REPORT

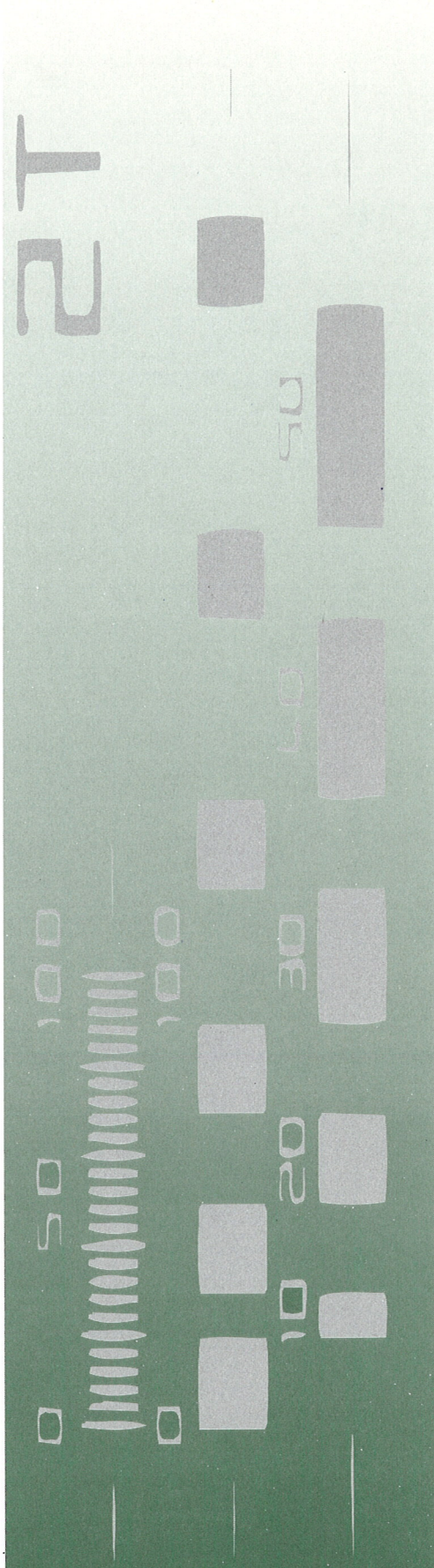
Hot Axisymmetric Uniaxial Compression Tests

Preliminary Studies Through a UK Interlaboratory Comparison

B Roebuck, L P Orkney, M Stewart,
R K Varma and J D Lord

July 1996

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ABSTRACT

A collaborative exercise was conducted to investigate the measurement method for hot axisymmetric uniaxial compression tests, in particular to provide the technical background for the development of good practice guidelines. Industry needs a standard method in order to minimise and quantify uncertainty levels for input data required by process control models and rolling/forging extrusion strategies. There is a need for standardising the test procedure to ensure that the levels of uncertainty associated with current testing procedures are as low as possible commensurate with good testing practice.

Tests were performed at seven UK organisations and Oulu University, Finland on two engineering materials, a low carbon steel and a Ni-base alloy. The compression tests were carried out at three strain rates, 0.1, 1 and 10 s^{-1} on testpieces deformed to a true strain of about 0.5. At imposed strains of 0.1 and 0.3 the uncertainties (repeatabilities) in flow stress measurements at each laboratory were quite variable, between ± 2 and ± 20%, (2 standard deviations - corresponding to the 95% confidence limits). By contrast the uncertainties (reproducibilities) between laboratories were higher, between ± 10 to ± 25%. The uncertainties also increased with increasing applied strain rate.

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Director, Centre for Materials Measurement and Technology.

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1 INTRODUCTION

Background

Industry needs standardised methods for the measurement of hot flow stress for both deformation process control models and for providing underpinning data for models to predict the evolution of microstructure. Constitutive equations for the hot working of metals are generally derived from hot deformation tests. The equations define stress, σ, in terms of strain, ε, strain rate, $\dot{\varepsilon}$, and temperature, T. Any standardised measurement method must be able to measure these parameters with an acceptable degree of accuracy. Quantitative information is required on the uncertainties associated with relevant measurement methods to give greater confidence in the predictions of finite element models for rolling and forging. For the foreseeable future both industry and academia will continue to use mechanical and structural measurements obtained from hot compressed testpieces for input into process models. At present there are no standardised methods for such hot compression tests, although in a currently funded DTI project at NPL it is expected that draft guidelines for axisymmetric compression tests will be available by the end of 1996.

Laboratory deformation studies are usually performed using either hot torsion, laboratory rolling mills, or uniaxial or plane strain compression rigs. The tension test is unstable through necking and is therefore difficult to analyse. Deformation rates of 10^{-4}-10^{2} s^{-1} are typical of those required to model deformation processes such as rolling, extrusion and forging. Each of the methods which have been used to simulate hot working processes have limitations.

- Solid rod torsion results in inhomogeneous deformation. However, it allows high strains without geometrical instabilities and stress and strain at the periphery are fairly easily computed. Specimens from the surface regions can be obtained for subsequent microstructural evaluation. The test thus has several advantages, a constant strain rate is relatively easy to maintain, no friction is involved, high fracture strains are possible, and controlled sequential deformations are possible. Hot torsion of tubes is a possible solution to overcome the strain gradient problems of hot torsion of rods but there can be problems with buckling at higher strains.

- In plane strain compression tests there is the issue of redundant work arising from shear in the non uniform deformation bands within the gauge volume. A flat testpiece of thickness, h; is compressed between two platens of width, w, which overlap the testpiece. Calculation of an equivalent stress requires a value for the friction coefficient, μ.

- Cylindrical compression requires progressively larger forces as the cross sectional area changes and there can be inhomogeneous deformation between the platen face contacts and testpiece centre which will vary depending on lubrication. High strains can be important in controlled deformation sequences but a three dimensional stress state prevails due to friction on both surfaces. However, judicious choice of lubricant can result in very little barrelling. In axisymmetric tests it is thought best to use a compression mode with a constant true strain rate. This needs the platen to move as an exponential function of time to main constant true-strain rates. Hot compression can require platen speeds of 1 m s^{-1}, which in general requires servohydraulic test machines.

All of these tests thus involve some strain heterogeneity. Also, errors can arise from testpiece heating at the high rates of strain imposed during the experiments. Clearly the choice of

testpiece size and strain rates will have some effect on the temperature rise that occurs in the test.

Kaspar et al (Steel Research, 1993) showed that a reasonable comparison of flow stresses from the three different types of test can be achieved if the correct formulae for calculating equivalent stresses in the plane strain compression and torsion tests is used. However, this was only over a limited range of strain and temperature and the range of agreement was also material dependent. The reasons for differences outside this limited range were not known. By contrast, tests conducted in a BRITE-EURAM project on Al alloys has shown that variability in flow stress data obtained in plane strain tests was a result of lubrication differences. The potential for obtaining reproducible data using plane strain compression on specific Al alloys by control of lubrication was good.

Thus there is no "ideal" hot deformation test from the three most widely reported:

- *Axisymmetric compression*
- *Torsion*
- *Plane strain compression*

although axisymmetric tests are probably the most widely used.

NPL is currently working with several groups based in a range of UK industries and academia to develop guidelines for conducting hot axisymmetric compression tests. As a precursor to this exercise the steering group for this collaborative work agreed to conduct an interlaboratory exercise to provide technical information to underpin the development of the guidelines.

Interlaboratory Exercise

Axisymmetric tests were chosen on the advice of industry and academic members of the project steering group. It was agreed that, of the three potential hot deformation test procedures, the axisymmetric tests were more widely available and more likely to minimise problems associated with strain and strain rate variations.

A preliminary interlaboratory exercise using hot axisymmetric compression tests was therefore carried out to provide background information to explore the potential for developing a standardised method. The tests were performed at seven UK organisations on two materials provided by industry, Nimonic 901 and a low C-Mn steel, at three strain rates - 0.1, 1 and 10 s^{-1}. The temperature was 1000 °C for the Ni alloy and 1100 °C for the steel. The testpieces were all manufactured at NPL, examined for homogeneity and consistency and circulated to participating laboratories. Each laboratory was allowed to use in-house procedures to a large extent in carrying out the test in order to provide data for discussion.

The results showed reasonable repeatability but less good reproducibility and it will therefore be necessary to perform further background experiments to establish controls on

- barrelling
- lubrication
- temperature measurement
- pre-exposure times
- heating rates
- Data analysis/models
- geometry, size and surface finish of testpiece
- temperature distribution
- calibration procedures (and machine stiffness effects)
- traceability
- anvil materials and surface finish
- strain/displacement measurement

This will enable the draft code of practice/best practice document to be written with supporting technical information to validate the written guidelines.

2 INTERLABORATORY TEST GUIDELINES

These guidelines were originally issued to the following participating organisations

British Steel	Sheffield University
Cambridge University	IMI Titanium
Swansea (IRC) University	MPD Technology
NPL	

At a later stage in the exercise a set of testpieces was also supplied to Oulu University in Finland.

Guidelines

Objectives - Perform hot compression test to measure load/displacement - stress/strain curve.

Fixed Parameters

MATERIALS:

(a) Nimonic 901 - [Ni-Fe-Cr alloy plus Ti, Al and Mo]

(b) Low alloy Steel - [C - 0.09, Mn - 1.4, Si - 0.3]

DIMENSIONS:

Cylinder - 15 mm long by 10 mm diameter.
Three samples per organisation - test at least 2.
(Sheffield and NPL also tested reduced size cylinders, either 10 mm diameter by 12 mm long or 8 mm diameter by 10 mm long.

PREPARATION:

Materials homogenised at about 50 °C greater than test temperature prior to machining (ie 1 h at 1145 °C and then air cooled for the steel and 3 h at 1090 °C for the Nimonic 901).

All testpieces were machined at NPL to reduce variability from surface conditions. The steel testpieces were machined from 15 mm (nominal) thick plate; the Nimonic 901 from 15 mm (nominal) diameter rod.

DEFORMATION TEMPERATURE

(a) Nimonic 901 - 1000 °C, hold for 10 min before test.
(b) Low alloy Steel - 1100 °C, hold for 10 min before test.

DEFORMATION STRAIN RATE:

i) 10^{-1} s^{-1}; ii) 1 s^{-1}; iii) 10 s^{-1}

(initial guidelines specified just two rates, 10^{-1} and 1 s^{-1} but some tests were also performed at 10 s^{-1})

TOTAL STRAIN:

Deform to a true strain of 0.5.

Laboratories were also asked to provide details of:

Strain rate control mode (eg Crosshead or extensometer)	Displacement measurement
Dates of calibration of strain measurement system	Method of calibration
Calibration standard (if appropriate)	Class/grade of extensometer
Method of heating	Temperature measurement technique
Calibration procedure for temperature measurement	Heating profile
Method of cooling	Test machine type/action
Load calibration date	Load calibration standard
Calibrating authority	Class/Grade of machine
Load cell capacity	Load cell range (if different from max.)
Method of analysis	Lubricant/oxide scale inhibitor
Atmosphere	Platen material

3 MATERIALS

Nimonic 901

Micrographs of the Nimonic 901 etched to show grain boundaries are shown in Fig 1 for transverse samples taken from the middle and front of the 15 mm diameter rod. The grain size (mean linear intercept) was about 25-35 μm and hardness (HV30) was about 150-160. The rod, supplied by INCO Ltd (Hereford), was homogenised at 1090 °C for 3h and air cooled prior to examination.

Low C-Mn steel

A 150 x 150 x 400 mm billet was supplied by British Steel Technical (Swinden Laboratories). A 15 mm thick transverse plate was cut from the billet and homogenised at 1145 °C for 1h and air cooled. Longitudinal and transverse micrographs from the plate centre are shown in Fig 2. Micrographs taken from other parts of the plate appeared similar. No quantitative measurements of structure were made but hardness values taken from both transverse and longitudinal sections at various positions in the plate gave values within the range 175-185 (HV30) indicating reasonable homogeneity in composition and structure.

For tests on the low C-Mn steel different organisations taking part in the exercise were constrained by their equipment to specific heating profiles prior to commencement of the deformation test. The heating rate through the transformation temperature could have affected the austenite grain size at the test temperature even though the sample had been homogenised previously. Therefore experiments were performed to examine the structure following specified heating profiles followed by fast cooling. The results of hardness tests are shown in Table 1 and micrographs of testpieces heated at different rates up to the test temperature are shown in Fig 3. The hardness values were fairly similar and the differences in austenite grain size appeared to be small. Therefore the differences in heating rate profiles to the test temperature between different organisations were not considered to be an important factor in scatter in the test results.

Table 1
Heating Profile Experiments
(Longitudinal section of axisymmetric testpieces)

	Approximate time to temperature min	Time at temperature min	Hardness[+++] HV30
NPL[+]	10	5	365
NPL[+]	10	10	360
NPL[+]	10	15	365
NPL[+]	10	20	370
NPL[+]	10	25	370
NPL[+]	10	30	360
NPL[+]	120	35	365
BSteel[++]	1	10	380
BSteel[++]	1	10	375

[+] Stand alone furnace
[++] Gleeble test machine
[+++] Rounded to nearest 5, average of 5 indentations

4 TESTING DETAILS

The participating laboratories supplied the following information:

Laboratory	*Machine Type*
Swansea	ESH
Cambridge	Fuji Electronics Thermecmaster Z
Sheffield	Servotest F72 (Type 216)
British Steel	Gleeble 1500
IMI	Cam Plastometer (in-house design)
NPL	Instron High Rate 1343
MPD	Zwick 1484 Screw (200 kN)
Oulu	Gleeble 1500

Laboratory	*Machine Action*
Swansea	High capacity servohydraulic
Cambridge	Computer controlled crosshead. True constant $\dot{\varepsilon}$
Sheffield	Computer controlled servohydraulic ram
British Steel	Servohydraulic ram, constant crosshead speed
IMI	Mechanical cam follower
NPL	Servohydraulic. Constant crosshead speed
MPD	Speed compensation for true $\dot{\varepsilon}$ control at 0.1 s^{-1}. Constant crosshead speed of 8.33 mm s^{-1} for nominal 1 s^{-1} strain rate
Oulu	Servohydraulic ram

Laboratory	*Force Calibration*
Swansea	EN10002/2 - tension BS1610/1 - compression (ESH - Namas)
Cambridge	In-house
Sheffield	Servotest (NAMAS)
British Steel	In-house load cell to calibrate Gleeble output
IMI	In-house
NPL	100 kN load cell, NAMAS calibration, BS 1610/1 compression
MPD	BS 1610 pt 1
Oulu	In-house (31/05/95) 40 kN load cell

Laboratory	*Displacement Calibration*
Swansea	Crosshead
Cambridge	LVDT (drum micrometer)
Sheffield	Transducer (Vernier calliper)
British Steel	Crosshead control; LVDT on diameter (drum micrometer)
IMI	Crosshead via cam rise (dial gauge) Static calibration of cam rise under zero load
NPL	LVDT in crosshead
MPD	Displacement transducer
Oulu	LVDT (Drum micrometer)

Laboratory	*Temperature Measurement*
Swansea	Type R. Calibrated DVM against standard thermocouple (T/C)
Cambridge	Type R (Pt-Pt/13%Rh) T/C Precalibrated
Sheffield	Percussion welded T/C calibrated against standard type R T/C. Calibrated DVM.
British Steel	Type R comparison indicator traceable to standards
IMI	Type K, compared with type R traceable to NPL standard
NPL	3 type R (furnace), 2 type K (testpiece)
MPD	3 type S (furnace), 2 type K (testpiece). Calibrated using voltage source and precision DVM. Uncertainty of ± 5 °C
Oulu	Type K (Chromel-Alumel Thermocouples

Laboratory	*Furnace Heating*
Swansea	Wire wound resistance
Cambridge	RF induction
Sheffield	Crusilite rods
British Steel	Electrical resistance heating
IMI	Muffle furnace (non-adiabatic)
NPL	Tube furnace (Resistance wound-Kanthal)
MPD	Resistance furnace, platinum wound
Oulu	Electrical resistance heating

Laboratory	*Heating/Cooling Profile* *(10 min at test temperature specified)*
Swansea	10 min to temperature (furnace already at temperature of test) Water quench
Cambridge	5 min to temperature Helium quench
Sheffield	15 min to temperature Air cool (withdrawn from furnace)
British Steel	1 min to temperature Air cooled (cooling rate)
IMI	15 min to temperature Air cooled
NPL	10 min to temperature Air cooled
MPD	9 mins to temperature, plus 15 min soak. Air cooled
Oulu	Not given, probably similar to B Steel, since test machine (Gleeble) was the same

Laboratory	*Lubricant*
Swansea	Acheson DPG 3479 lead free glass in water with styrene acrylic binder
Cambridge	Mica sheet
Sheffield	None
British Steel	Graphite foil
IMI	Various; glass x8, c6 or H26x
NPL	Acheson DPG 3479 lead free glass in water with styrene acrylic binder
MPD	Boron nitride (Acheson 5907) - applied to platens
Oulu	Graphite foil

Laboratory	*Oxide Scale Inhibitor*
MPD	Borate glaze (applied first to testpiece + BN on top of glass)
Rest	None

Laboratory	*Atmosphere*
British Steel	Argon
Oulu	Vacuum
Rest	Air (Cambridge, air at ~ 0.05 Pa)

Laboratory	*Platens*
Swansea	Mar M200
Cambridge	Si_3N_4
Sheffield	Nimonic alloy (Cast M2 - Mar M200)
British Steel	WC/Co (cemented carbide)
IMI	Stellite
NPL	Sialon
MPD	Ni-base alloy, M22B
Oulu	-

Laboratory	*Analysis*
Swansea	Assume constant volume homogenous deformation No corrections for barrelling Machine elastic stretch subtracted from total displacement
Cambridge	In-house corrections for stress and strain, derived empirically
Sheffield	Stress from load and instantaneous area. Strain from instantaneous height
British Steel	Stress from load and instantaneous area. Strain from crosshead motion
IMI	Stress from load and instantaneous area. Strain from instantaneous height
NPL	Stress from load and instantaneous area. Strain from instantaneous height
MPD	Stress from load and instantaneous area. Strain from instantaneous height Machine elastic stretch subtracted from total displacement
Oulu	-

5 RESULTS AND DISCUSSION

Table 2 shows a matrix of the testpiece codes for each group of tests. Not all organisations tested samples at every temperature and strain rate.

Table 2
Testpiece codes, 10 mm diameter x 15 mm long (except $^{+}$ and *)

Organisation	Nimonic (EAT)			Steel (GBX)		
	Nominal strain rate s^{-1}			Nominal strain rate s^{-1}		
	0.1	1	10	0.1	1	10
Swansea	64/47	3/10/30	-	58/53	46/24/8	-
Cambridge	38/24	43/54	-	45/48	44	-
Sheffield	-	(66/67)*	(68/69/70)*	-	(66/67)*	(68/71/72)*
British Steel	74/76	73/71	-	-	17/33	55/64
IMI	-	13/17/31	33/59/62		13/14	57/60
NPL	6/26/(55)$^{+}$	(30/52)$^{+}$	-	-	-	-
MPD	42/46/25	19/28/58	-	59/61	15/56	-
Oulu	66/69	70/75	-	GBX(76/82/83)$^{+}$ GBZ(5/24/27)$^{++}$	GBX(77/78/84)$^{+}$ GBZ(12/52/62)$^{++}$	-

* 8 mm diameter x 8 mm long
\+ 8 mm diameter x 12 mm long
++ These testpieces were taken from a 15 mm thick slab (GBZ) adjacent to the slab (GBX) used for all the other tests. Microstructure and hardness were similar for both slabs.

