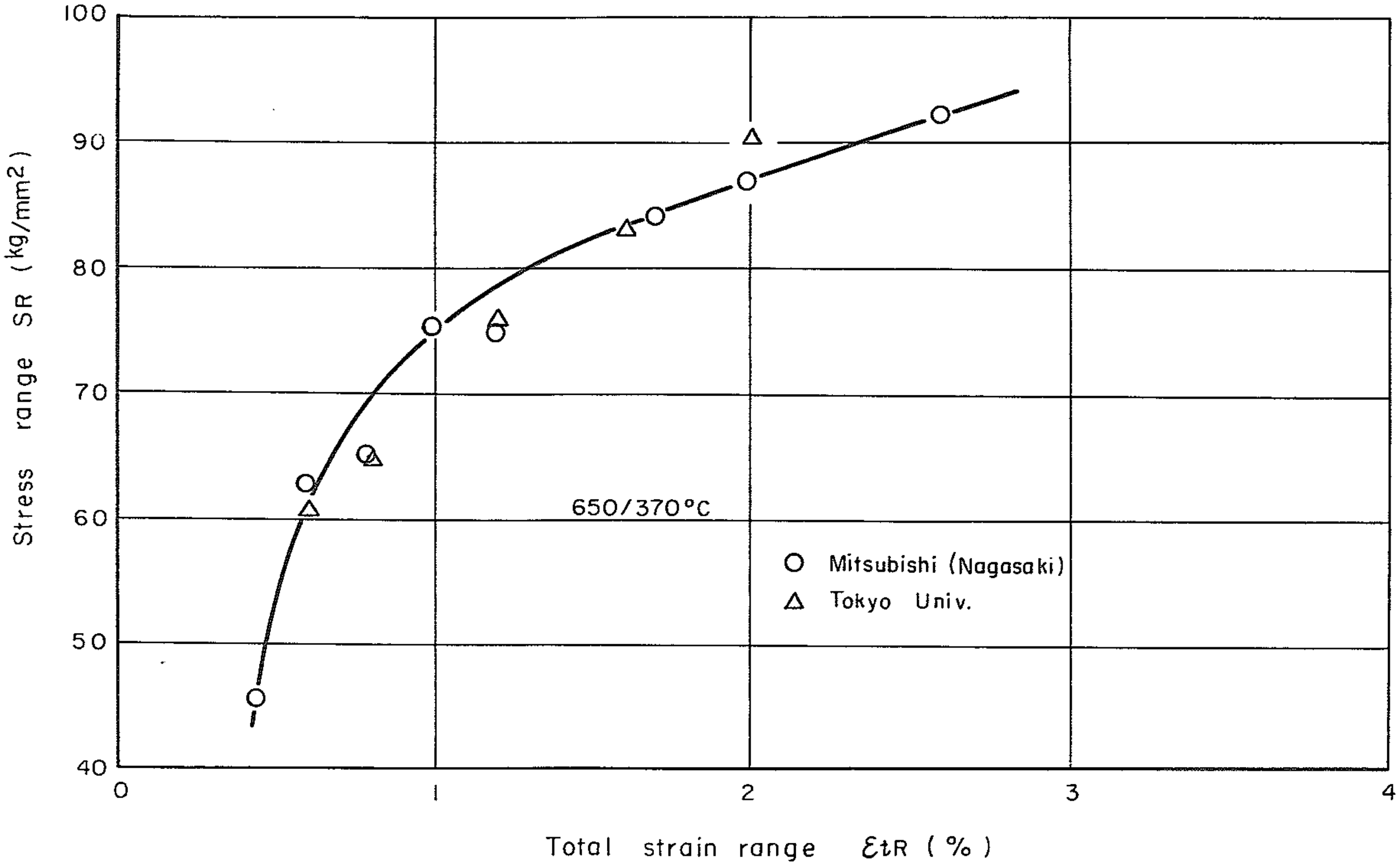

Fig. 16. Stress range vs. total strain range (650/370°C).