The stress/strain results for all the testpieces are given in Table 3 (Nimonic 901) and Table 4 (low C-Mn steel) at specified 0.05 increments of true strain. Each participant constructed an appropriate table from their input stress/strain data.

Representative load/displacement data and stress/strain curves supplied by the participating organisations are shown in Appendix A and Appendix B respectively for the Nimonic 901 and for the low C-Mn steel testpieces.

The stress/strain results from the abbreviated data in Tables 3 and 4 are plotted in Figs 4 (Nimonic 901) and 5 (low C-Mn steel) showing the repeatability of the tests for each organisation; and in Fig 6 showing comparisons between organisations for each material and strain rate. Some of the testpieces were of considerable difference in size, ie 8 x 8 mm, 8 x 12 mm and 10 x 15 mm. No obvious trend could be observed between measured value of flow stress and testpiece size. However, it was observed in tests at NPL that the test machine ran out of power (resulting in low values of flow stress because the strain rate could not be maintained) at high values of strain on the larger testpieces and the tests at Oulu on smaller testpieces gave higher stresses. Following discussion at an industrial advisory group meeting for the PMP6 project it was recommended that in test guidelines it should be mandatory to plot $\dot{\varepsilon}$ vs ε for each test to ensure that constant true strain rate is maintained throughout the complete test.

Mean values of flow stress obtained by each organisation are given in Table 5 and the uncertainties (repeatability and reproducibility) were assessed by comparing flow stress data

at specified strain values of 0.1 and 0.3 (Table 6). The deviations from the overall means are shown in Fig 7.

The results can be summarised as follows; at true strain values of 0.1 and 0.3 the repeatability in flow stress measurements at each laboratory were quite variable, between 2-20% (2 standard deviations corresponding to the 95% confidence limit). By contrast the reproducibility between laboratories was higher, between 10-25%. The uncertainties also increased with increasing applied strain rate. It must be noted that the uncertainties for individual laboratories were mostly calculated from less than five measurements and are therefore statistically imprecise. The correction factors are generally in the range 1-2 for the 95% confidence limit. This correction factor has been ignored for this report.

It was also noted that the differences in stress/strain behaviour below strain values of 0.1 were greater than those quantified for this report at the selected arbitrary values of 0.1 and 0.3. Further work is clearly needed to improve the accuracy of stress/strain data at low values of applied strain. This aspect of hot compression tests will be addressed in the new MMP project, MMP4 (Hot Flow Stress Measurement Methods).

The primary sources of uncertainty arise from the three measured parameters; load, displacement and temperature. Thus

- Calibration of load
- Strain calibration (and hence strain rate)
- Temperature calibration.

are of primary importance. Calibration of load is the least likely source of uncertainty and is probably less than ± 1% (ie within the specification for the load cell). It is not possible at present to quantify the level of uncertainty that might be expected from specified uncertainties in either strain rate variation or in the temperature of the testpiece. These will in any way be material dependent because of differences in strain rate and temperature response of the different material types.

Less obvious sources of uncertainty are friction and temperature gradients, which manifest themselves in deformed testpieces which are barrel shaped. Consequently, an attempt was made to quantify the degree of barrelling in the different Nimonic 901 testpieces. There is no standard method for measurement of barrelling. Therefore three methods, specified B1, B2 and B3, were examined and for each one a barrelling coefficient was calculated.

Definitions:

Initial length	ℓ_o	Final length - measured	ℓ_f
Initial diameter	d_o	Final diameter - measured (at midpt)	d_f
Final diameter - calculated (for constant volume)	d_c		

Barrelling coefficient 1 (B1) - direct measurement

$$B1 = \frac{\ell_o d_o^2}{\ell_f d_f^2}$$

Barrelling coefficient 2 (B2) - direct measurement

$$B2 = \left[100(d_c - d_f)/d_o\right]\%$$

B1 and B2 are mathematically similar descriptions but expressed either as a fraction or a percentage.

Barrelling coefficient 3 (B3) - image analysis

$$B3 = \frac{(100(A+C))}{(A+B+C)} \% \qquad \text{(see Fig 8)}$$

The results are given in Table 7.

Following discussion at a project industrial advisory meeting it was agreed that coefficient B1 would be recommended for inclusion in a best practice guide and that measurement of the barrelling coefficient, B, would constitute a validity criterion for the test. For example, if the value was less than a specified amount, yet to be agreed, the test would be considered to be invalid. No correlation could be found between the degree of barrelling of the tests carried out for this exercise and deviation from the flow stress mean values, although it was noted that the largest amount of barrelling appeared to be in those test systems where there was believed to be the largest temperature gradients.

Further work is planned in a new DTI project on hot flow stress measurements (MMP4) which will use computer modelling and experiments to provide additional information with which these uncertainties can be quantified more accurately.

6 SUMMARY

An interlaboratory exercise has been performed to examine the hot axisymmetric compression test method. The exercise has shown that tests at participating organisations were generally very repeatable (5-10% at the 95% confidence limit) but that the reproducibility between laboratories was often much greater than 10% (95% confidence limit), particularly for true strain values less than 0.1. The exercise has provided information that is helping to develop a best practice guide for these types of test.

7 ACKNOWLEDGEMENTS

The work conducted for this report by NPL was funded by the DTI MTS programme on Processability (Project PMP6). Additional thanks must also go to the organisations that took part in the interlaboratory testing exercise.

Table 3
Nimonic 901
Hot compression data

Sheffield	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT66 1 s^{-1}	EAT67 1 s^{-1}	EAT68 10 s^{-1}	EAT69 10 s^{-1}	EAT70 10 s^{-1}
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	242	252	240	268	254
0.1	282	288	340	366	340
0.15	287	291	384	408	392
0.2	286	290	404	424	406
0.25	285	289	402	423	403
0.3	284	288	400	420	400
0.35	283	287	398	417	398
0.4	282	286	396	414	395
0.45	281	285	394	411	393
0.5	280	284	392	408	390
Cambridge	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT43 1 s^{-1}	EAT54 1 s^{-1}	EAT38 10 s^{-1}	EAT24 10 s^{-1}	
Strain	Stress	Stress	Stress	Stress	
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	
0.05	268	268	182	202	
0.1	280	284	195	217	
0.15	279	286	205	229	
0.2	274	284	210	233	
0.25	270	282	213	235	
0.3	265	279	212	230	
0.35	261	275	209	218	
0.4	257	273	203	201	
0.45	252	269	198	190	
0.5					

Table 3 continued
Nimonic 901
Hot compression data

Swansea	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT64 $0.1\ s^{-1}$	EAT47 $0.1\ s^{-1}$	EAT3 $1\ s^{-1}$	EAT10 $1\ s^{-1}$	EAT30 $1\ s^{-1}$
Strain	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.05	198	216	314	314	300
0.1	214	223	339	331	328
0.15	220	226	344	335	331
0.2	221	228	345		332
0.25	224	231	348		330
0.3	225	232	348		328
0.35	225	235	348		325
0.4	226	238			
0.45					
0.5					
IMI	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT13 $\sim 1.75\ s^{-1}$	EAT17 $\sim 1.75\ s^{-1}$	EAT31 $\sim 1.75\ s^{-1}$	EAT33 $\sim 7\ s^{-1}$	EAT59 $\sim 7\ s^{-1}$
Strain^{+}	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.02	109	125	92	141	181
0.05	142	183	150	197	216
0.10	247	244	235	272	280
0.15	304	276	278	339	346
0.20	315	283	296	391	387
0.25	314	280	301	421	390
0.30	316	280	297	432	399
0.35	319	290	291	432	400
0.40	308	289	284	437	407
0.43	305	288	279	430	407
0.46	308	292	287	424	404

$^{+}$ within about ± 0.02 at $\varepsilon \geq 0.35$ and ± 0.01 at $\varepsilon < 0.35$

Table 3 continued
Nimonic 901
Hot compression data

IMI	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT62 ~9 s^{-1}				
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.02	171				
0.05	206				
0.10	280				
0.15	346				
0.20	384				
0.25	408				
0.30	415				
0.35	419				
0.40	422				
0.43	418				
0.46	417				
MPD	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT42 0.1 s^{-1}	EAT46 0.1 s^{-1}	EAT25 0.1 s^{-1}	EAT19 1 s^{-1}	EAT28 1 s^{-1}
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	185	184	187	203	192
0.1	201	202	205	239	250
0.15	212	208	207	258	266
0.2	215	210	207	264	272
0.25	218	216	210	269	271
0.3	222	215	210	268	272
0.35	223	217	211	267	270
0.4	223	220	208	268	267
0.45	225		208	266	263
			206	264	259

Table 3 continued
Nimonic 901
Hot compression data

MPD	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT58 1 s^{-1}				
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	202				
0.1	248				
0.15	266				
0.2	276				
0.25	276				
0.3	275				
0.35	274				
0.4	272				
0.45	271				
0.5	267				
NPL	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	EAT55 0.1 s^{-1}	EAT6 0.1 s^{-1}	EAT26 0.1 s^{-1}	EAT52 1 s^{-1}	EAT30 1 s^{-1}
Strain	Stress	Stress	Stress	Stress	Stress
0.05	199	195	204	227	237
0.1	210	210	224	304	305
0.15	217	213	230	324	325
0.2	217	215	232	334	328
0.25	220	214	232	329	324
0.3	222	218	229	330	326
0.35	226	217	223	329	323
0.4	229	211	214	322	318
0.45	233	203	204	315	310
0.5	232	193	194	301	298

Table 3 continued
Nimonic 901
Hot compression data

British Steel	Strain rate	Strain rate	Strain rate	Strain rate	
	EAT74 0.1 s^{-1}	EAT76 0.1 s^{-1}	EAT73 1 s^{-1}	EAT71 1 s^{-1}	
Strain	Stress	Stress	Stress	Stress	
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	
0.05	182	186	240	231	
0.1	188	191	253	248	
0.15	192	194	257	253	
0.2	194	196	259	255	
0.25	196	199	261	258	
0.3	198	201	262	260	
0.35	199	202	262	261	
0.4	199	203	261	260	
0.45	198	204	260	260	
0.5	197	205	258	260	
Oulu	Strain Rate	Strain Rate	Strain Rate	Strain Rate	
	EAT66 0.1	EAT69 0.1	EAT70 1	EAT75 1	
Strain	Stress	Stress	Stress	Stress	
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	
0.05	190	185	260	276	
0.1	200	187	285	285	
0.15	201	191	295	296	
0.2	205	192	294	297	
0.25	204	191	290	290	
0.3	205	191	288	291	
0.35	202	190	287	287	
0.4	200	187	284	285	
0.45	199	187	285	283	
0.5	197	182	283	280	

Table 4
Low C-Mn Steels
Hot compression data

Sheffield	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX66 1 s^{-1}	GBX67 1 s^{-1}	GBX68 10 s^{-1}	GBX71 10 s^{-1}	GBX72 10 s^{-1}
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	51.7	50.4	68.3	66.6	64.4
0.1	62.8	63.8	85.1	84	84.6
0.15	70.7	71.3	95.2	94.1	95.2
0.2	76.1	76.7	102	103	103
0.25	80	80	107	109	109
0.3	83	81.2	111	112	112
0.35	83.4	82.9	114	116	115
0.4	83.5	82.9	116	120	118
0.45	83.4	82.4	118	122	120
0.5	83.4	81.8	120	124	121
Cambridge	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX45 0.1 s^{-1}	GBX48 0.1 s^{-1}	GBX44 1 s^{-1}	GBX51 1 s^{-1}	
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	41.7	44.7	53.1	64.7	
0.1	52.2	54.8	65.2	76.3	
0.15	59	61.6	72	82.1	
0.2	61.5	64.5	76.2	85.1	
0.25	58.8	63.9	78.9	86.5	
0.3	54.3	62.4	79.7	86	
0.35	51.2	61	79.2	84.2	
0.4	49.4	59.7	77.5	81.7	
0.45	48	57.9	75.5	79.5	
0.5	47.8	57.2	73.9	75.2	

Table 4 continued
Low C-Mn Steels
Hot compression data

Swansea	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX58 $0.1\ s^{-1}$	GBX53 $0.1\ s^{-1}$	GBX46 $1\ s^{-1}$	GBX8 $1\ s^{-1}$	GBX24 $1\ s^{-1}$
Strain	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.05	46.4	43.9	55.7	60.9	60
0.1	54.3	53.3	68.2	71.9	72.2
0.15	61.2	61.2	77.6	80.5	80.8
0.2	65.6	64.2	84.7	86.3	87.1
0.25	66.8	66.4	88.6	90.6	92.2
0.3	65.6	65.1	91.8	94.9	95
0.35	62.1	62	94.1	96.5	96.5
0.4	61.2	60.4	94.9	96.9	96.5
0.45	60.2	60.4	94.5		
0.5					
British Steel	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX33 $1\ s^{-1}$	GBX17 $1\ s^{-1}$	GBX55 $10\ s^{-1}$	GBX64 $10\ s^{-1}$	
Strain	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.05	57	58	65.4	65	
0.1	75.2	74.4	85.3	79.3	
0.15	83.7	83.1	93.4	88.8	
0.2	90.3	89.2	98.8	94.2	
0.25	94.3	93.2	102.4	98	
0.3	97.1	95.5	103.7	100	
0.35	98.5	96.5	105.2	101.3	
0.4	98.2	96.8	103.9	100.6	
0.45	97.5	94.5	101	99.2	
0.5	95.8	92.5	98.7	96.8	

Table 4 continued
Low C-Mn Steels
Hot compression data

IMI	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX13 ~1.5 s^{-1}	GBX14 ~1.5 s^{-1}	GBX57 ~8 s^{-1}	GBX60 ~8 s^{-1}	
Strain+	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.025	45	25	56	56	
0.05	64	55	62	68	
0.10	84	69	73	74	
0.15	88	88	92	102	
0.25	96	94	99	108	
0.25	103	99	109	113	
0.30	112	103	114	119	
0.35	113	107	120	126	
0.42	120	110	120	129	
0.46	119	110	126	129	
0.50	124	111	124	131	
MPD	Strain rate	Strain rate	Strain rate	Strain rate	Strain rate
	GBX59 0.1 s^{-1}	GBX61 0.1 s^{-1}	GBX15 1 s^{-1}	GBX56 1 s^{-1}	
Strain	Stress	Stress	Stress	Stress	Stress
	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}
0.05	39	39	49	36	
0.1	48	48	64	52	
0.15	54	54	74	61	
0.2	59	57	80	68	
0.25	59	57	83	73	
0.3	54	55	83	76	
0.35	51	52	81	78	
0.4	50	51	80	78	
		50		78	

+ within about ± 0.02 at $\varepsilon \geq 0.35$ and ± 0.01 at $\varepsilon < 0.35$

Table 4 continued
Low C-Mn Steels
Hot compression data

Oulu	Strain Rate	Strain Rate	Strain Rate	Strain Rate	Strain Rate
	GBX76 $0.1\ s^{-1}$	GBX82 $0.1\ s^{-1}$	GBX83 $0.1\ s^{-1}$	GBX77 $1\ s^{-1}$	GBX78 $1\ s^{-1}$
Strain	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.05	52.7	51.7	50.8	66.5	64.6
0.1	63.3	60.6	60.7	79.1	77.4
0.15	67.7	66.0	66.1	86.1	86.1
0.2	71.6	70.8	70.0	93.1	90.6
0.25	70.3	71.1	69.6	96.8	96.0
0.3	67.7	67.6	66.2	101	97.9
0.35	64.4	65.0	63.7	102	100
0.4	63.2	63.2	62.5	103	99.6
0.45	61.3	62.0	61.3	102	99.7
0.5	60.1	60.7	61.3	98.9	99.5

Oulu	Strain Rate	Strain Rate	Strain Rate	Strain Rate	Strain Rate
	GBX84 $1\ s^{-1}$	GBZ5 $0.1\ s^{-1}$	GBZ24 $0.1\ s^{-1}$	GBZ27 $0.1\ s^{-1}$	GBZ12 $1\ s^{-1}$
Strain	Stress	Stress	Stress	Stress	Stress
	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$	$N\ mm^{-2}$
0.05	67.5	46.7	46.7	46.1	62.1
0.1	81.6	56.2	55.7	55.7	74.2
0.15	86.9	63.1	62.6	61.6	79.7
0.2	95.2	66.7	66.7	66.2	85.5
0.25	97.0	66.8	67.3	65.9	89.6
0.3	101	61.7	62.2	61.3	92.0
0.35	102	57.8	58.3	57.0	93.3
0.4	102	56.3	57.1	54.6	92.9
0.45	98.4	55.5	56.3	54.3	93.2
0.5	98.0	55.4	56.5	54.3	91.2

Table 4 continued
Low C-Mn Steels
Hot compression data

Oulu	Strain Rate	Strain Rate			
	GBZ52 1 s^{-1}	GBZ62 1 s^{-1}			
Strain	Stress	Stress			
	N mm^{-2}	N mm^{-2}			
0.05	61.5	62.7			
0.1	73.7	72.5			
0.15	80.8	79.7			
0.2	86.0	85.0			
0.25	89.2	87.7			
0.3	92.0	90.3			
0.35	92.5	91.6			
0.4	93.3	91.2			
0.45	91.2	89.9			
0.5	90.1	87.1			

Table 5

Hot Flow Stress
Mean Values at 0.1 and 0.3 Strain

Organisation		Nimonic 901 (1000 °C)						Low C-Mn Steel (1100 °C)					
	Strain rate s^{-1}	0.1		1		10		0.1		1		10	
	Strain	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3
Swansea		219	229	333	338	-	-	53.8	65.4	70.8	93.9	-	-
Cambridge		206	221	282	272	-	-	53.5	58.4	70.8	82.9	-	-
Sheffield		-	-	285	286	349	407	-	-	63.3	82.1	84.6	111.5
British Steel		190	200	251	261	-	-	-	-	74.8	96.3	82.3	101.9
IMI		-	-	242	298	277	414	-	-	76.5	105	73.5	114
NPL		215	223	305	328	-	-	-	-	-	-	-	-
MPD		203	216	246	272	-	-	48.0	54.5	58.0	79.5	-	-
Oulu		194	198	285	290	-	-	55.9	61.7	73.4	91.4	-	-
All		205	215	278	292	313	410	53.1	60.2	70.0	90.5	80.8	109.5

Table 6

Uncertainty in Hot Flow Stress
One Standard Deviation, %

Organisation		Nimonic 901 (1000 °C)						Low C-Mn Steel (1100 °C)					
	Strain rate s^{-1}	0.1		1		10		0.1		1		10	
	Strain	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3
Swansea		2.9	2.2	1.7	4.2	-	-	1.3	0.5	3.1	1.9	-	-
Cambridge		7.6	5.8	1.0	3.6	-	-	3.4	9.8	11.0	5.3	-	-
Sheffield		-	-	1.5	1.0	4.3	2.8	-	-	1.1	1.5	0.6	0.5
British Steel		1.1	1.1	1.4	0.5	-	-	-	-	0.8	1.2	5.1	2.6
IMI		-	-	2.6	6.1	1.7	4.5	-	-	13.9	6.7	9.6	2.5
NPL		3.8	2.5	0.2	0.9	-	-	-	-	-	-	-	-
MPD		1.0	2.8	2.4	1.3	-	-	0.0	1.3	14.6	6.2	-	-
Oulu		4.8	5.0	0.0	0.7	-	-	0.5	0.7	1.2	1.1	-	-
All		5.9	5.9	11.8	9.1	12.8	3.5	6.0	7.6	10.5	9.6	6.6	5.1

Table 7
Barrelling - Nimonic 901

Test-piece number	Organisation	Strain rate s^{-1}	Geometry, mm				Final true strain	Barrelling coefficients		
			Before test		After test			B1	B2	B3
			length, ℓ_o	diameter, d_o	length, ℓ_f	diameter, d_f			%	%
47	Swansea	0.1	15	10	9.69	12.69	0.44	0.94	-3.71	5.46
64	Swansea	0.1	15	10	10.12	12.47	0.40	0.94	-3.55	4.51
10	Swansea	1	15	10	12.13	11.36	0.22	0.97	-1.87	1.55
30	Swansea	1	15	10	9.65	12.84	0.45	0.96	-2.80	4.55
3	Swansea	1	15	10	9.34	13.06	0.47	0.95	-3.07	3.53
38	Cambridge	0.1	15	10	9.37	13.68	0.47	0.86	-10.32	14.61
24	Cambridge	0.1	15	10	9.34	13.73	0.48	0.86	-10.04	14.28
43	Cambridge	1	15	10	9.44	13.39	0.46	0.91	-5.87	10.91
54	Cambridge	1	15	10	9.36	13.67	0.47	0.86	-10.11	12.05
66	Sheffield	1	8	8	4.84	10.86	0.51	0.92	-5.15	9.55
67	Sheffield	1	8	8	4.85	10.77	0.50	0.91	-5.86	9.76
68	Sheffield	10	8	8	4.95	10.67	0.48	0.93	-4.60	9.17
69	Sheffield	10	8	8	4.92	10.61	0.49	0.92	-5.41	9.00
70	Sheffield	10	8	8	4.88	10.83	0.50	0.92	-5.67	9.59
74	British Steel	0.1	15	10	7.89	14.67	0.64	0.88	-8.82	12.01
76	British Steel	0.1	15	10	7.91	14.57	0.64	0.89	-7.99	10.35
71	British Steel	1	15	10	7.93	14.55	0.47	0.89	-7.97	10.95
73	British Steel	1	15	10	7.91	14.69	0.64	0.88	-9.19	10.64
13	IMI	1	15	10	9.47	13.21	0.46	0.94	-4.29	-
17	IMI	1	15	10	9.53	13.18	0.46	0.90	-6.44	-
31	IMI	1	15	10	9.68	12.41	0.44	1.02	1.22	-
33	IMI	10	15	10	9.65	12.90	0.45	0.93	-4.72	-
59	IMI	10	15	10	9.32	12.90	0.48	0.96	-2.92	-
62	IMI	10	15	10	9.53	12.99	0.46	0.93	-4.63	-
6	NPL	0.1	15	10	8.45	13.85	0.57	0.93	-5.27	-
26	NPL	0.1	15	10	7.78	14.72	0.66	0.89	-8.35	-
55	NPL	0.1	12	8	6.00	11.81	0.69	0.92	-6.20	5.24
30	NPL	1	12	8	3.70	15.03	1.18	0.92	-7.78	4.73
52	NPL	1	12	8	5.00	12.94	0.88	0.92	-6.83	4.88
25	MPD	0.1	15	10	9.17	13.26	0.49	0.93	-5.04	8.20
42	MPD	0.1	15	10	9.45	14.10	0.46	0.81	-14.31	9.25
46	MPD	0.1	15	10	9.95	13.43	0.41	0.84	-11.42	8.10
19	MPD	1	14	10	7.66	14.06	0.60	0.93	-5.12	7.70
28	MPD	1	14	10	6.28	15.50	0.80	0.94	-4.70	8.28
58	MPD	1	14	10	8.25	13.23	0.51	0.95	-3.41	7.47

Summary

	Strain rate, $\dot{\varepsilon}$ = 0.1 s^{-1}			Strain rate, $\dot{\varepsilon}$ = 1 s^{-1}			Strain rate, $\dot{\varepsilon}$ = 10 s^{-1}		
	B1	B2, %	B3, %	B1	B2, %	B3, %	B1	B2, %	B3, %
Swansea	0.94	-3.6	5.0	0.96	-2.6	3.2	-	-	-
Cambridge	0.86	-10.2	14.5	0.88	-8.0	11.6	-	-	-
Sheffield	-	-	-	0.92	-5.6	9.7	0.92	-5.2	9.3
British Steel	0.89	-8.4	11.2	0.89	-8.6	10.8	-	-	-
IMI	-	-	-	0.95	-3.2	-	0.94	-4.1	-
NPL	0.91	-6.6	-	0.92	-7.3	-	-	-	-
MPD	0.86	-10.3	8.5	0.94	-4.4	7.8	-	-	-

List of Captions

Fig 1 Nimonic 901 microstructures, X100.

Fig 2 Low C-Mn steel microstructures, X100.

Fig 3 Effect of heating rate and hold time on austenite grain size, X200.

a) NPL - 10 min to T, 5 min at T
b) B Steel - 1 min to T, 10 min at T
c) NPL - 10 min to T, 30 min at T
d) NPL - 120 min to T, 35 min at T

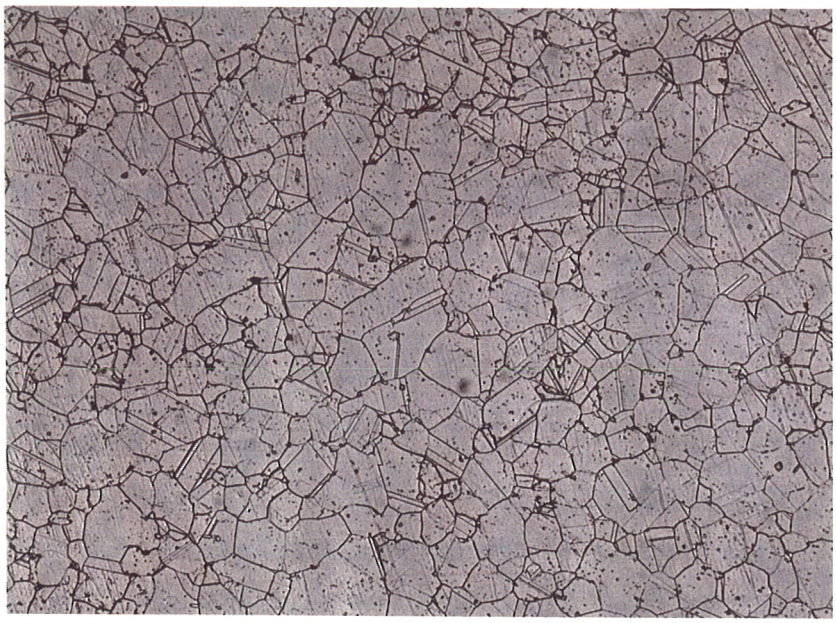
Fig 4 Repeatability of Nimonic 901 stress/strain curves.

Fig 5 Repeatability of low C-Mn steel stress/strain curves.

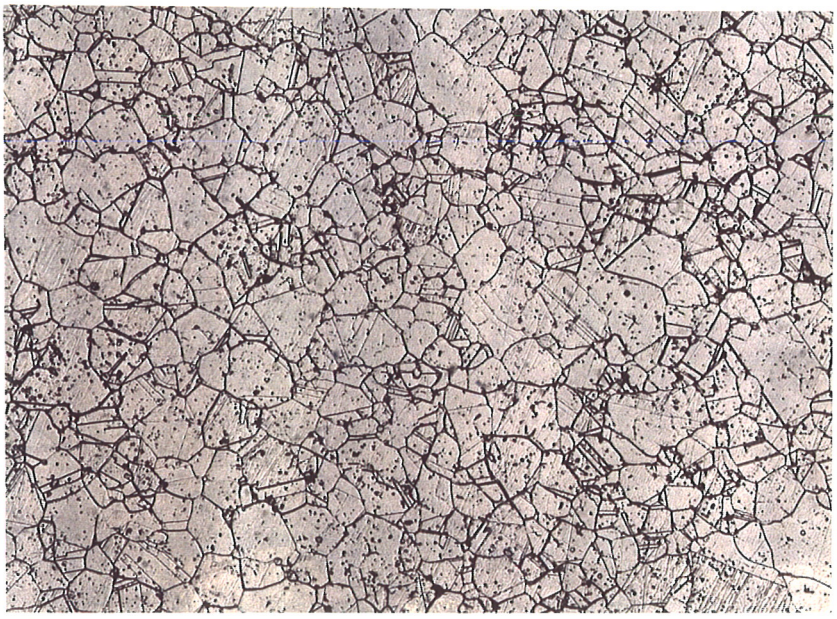
Fig 6 Reproducibility of flow stresses.

Fig 7 Comparison of mean flow stresses with overall mean value for each organisation.

Fig 8 Schematic diagrams of barrelling.



Front



Middle

Fig 1 Nimonic 901 microstructures, X100.

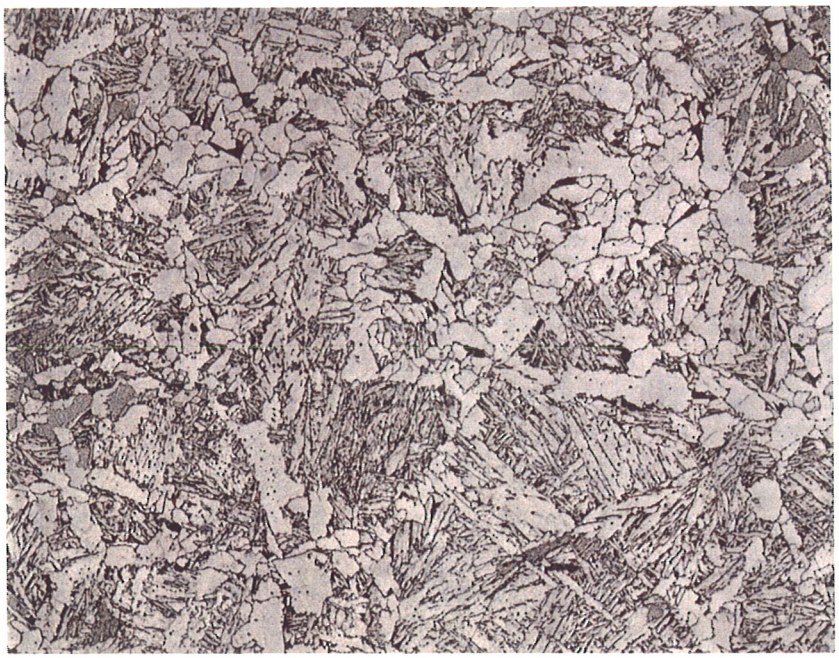


Plate Centre - Longitudinal



Plate Centre - Transverse

Fig 2 Low C-Mn steel microstructures, X100.

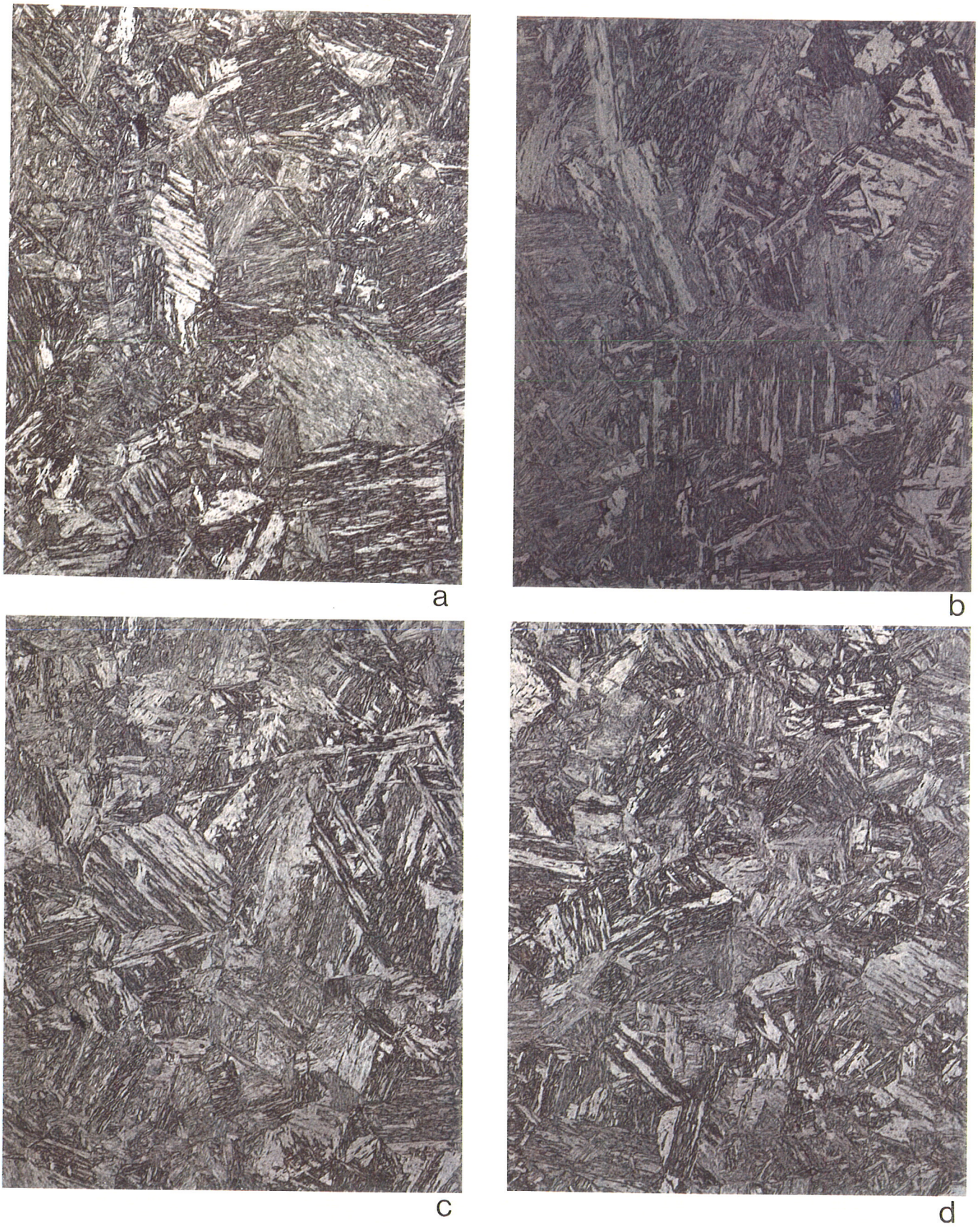
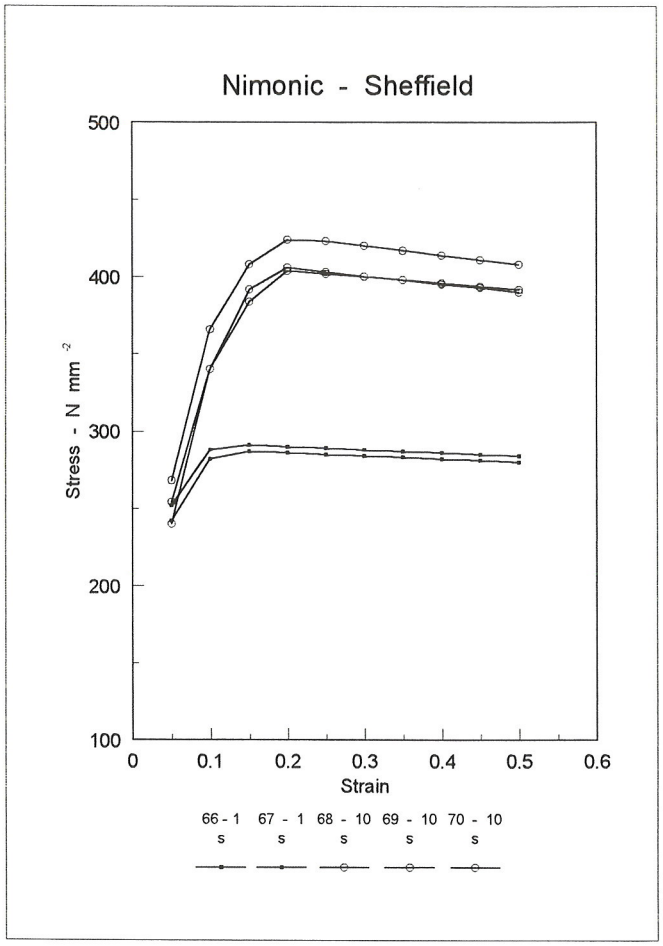
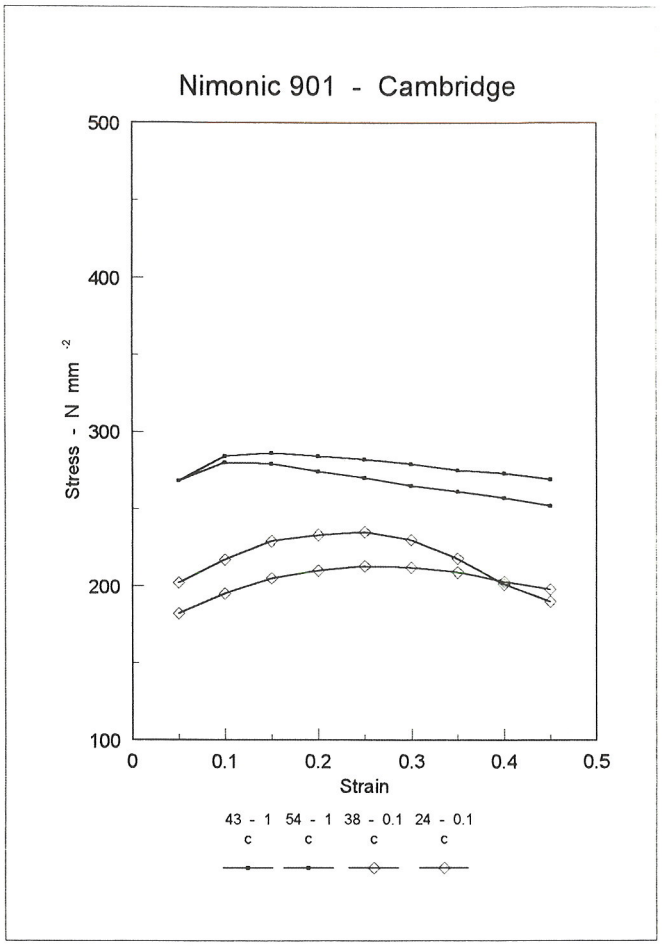


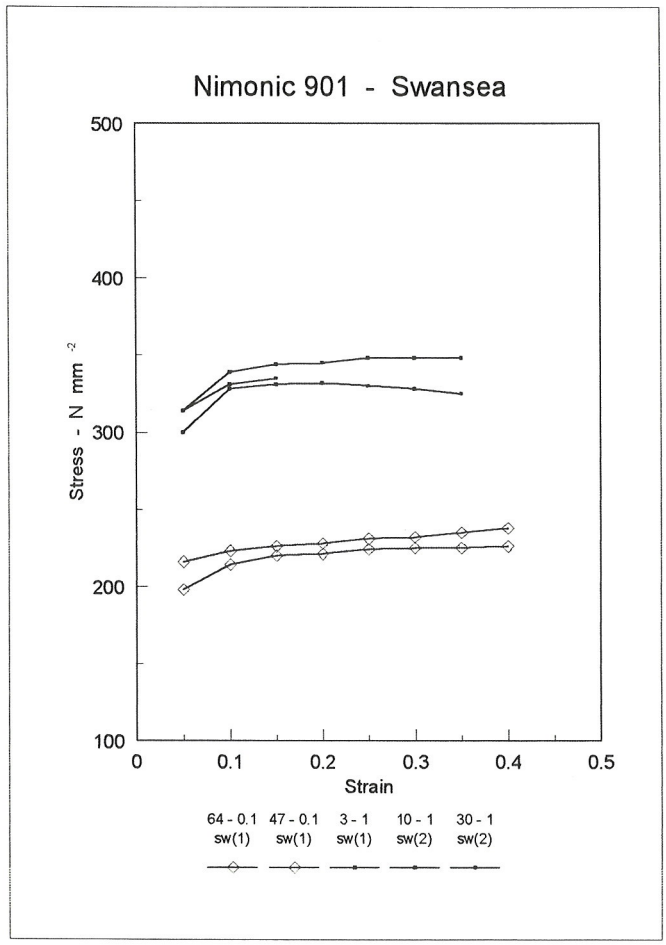
Fig 3 Effect of heating rate and hold time on austenite grain size, X200.