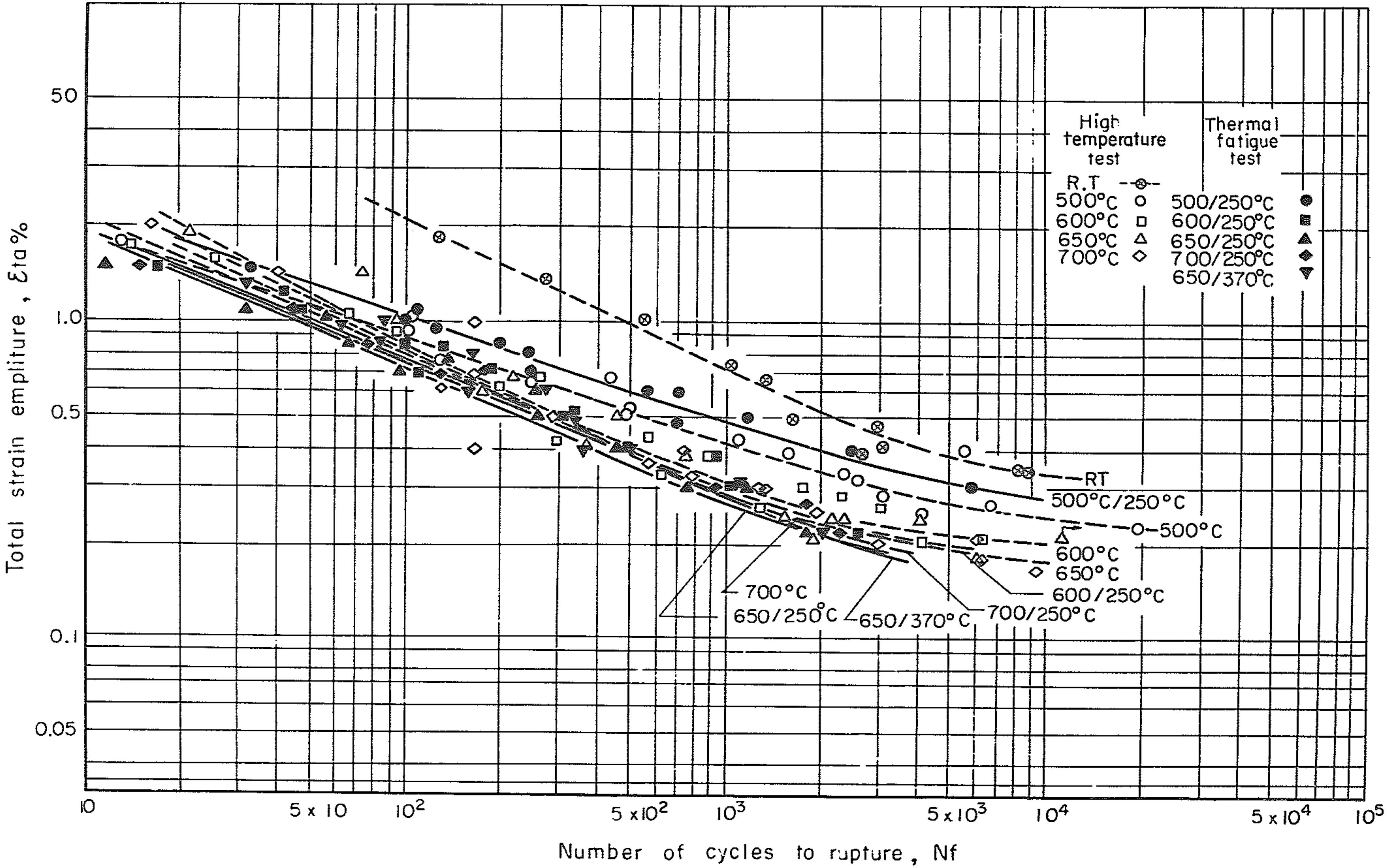

Fig. 17. Ɛta Nf diagram.