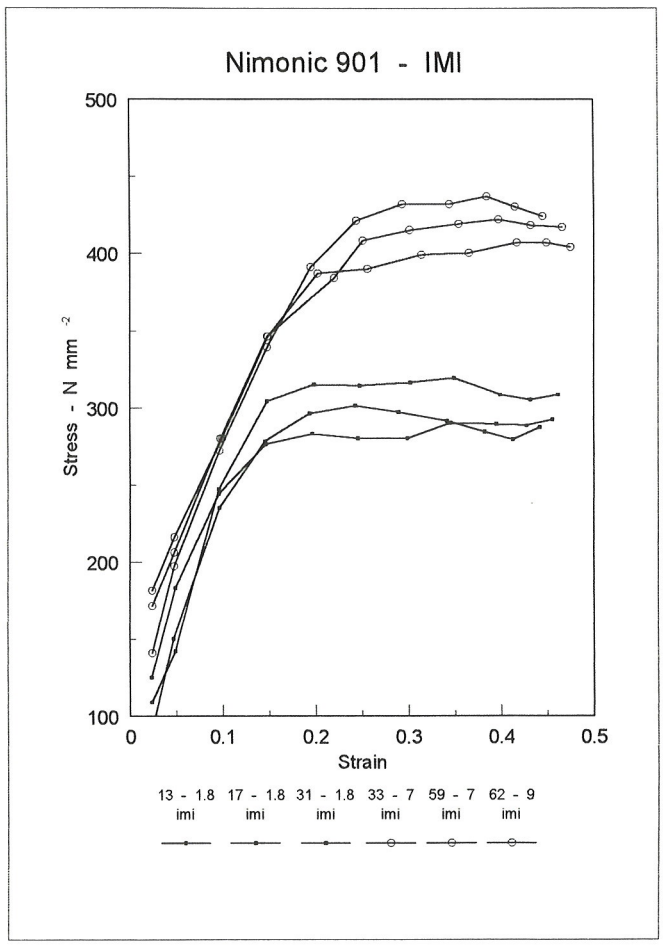
a) NPL - 10 min to T, 5 min at T
b) B Steel - 1 min to T, 10 min at T
c) NPL - 10 min to T, 30 min at T
d) NPL - 120 min to T, 35 min at T

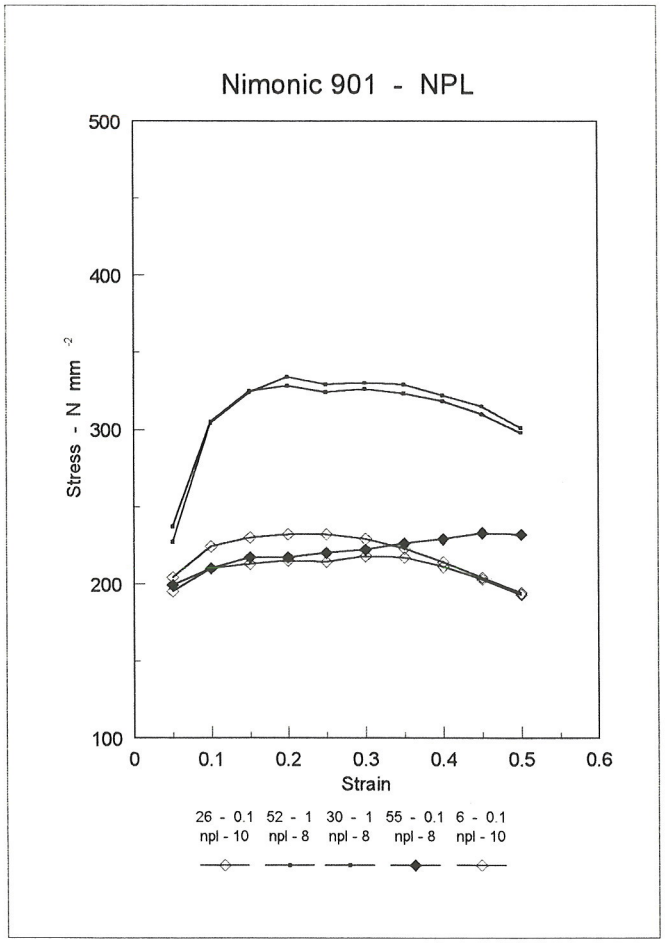
Fig 4 Repeatability of Nimonic 901 stress/strain curves.

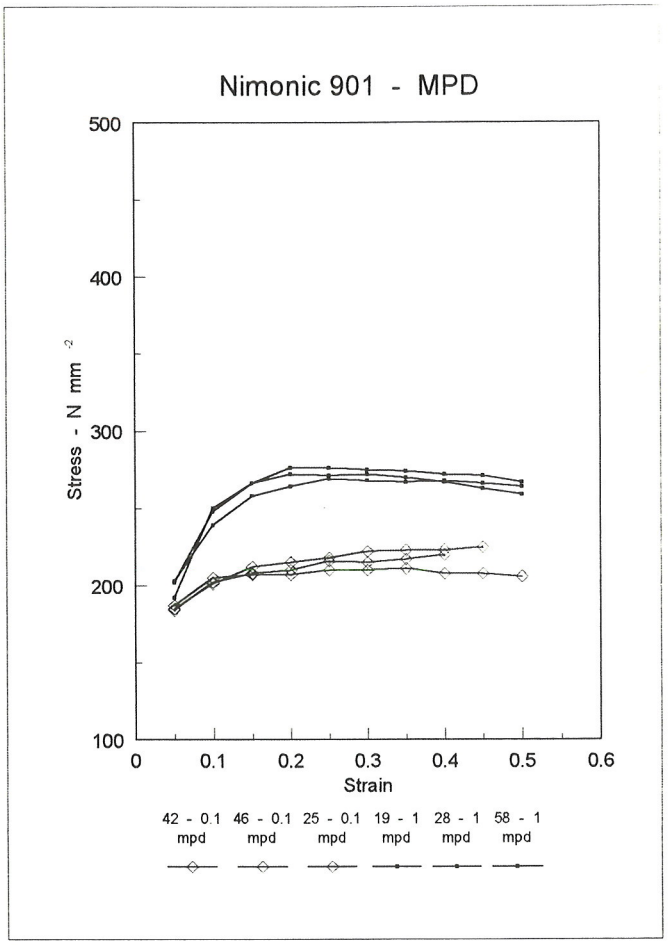

Nimonic - Sheffield
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
Strain
66 - 1 s
67 - 1 s
68 - 10 s
69 - 10 s
70 - 10 s

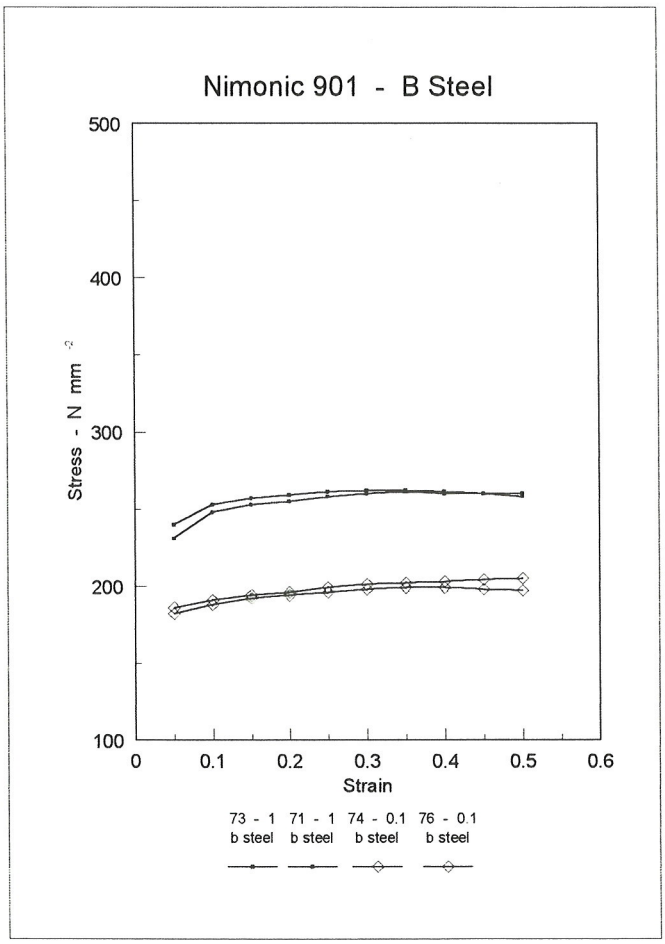

Nimonic 901 - Cambridge
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
Strain
43 - 1 c
54 - 1 c
38 - 0.1 c
24 - 0.1 c


Nimonic 901 - Swansea
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
Strain
64 - 0.1 sw(1)
47 - 0.1 sw(1)
3 - 1 sw(1)
10 - 1 sw(2)
30 - 1 sw(2)


Nimonic 901 - IMI
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
Strain
13 - 1.8 imi
17 - 1.8 imi
31 - 1.8 imi
33 - 7 imi
59 - 7 imi
62 - 9 imi


Nimonic 901 - NPL
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
Strain
26 - 0.1 npl - 10
52 - 1 npl - 8
30 - 1 npl - 8
55 - 0.1 npl - 8
6 - 0.1 npl - 10


Nimonic 901 - MPD
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
Strain
42 - 0.1 mpd
46 - 0.1 mpd
25 - 0.1 mpd
19 - 1 mpd
28 - 1 mpd
58 - 1 mpd


Nimonic 901 - B Steel
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
Strain
73 - 1 b steel
71 - 1 b steel
74 - 0.1 b steel
76 - 0.1 b steel

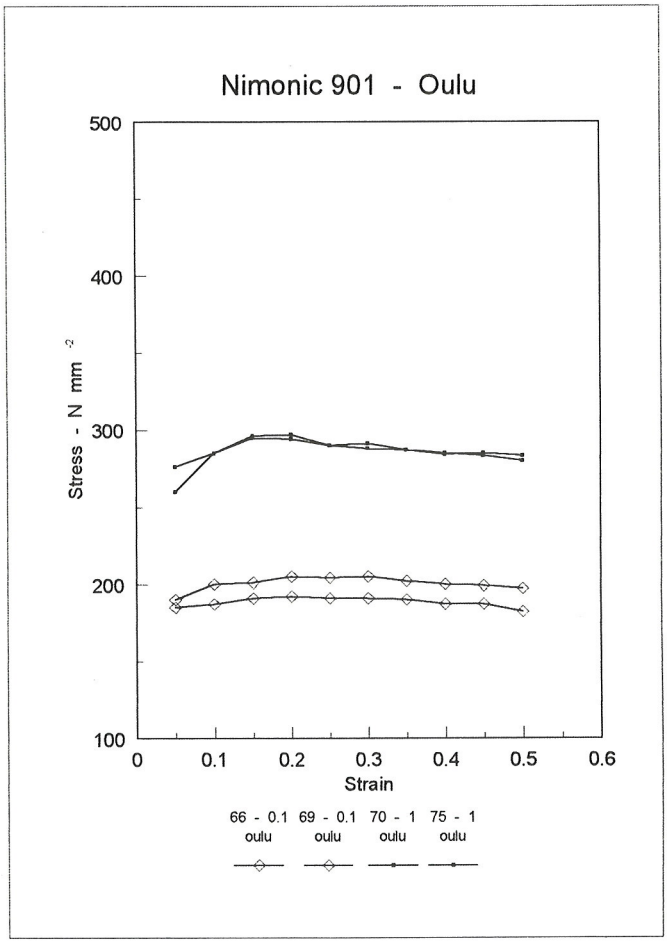
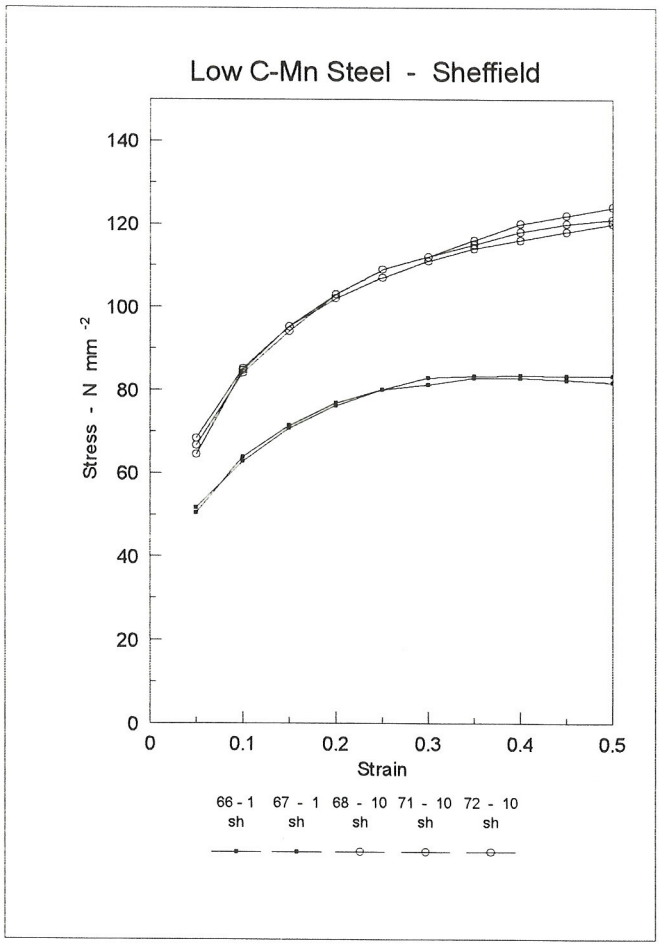
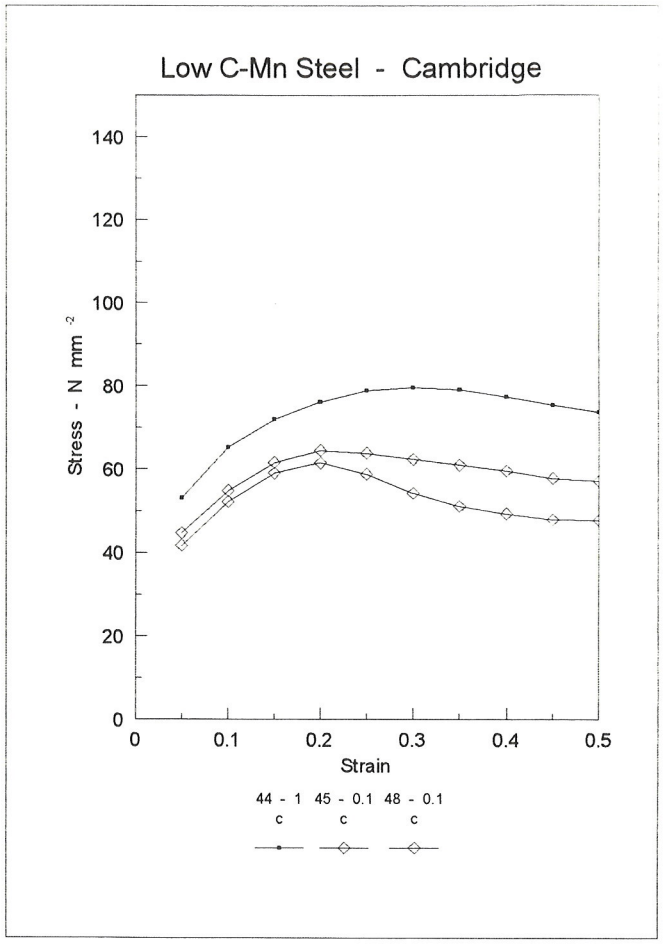
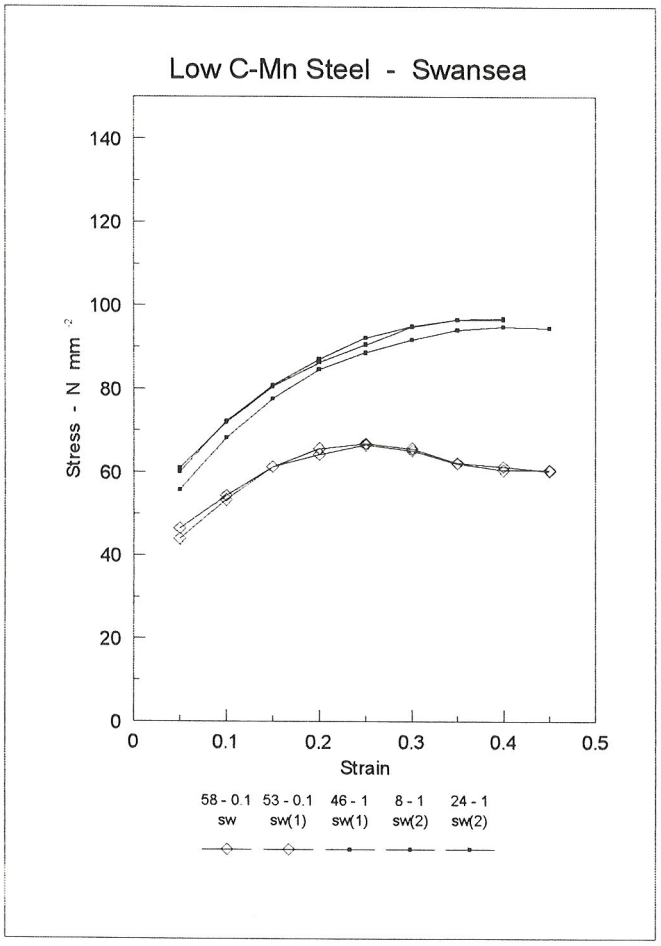
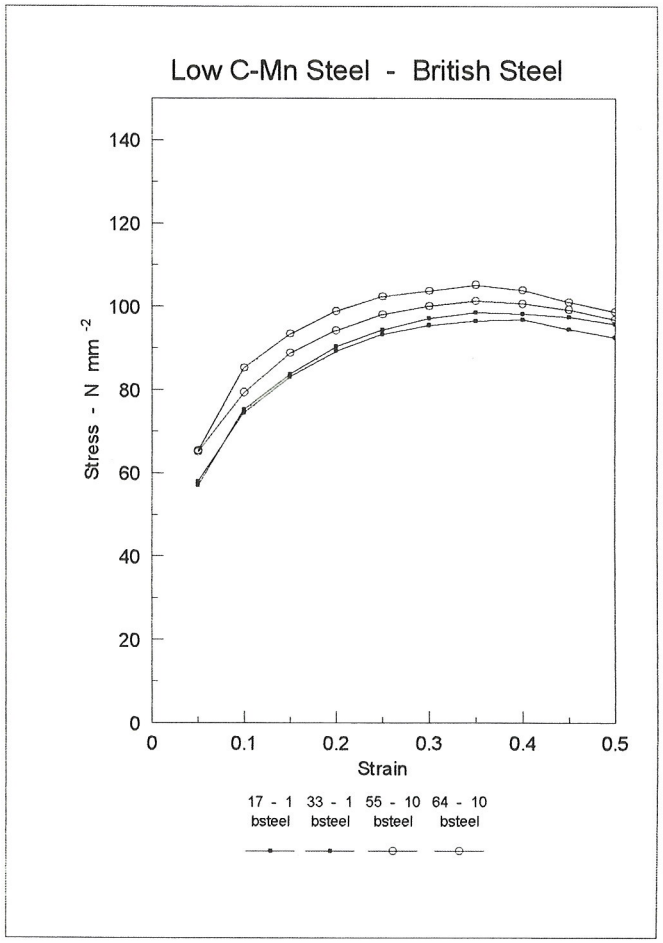