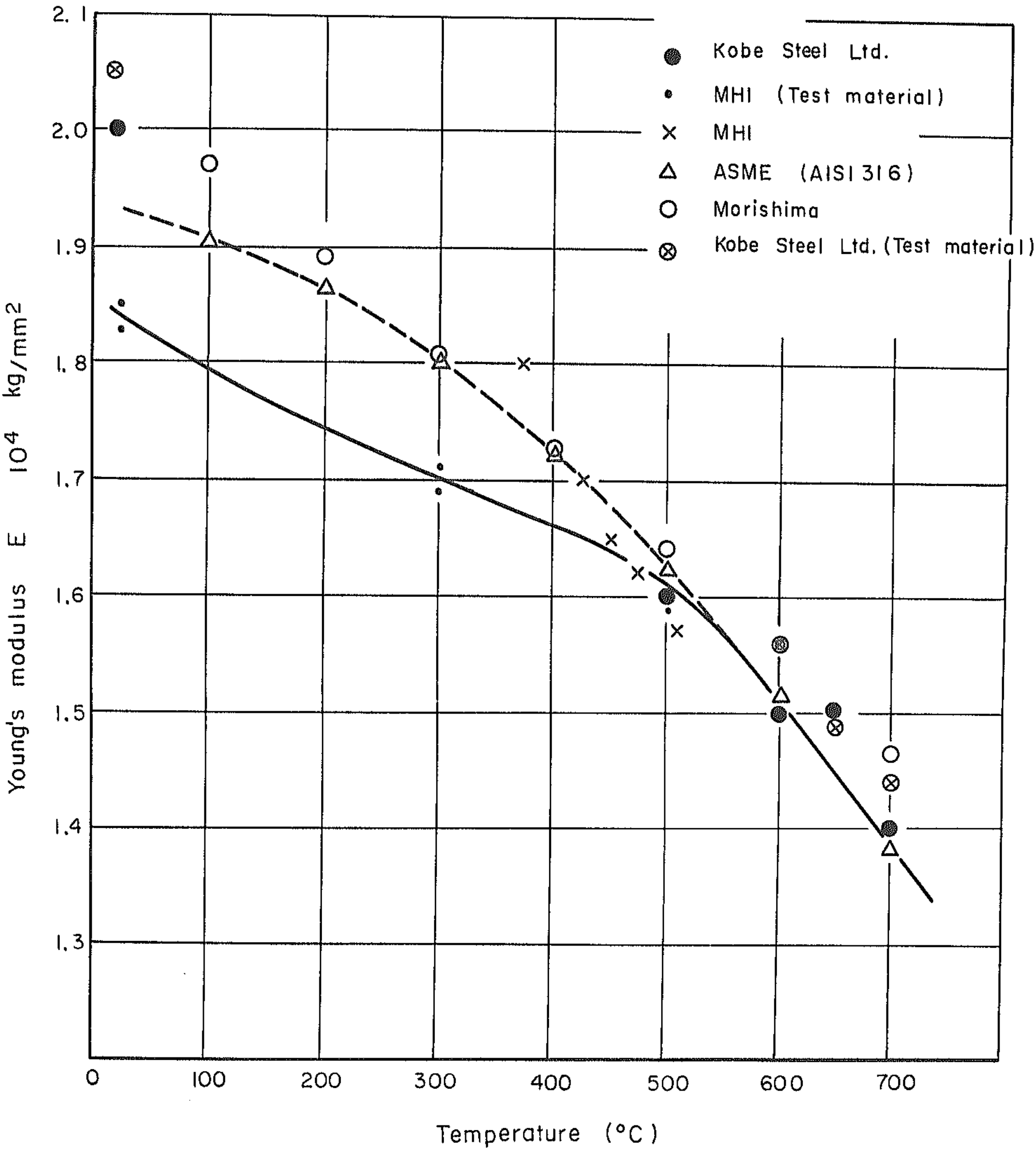

Fig. 18. Young's modulus of SUS32 at high temperature.