Nimonic 901 - Oulu
Stress - N mm -2
500
400
300
200
100
0
0.1
0.2
0.3
0.4
0.5
0.6
Strain
66 - 0.1 oulu
69 - 0.1 oulu
70 - 1 oulu
75 - 1 oulu

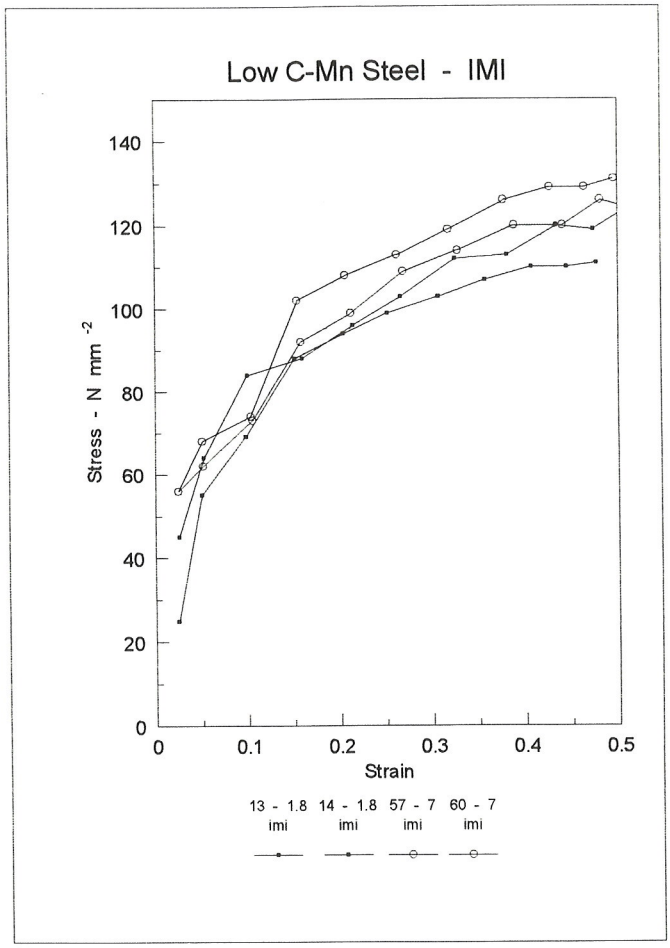
Fig 5 Repeatability of low C-Mn steel stress/strain curves.

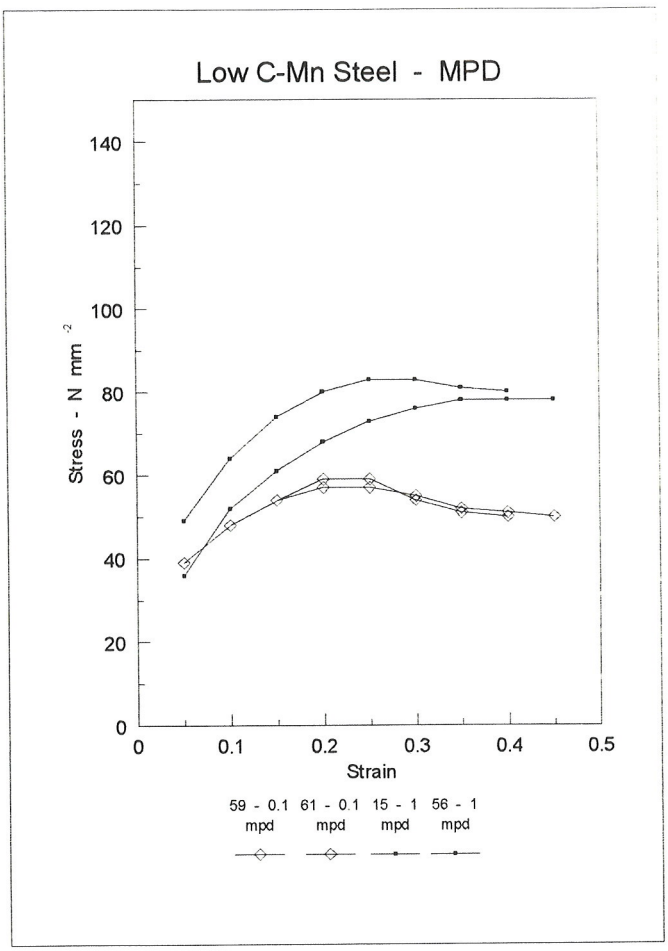

Low C-Mn Steel - Sheffield
Stress - N mm -2
Strain
66 - 1 sh
67 - 1 sh
68 - 10 sh
71 - 10 sh
72 - 10 sh


Low C-Mn Steel - Cambridge
Stress - N mm -2
Strain
44 - 1 c
45 - 0.1 c
48 - 0.1 c


Low C-Mn Steel - Swansea
Stress - N mm -2
Strain
58 - 0.1 sw
53 - 0.1 sw(1)
46 - 1 sw(1)
8 - 1 sw(2)
24 - 1 sw(2)


Low C-Mn Steel - British Steel
Stress - N mm -2
Strain
17 - 1 bsteel
33 - 1 bsteel
55 - 10 bsteel
64 - 10 bsteel


Low C-Mn Steel - IMI
Stress - N mm -2
Strain
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
13 - 1.8 imi
14 - 1.8 imi
57 - 7 imi
60 - 7 imi


Low C-Mn Steel - MPD
Stress - N mm -2
Strain
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
59 - 0.1 mpd
61 - 0.1 mpd
15 - 1 mpd
56 - 1 mpd

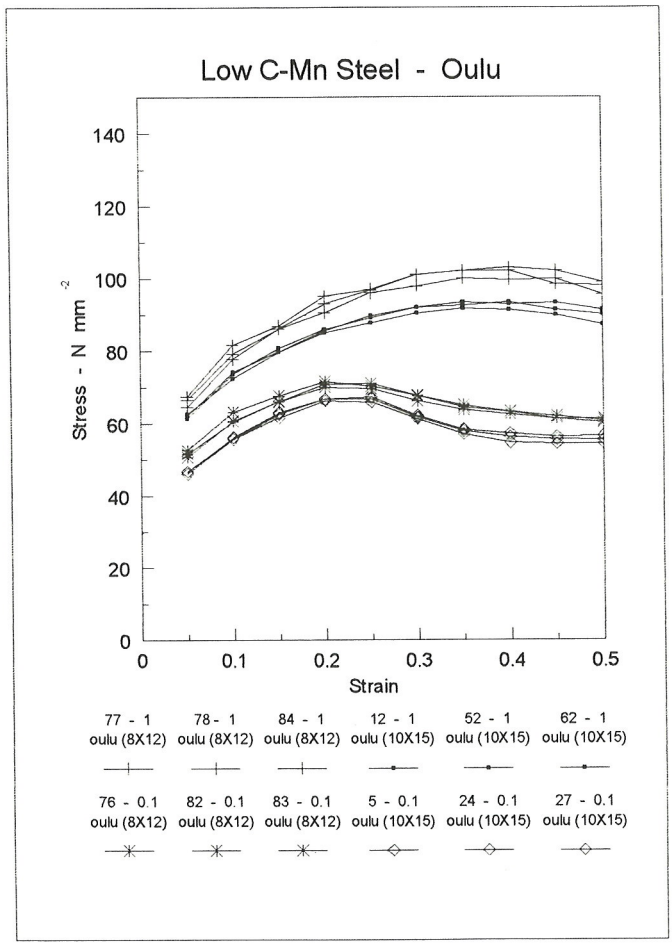
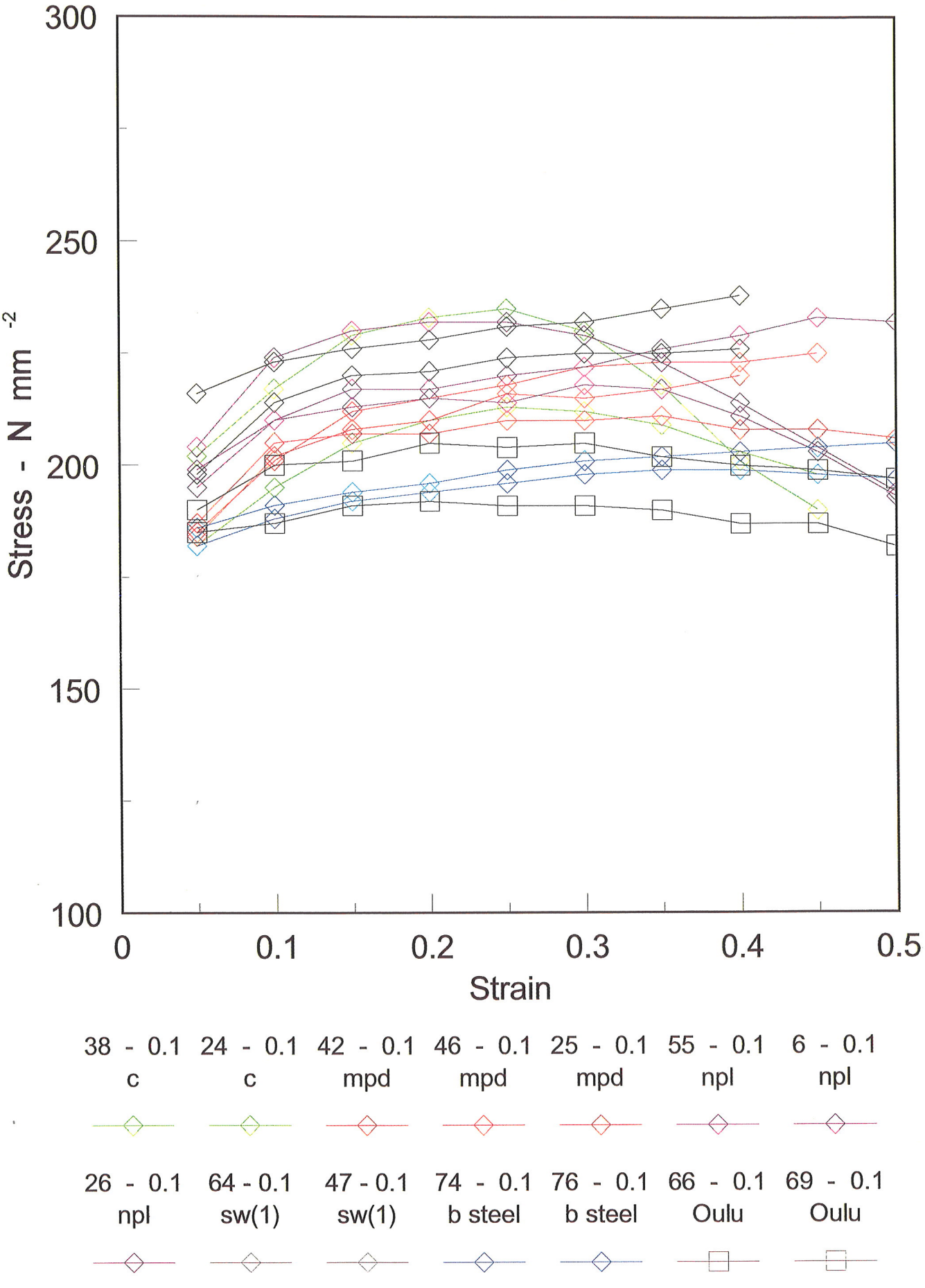
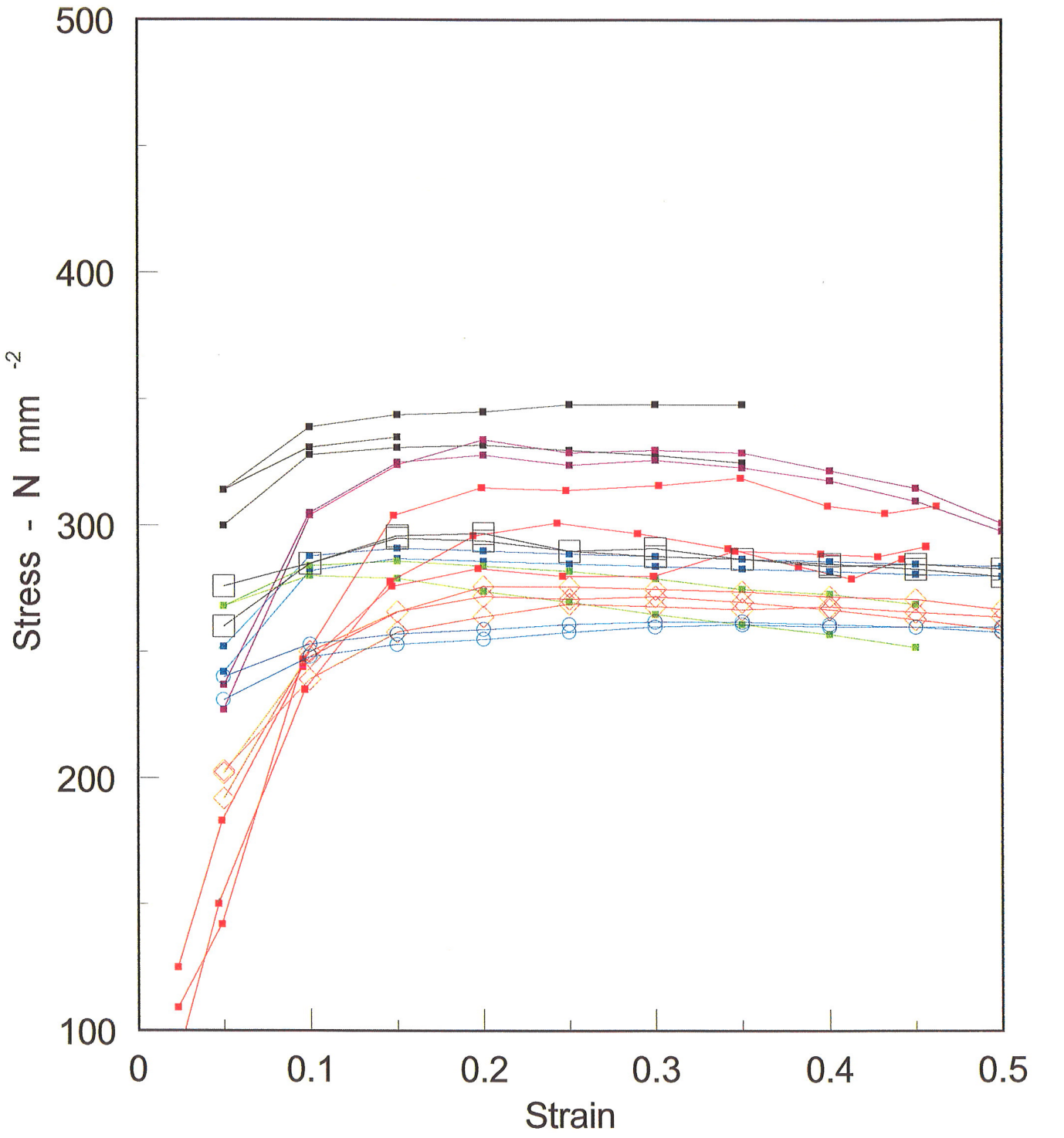

Low C-Mn Steel - Oulu
Stress - N mm -2
Strain
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
77 - 1 oulu (8X12)
78 - 1 oulu (8X12)
84 - 1 oulu (8X12)
12 - 1 oulu (10X15)
52 - 1 oulu (10X15)
62 - 1 oulu (10X15)
76 - 0.1 oulu (8X12)
82 - 0.1 oulu (8X12)
83 - 0.1 oulu (8X12)
5 - 0.1 oulu (10X15)
24 - 0.1 oulu (10X15)
27 - 0.1 oulu (10X15)

Fig 6 Reproducibility of flow stress.

Nimonic 901 - Strain rate, 0.1



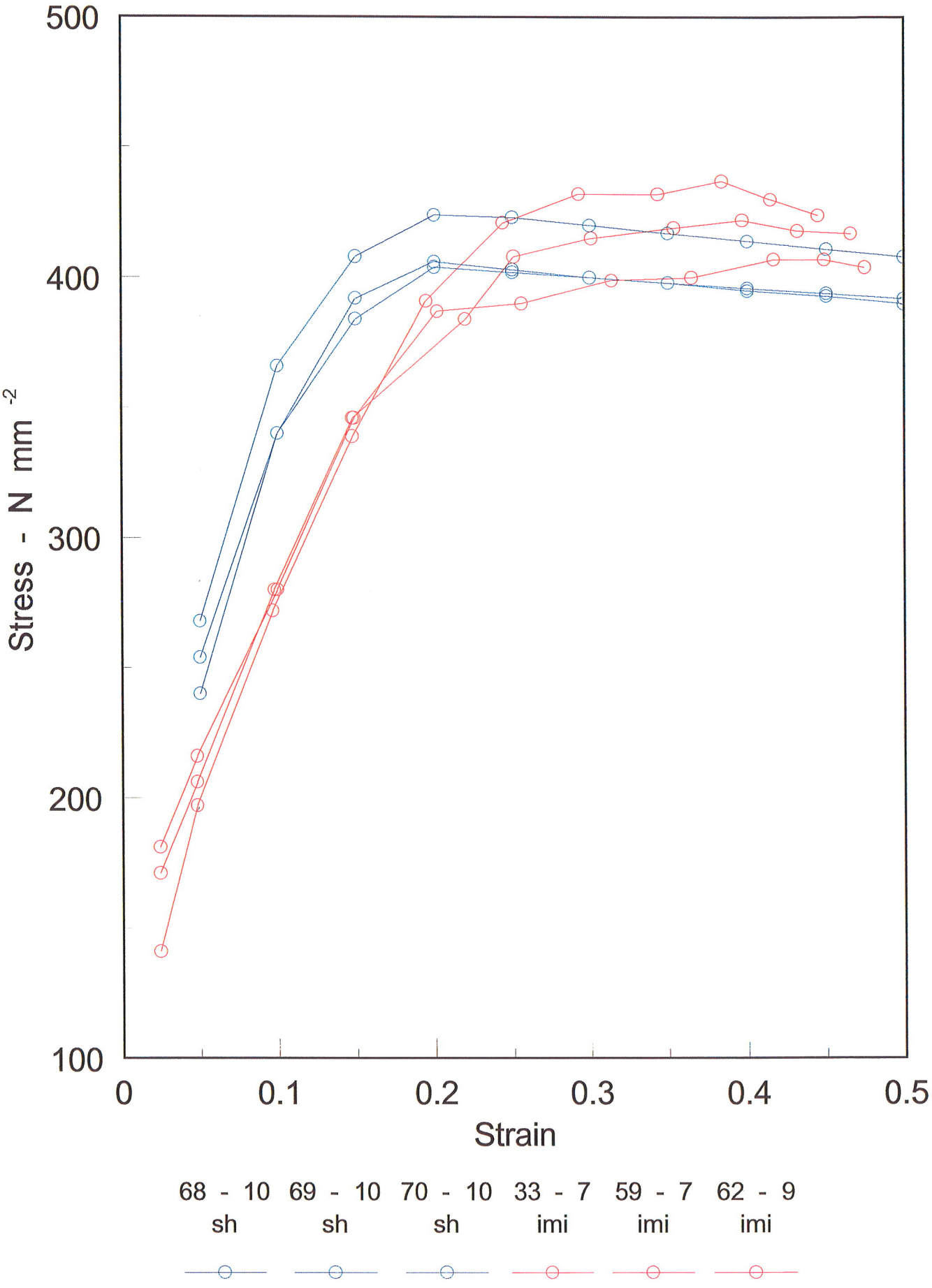
Nimonic 901 - Strain rate, 1



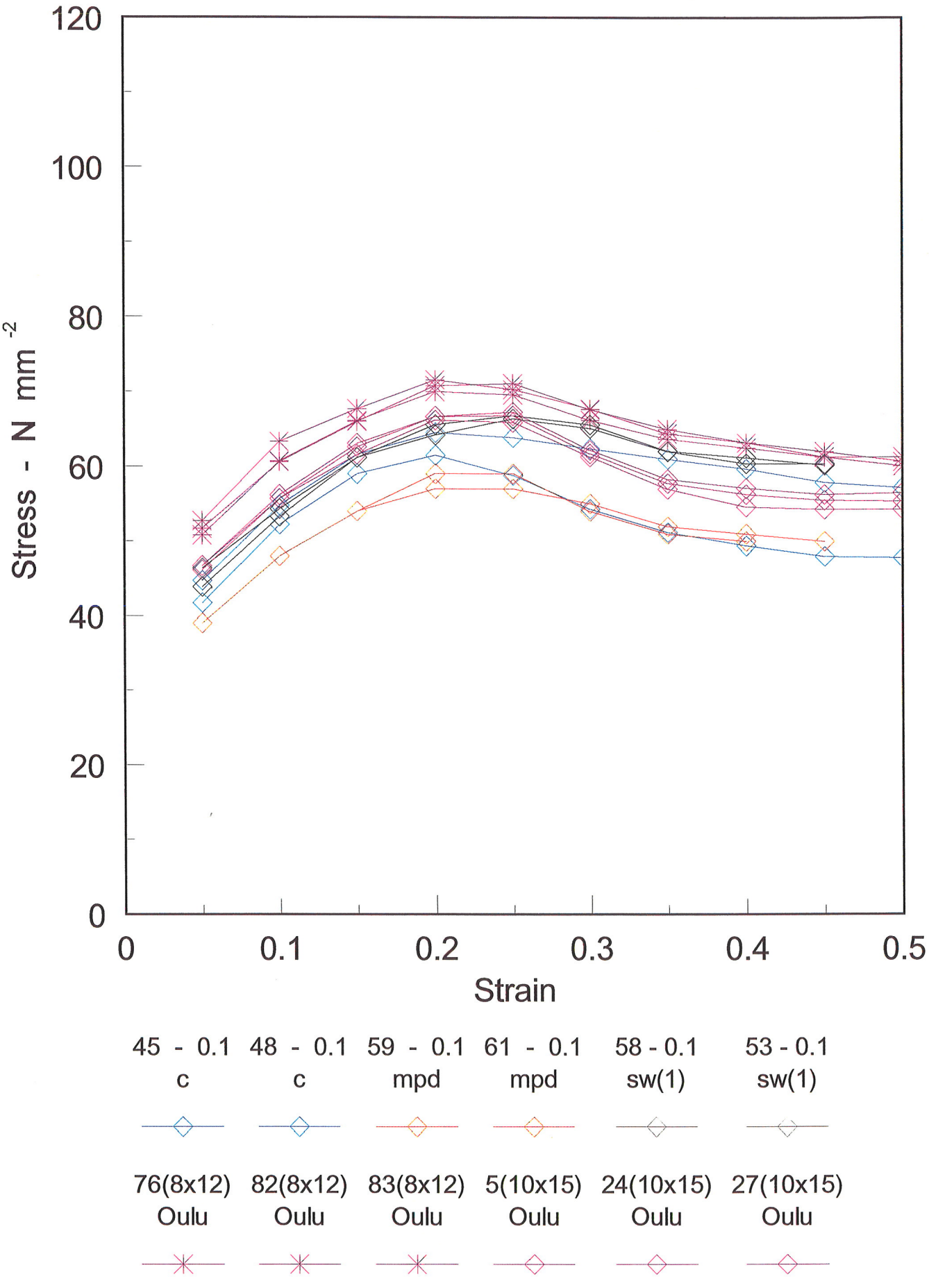
66 - 1 sh
67 - 1 sh
3 - 1 sw
10 - 1 sw
30 - 1 sw
43 - 1 c
54 - 1 c
13 - 1 imi
17 - 1 imi
31 - 1 imi

19 - 1 mpd
28 - 1 mpd
58 - 1 mpd
52 - 1 npl
30 - 1 npl
73 - 1 b steel
71 - 1 b steel
70 - 1 Oulu
75 - 1 Oulu

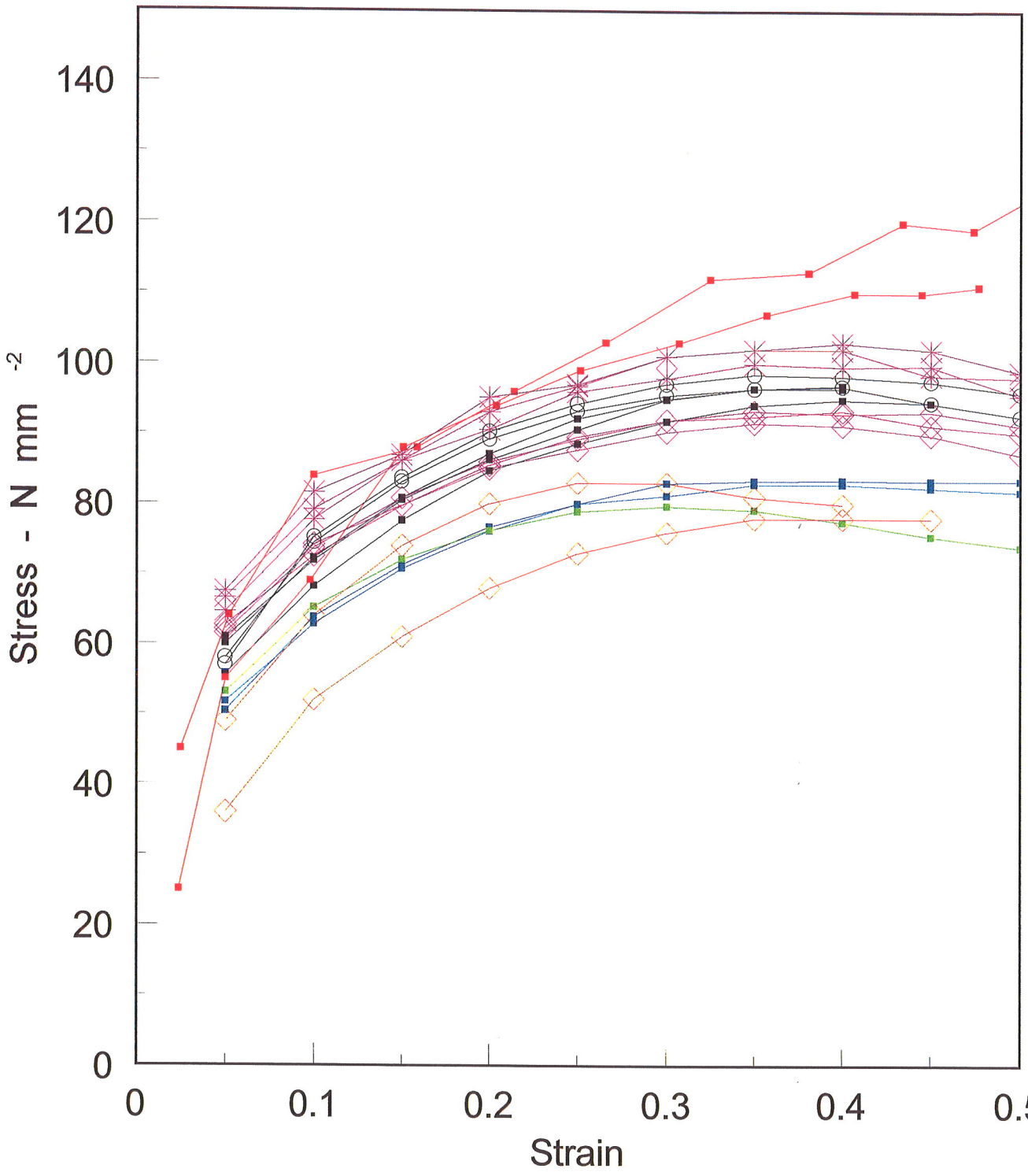
Nimonic 901 - Strain rate, 10



Low C-Mn Steel - Strain rate, 0.1



Low C-Mn Steel - Strain rate, 1



66 - 1 sh
67 - 1 sh
46 - 1 sw
8 - 1 sw
24 - 1 sw
44 - 1 c
13 - 1 imi
14 - 1 imi
15 - 1 mpd

56 - 1 mpd
33 - 1 bsteel
17 - 1 bsteel
77(8x12) Oulu
78(8x12) Oulu
84(8x12) Oulu
12(10x15) Oulu
52(10x15) Oulu
62(10x15) Oulu