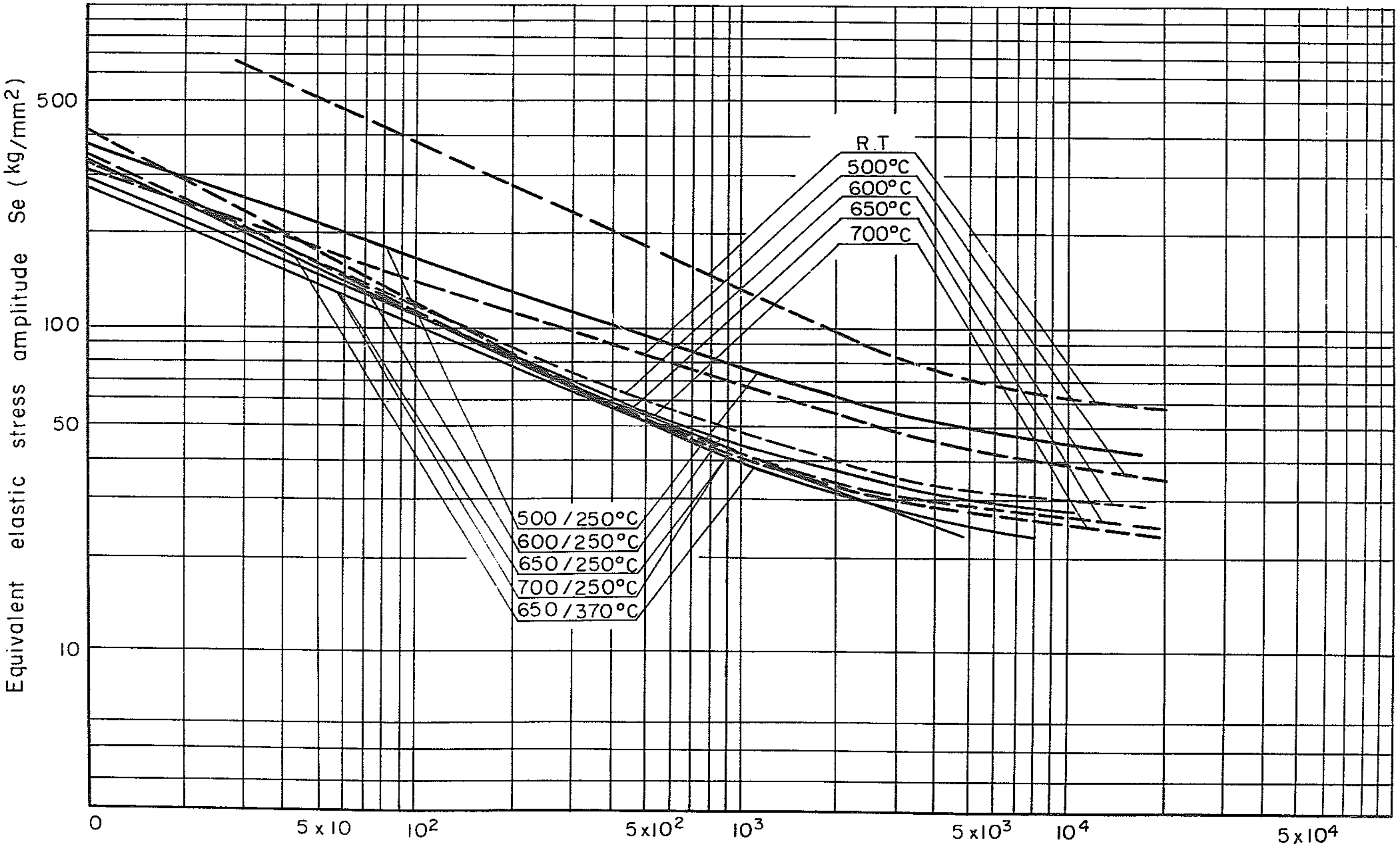

Fig. 19. Se~Nf diagram.