Low C-Mn Steel - Strain rate, 10

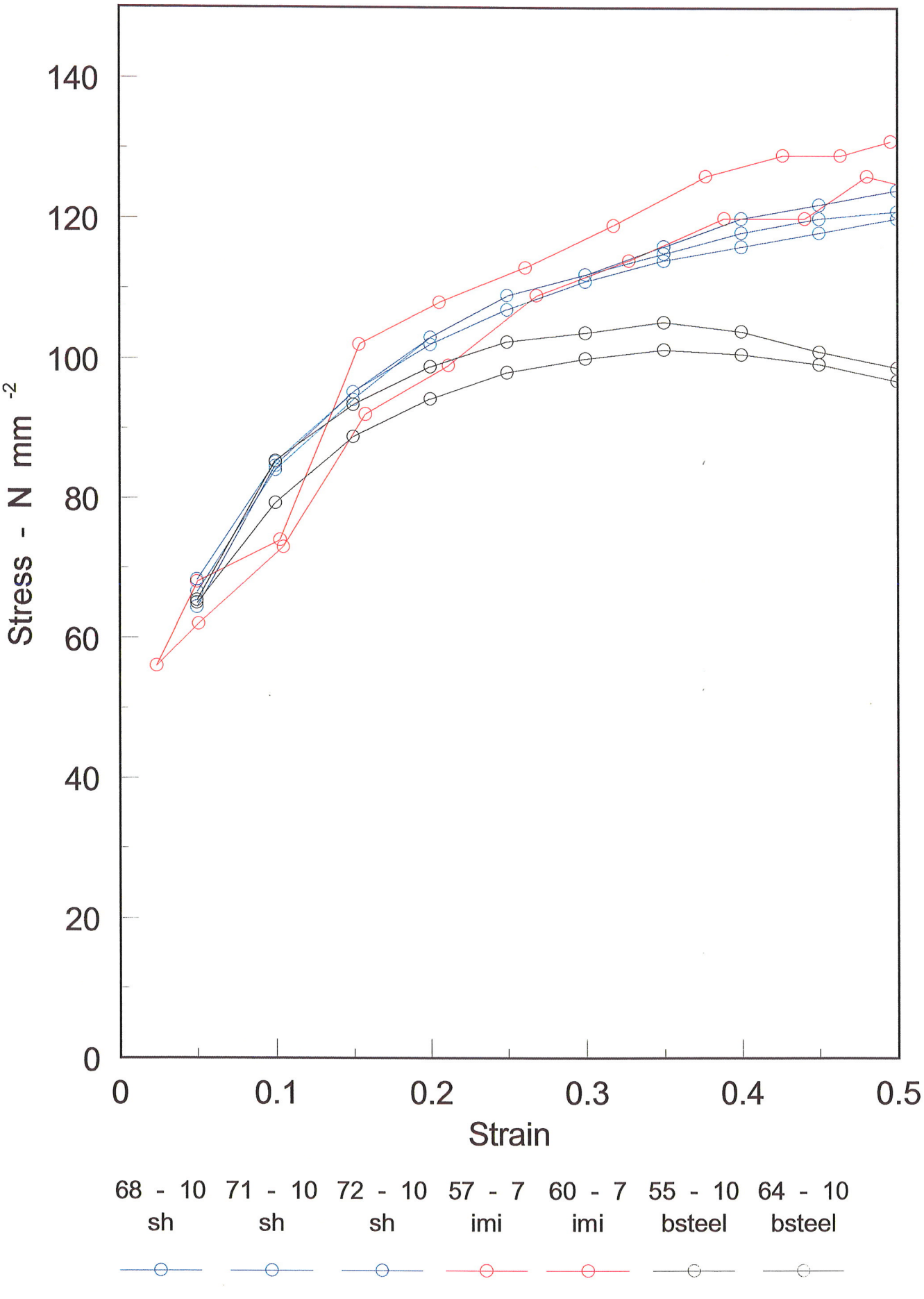
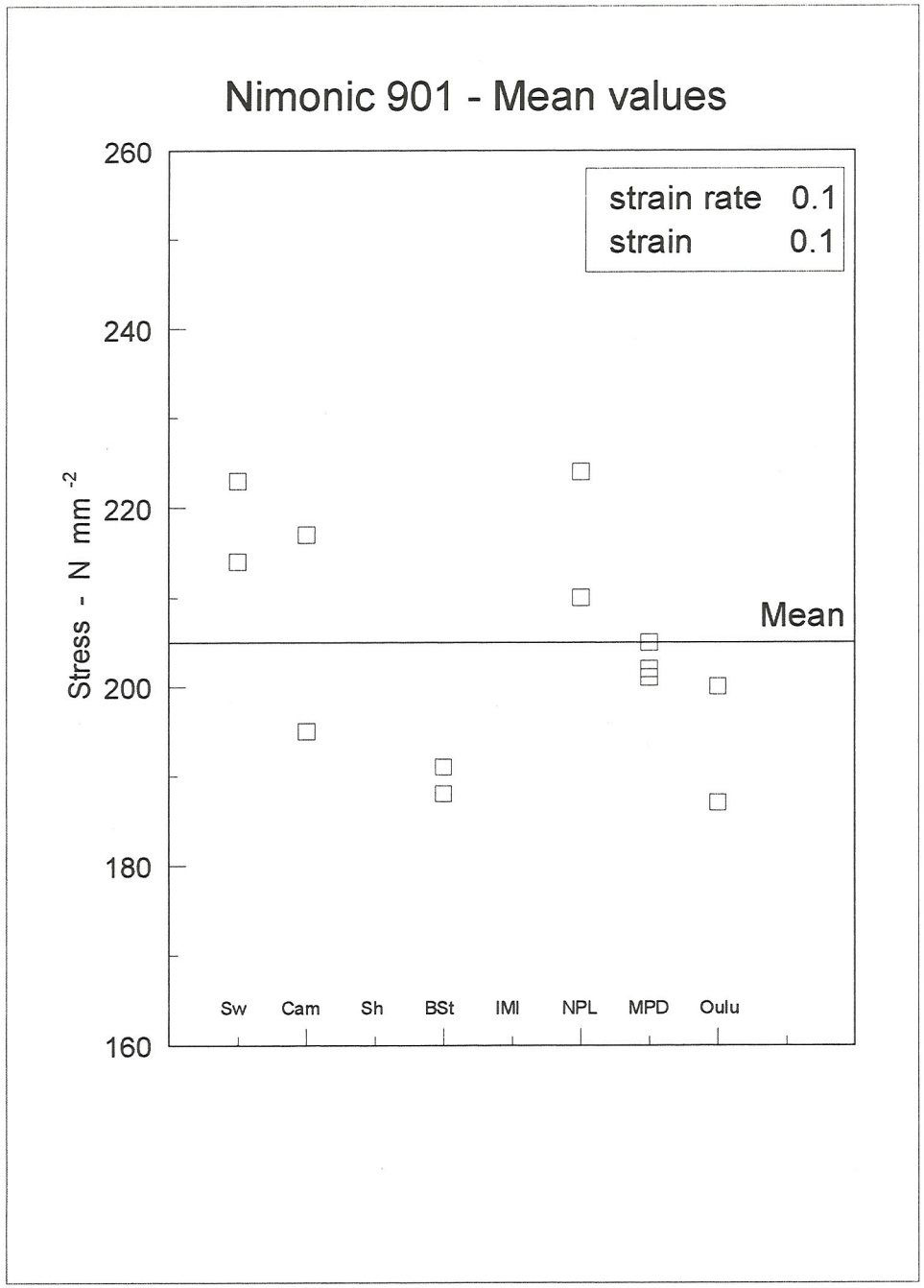
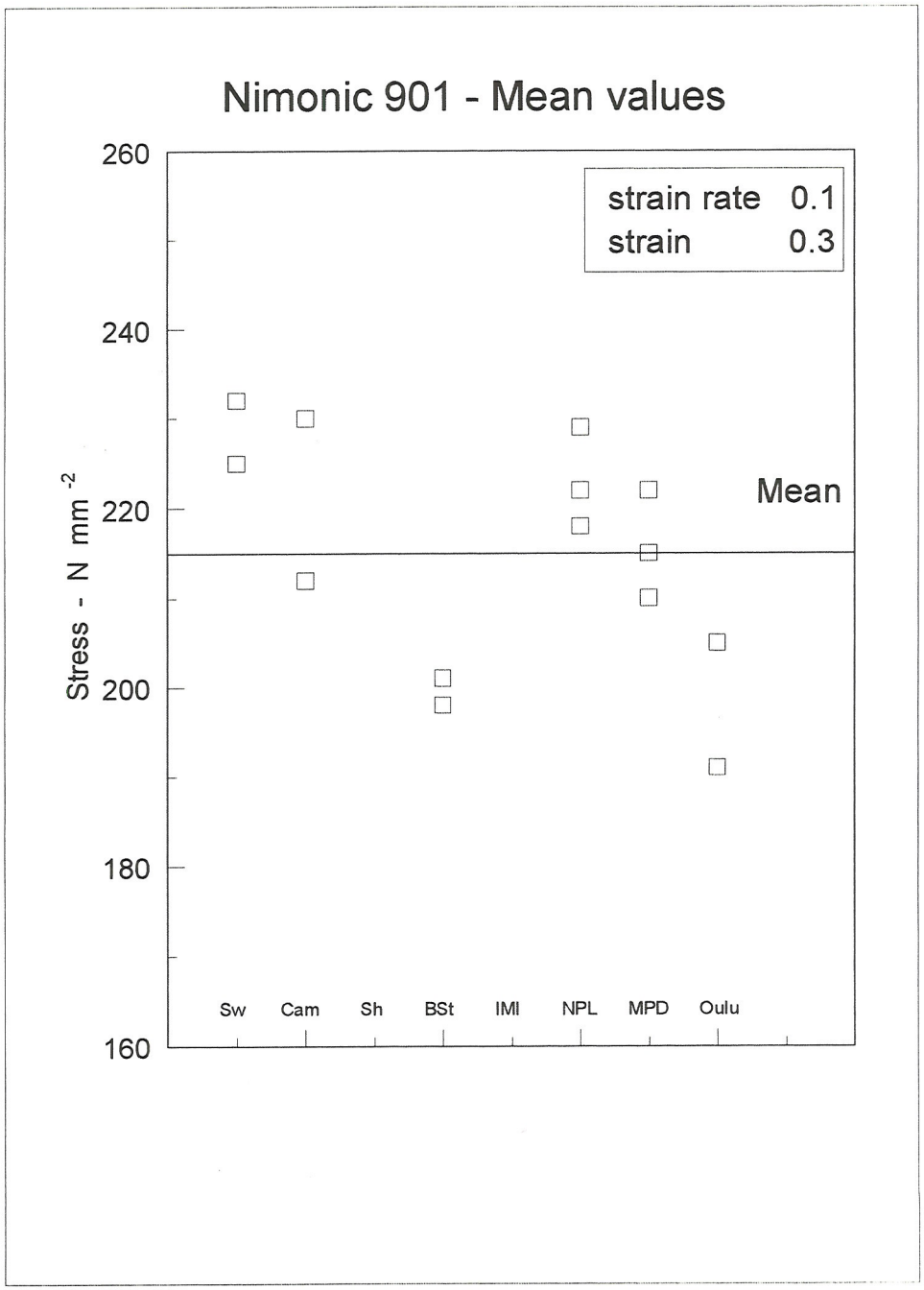
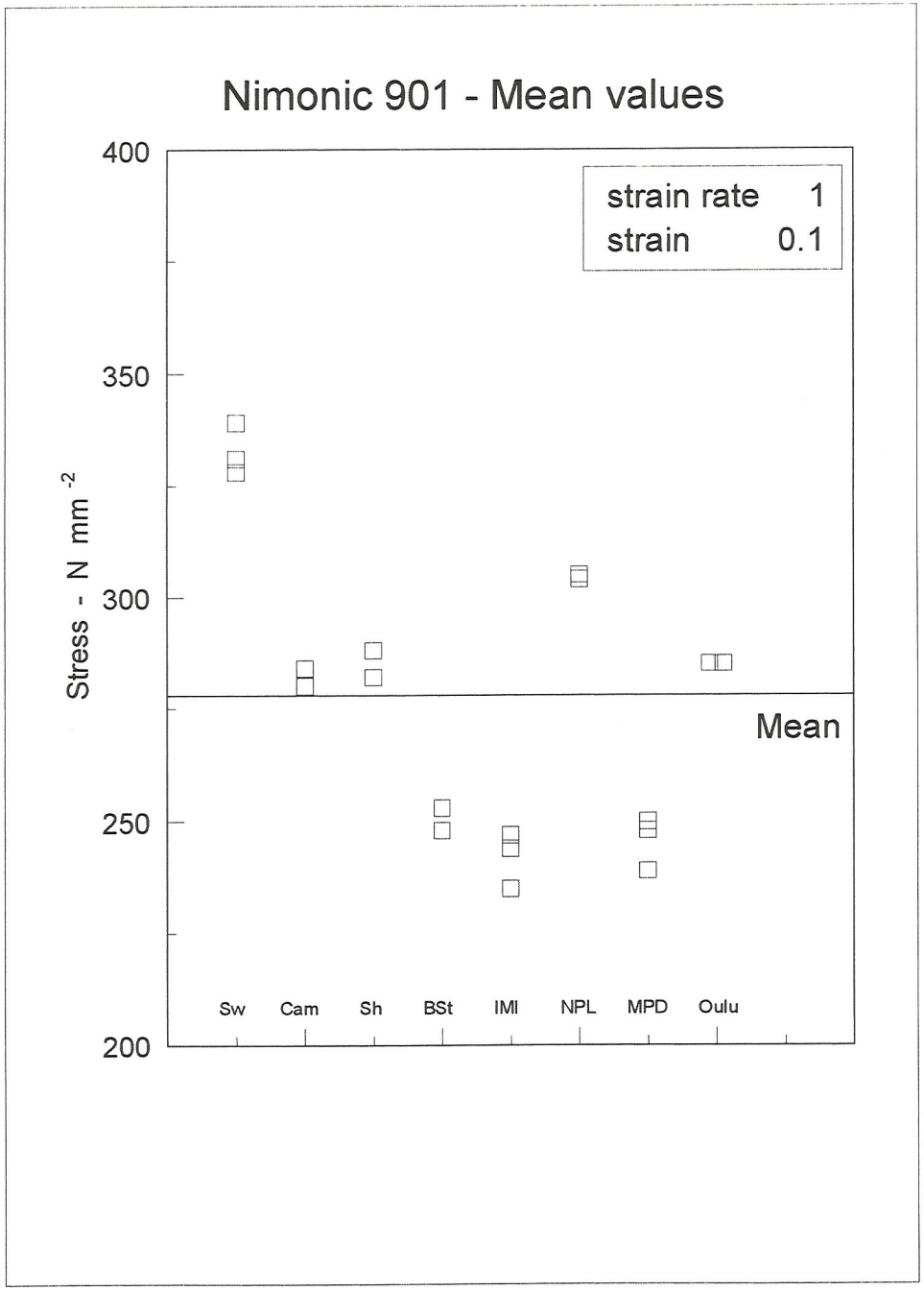
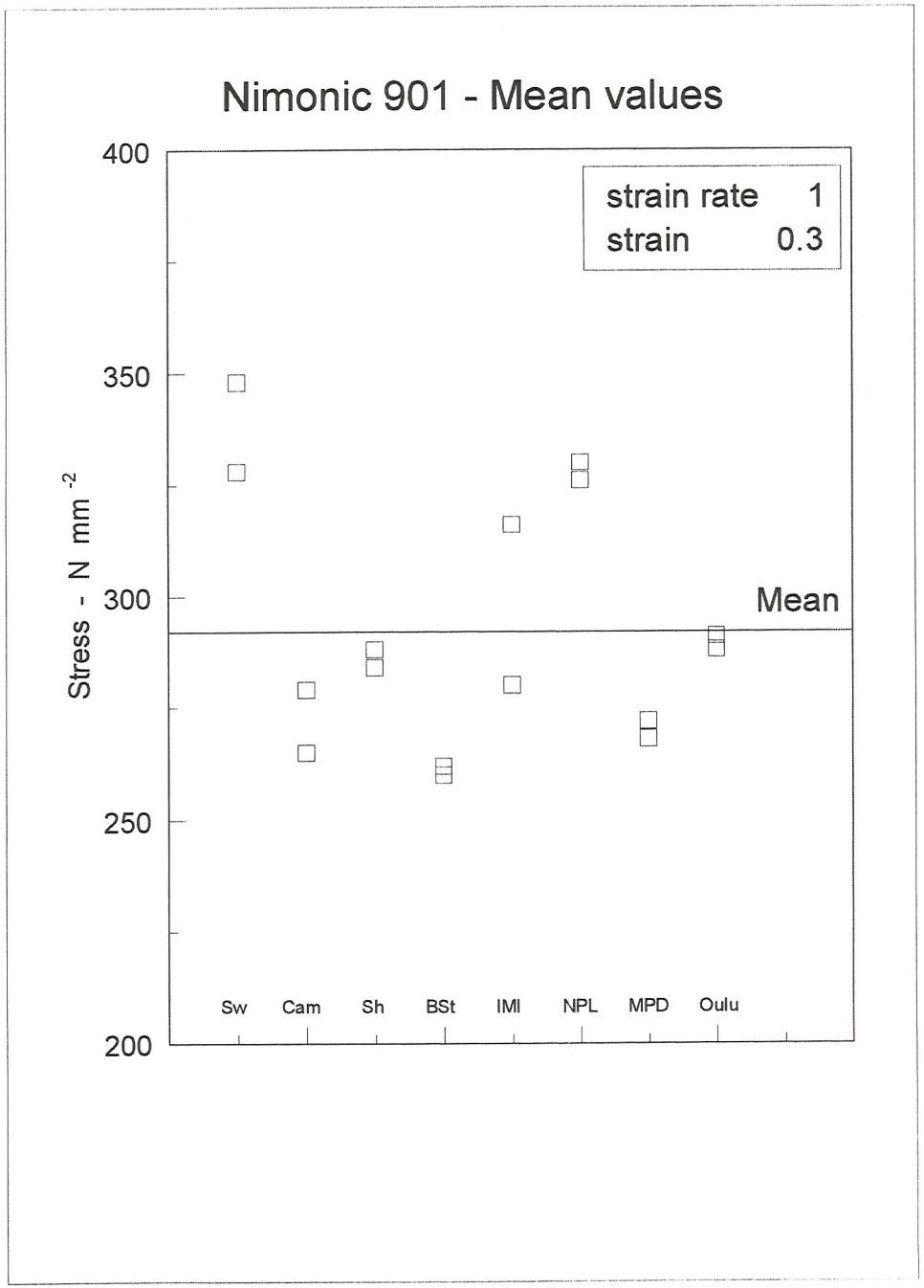


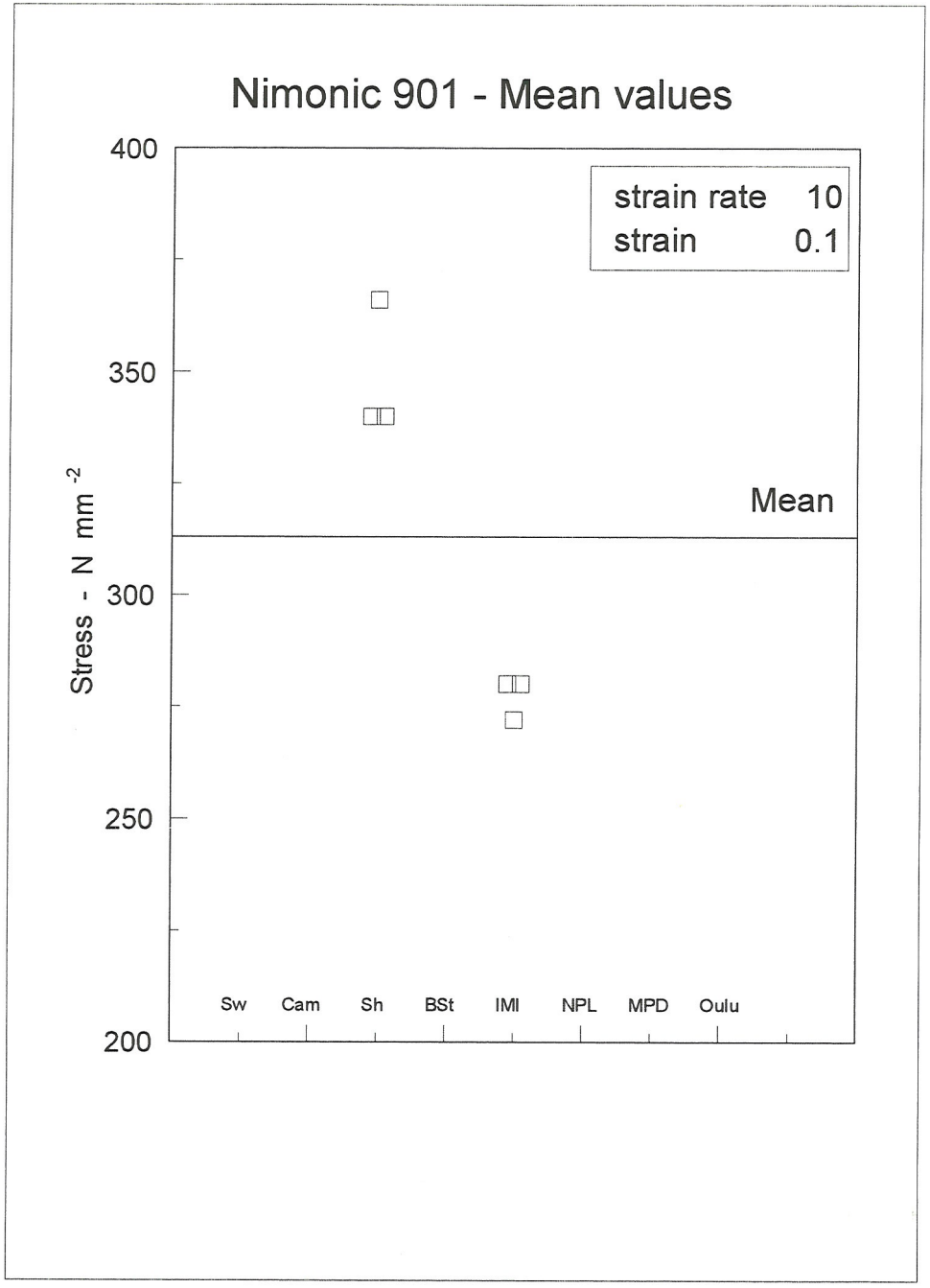
Fig 7 Comparison of mean flow stresses with overall mean value for each organisation.

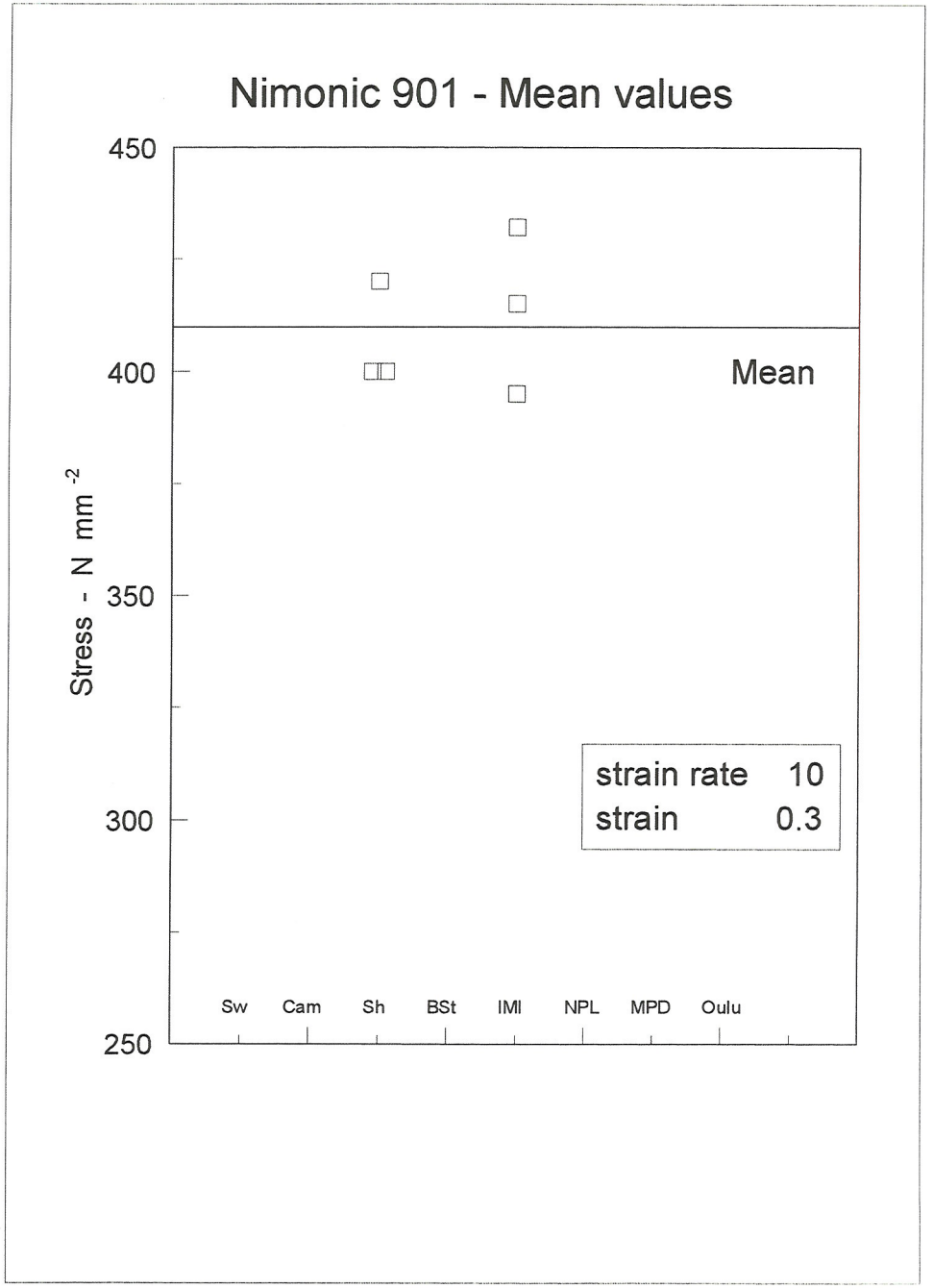

Nimonic 901 - Mean values
strain rate 0.1
strain 0.1
Mean
Stress - N mm -2
260
240
220
200
180
160
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

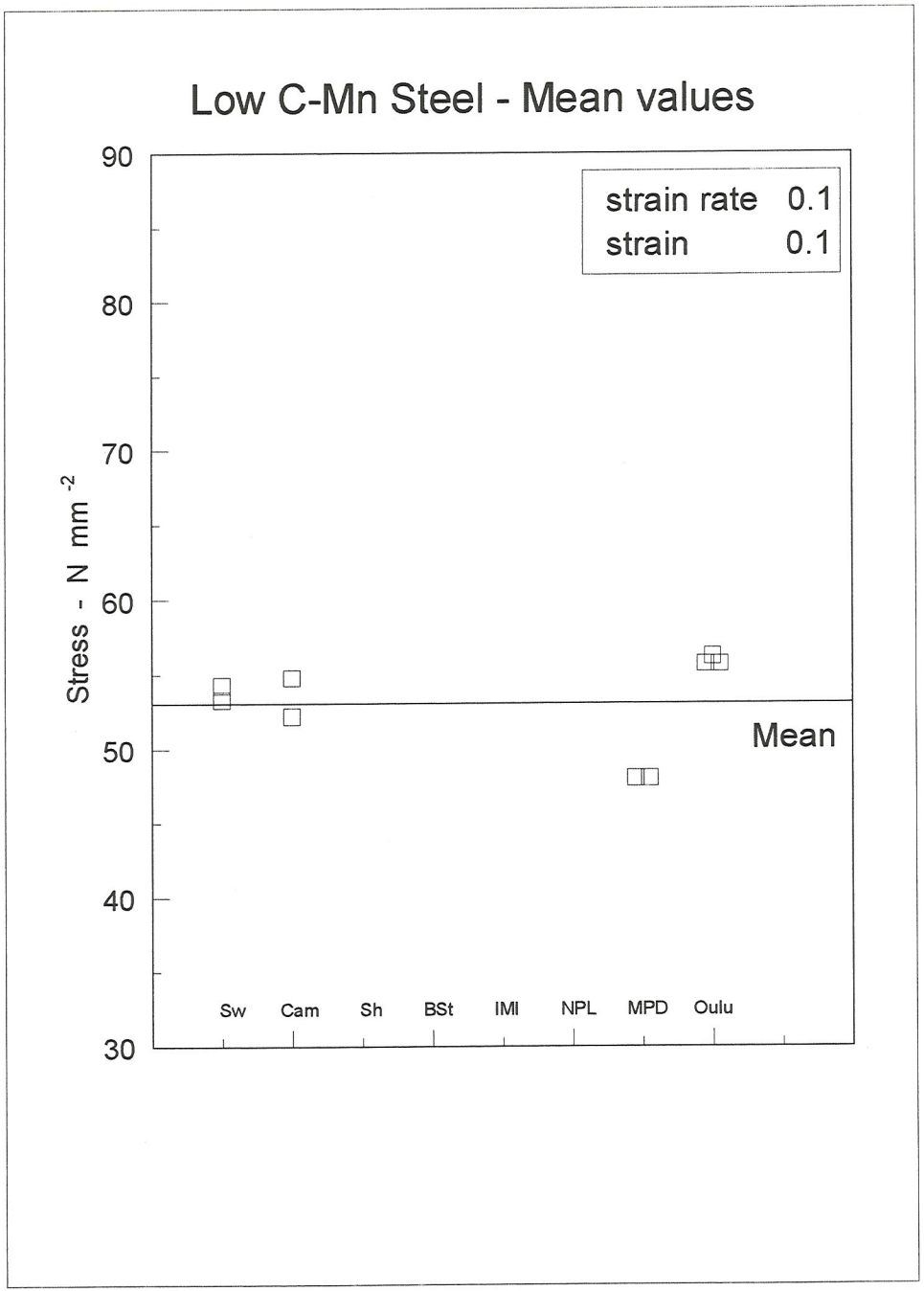

Nimonic 901 - Mean values
strain rate 0.1
strain 0.3
Mean
Stress - N mm -2
260
240
220
200
180
160
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

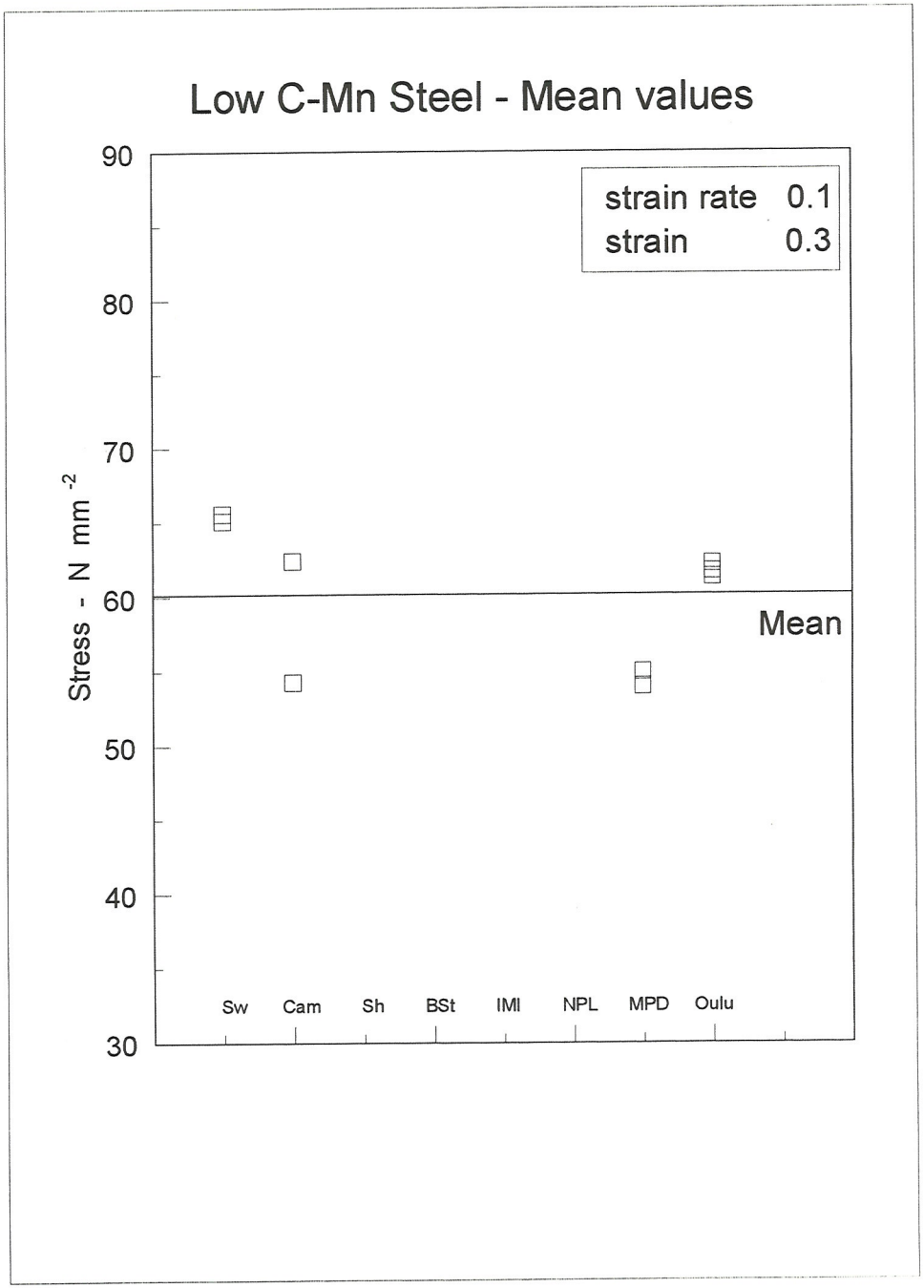

Nimonic 901 - Mean values
strain rate 1
strain 0.1
Stress - N mm -2
400
350
300
250
200
Mean
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

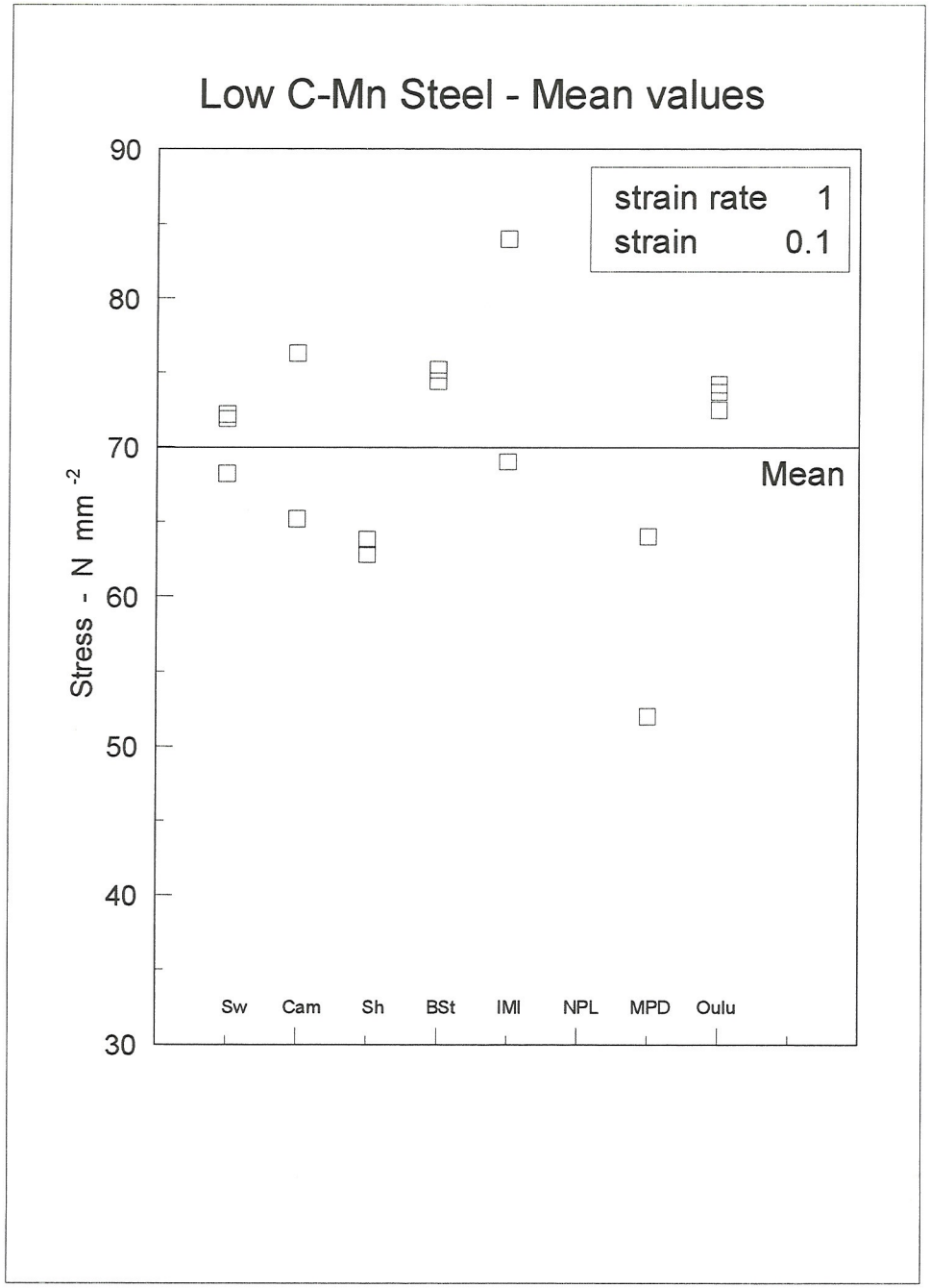

Nimonic 901 - Mean values
strain rate 1
strain 0.3
Stress - N mm -2
400
350
300
250
200
Mean
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

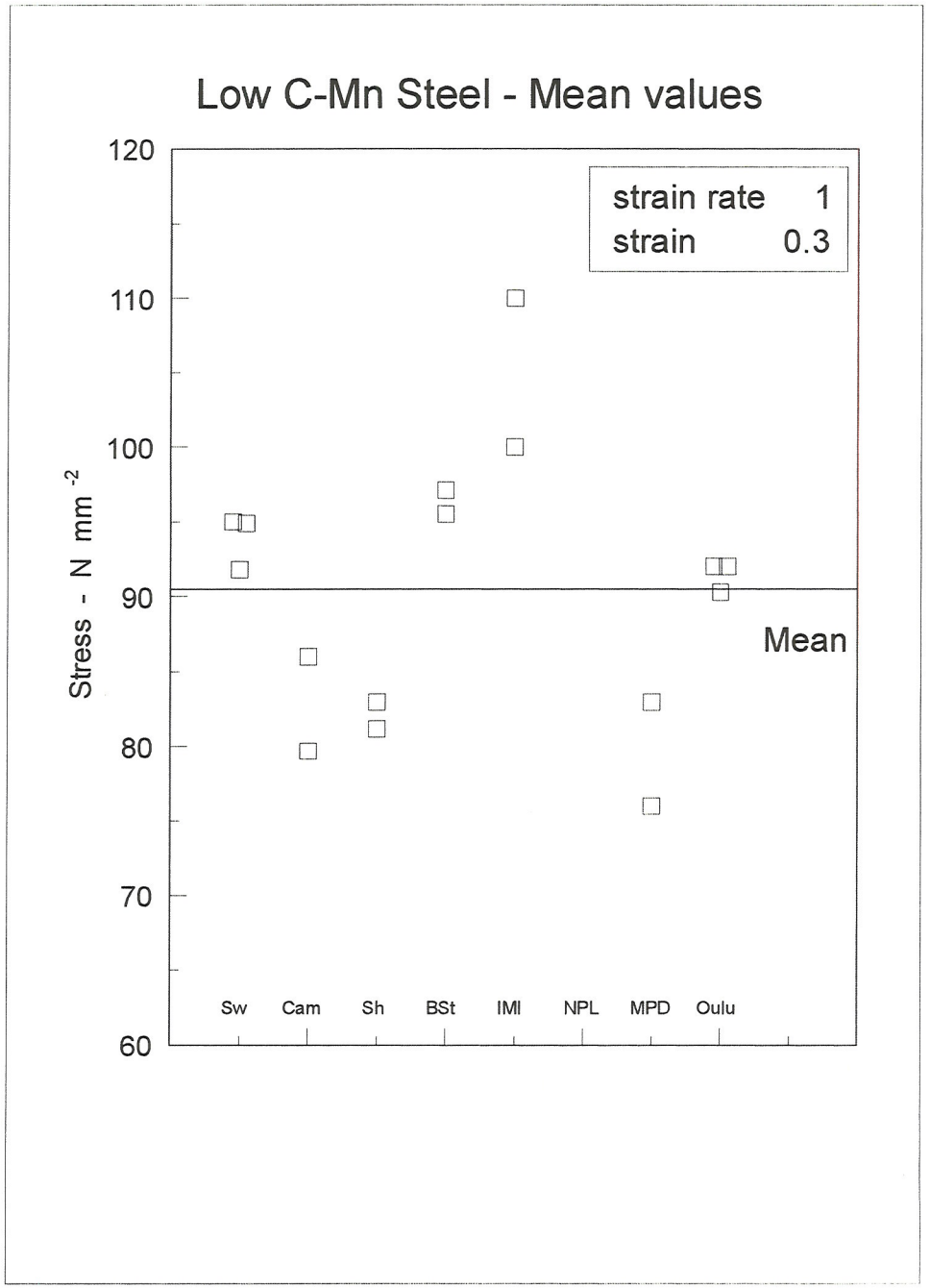

Nimonic 901 - Mean values
400
350
300
250
200
Stress - N mm -2
strain rate 10
strain 0.1
Mean
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

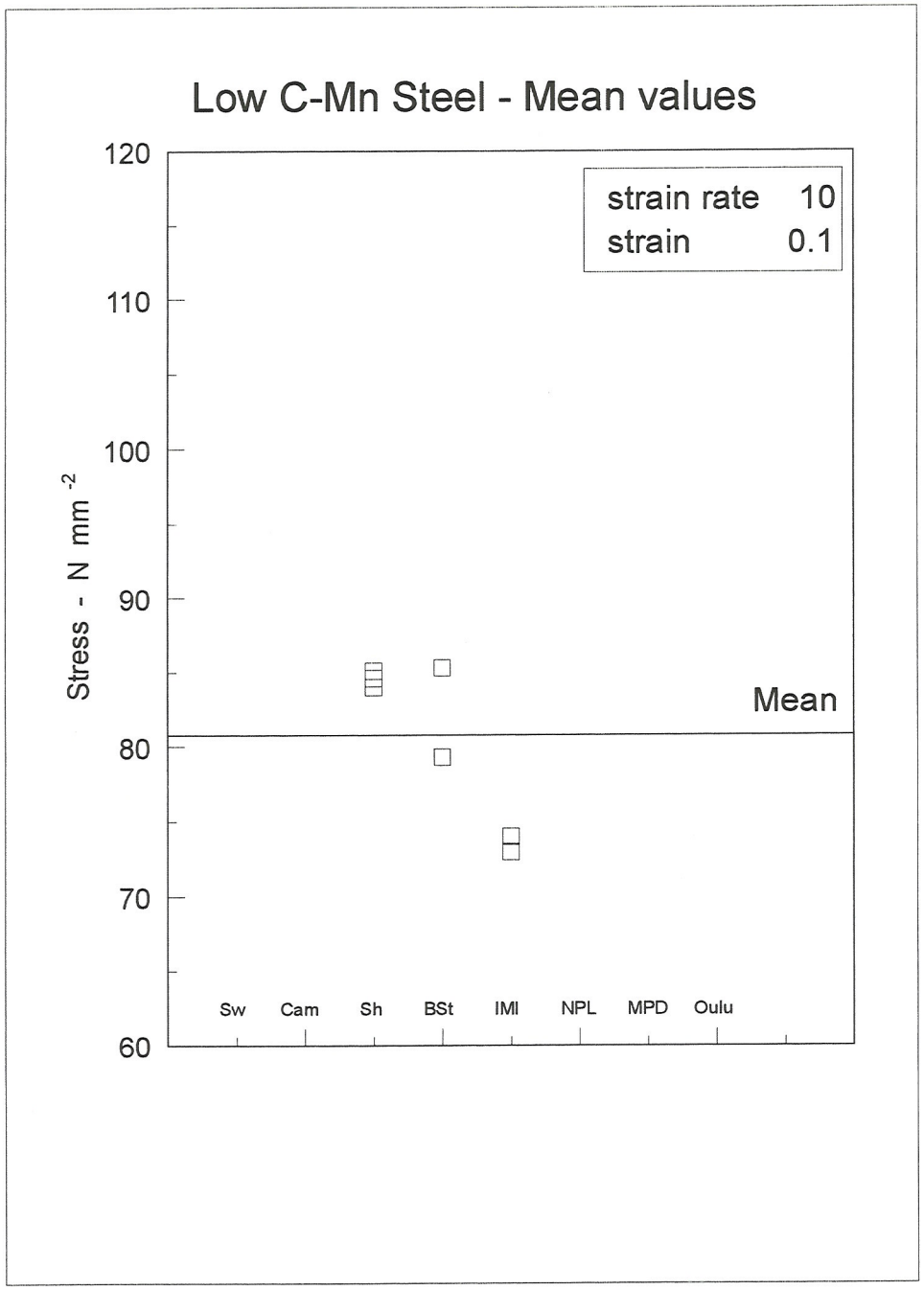

Nimonic 901 - Mean values
450
400
350
300
250
Stress - N mm -2
Mean
strain rate 10
strain 0.3
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

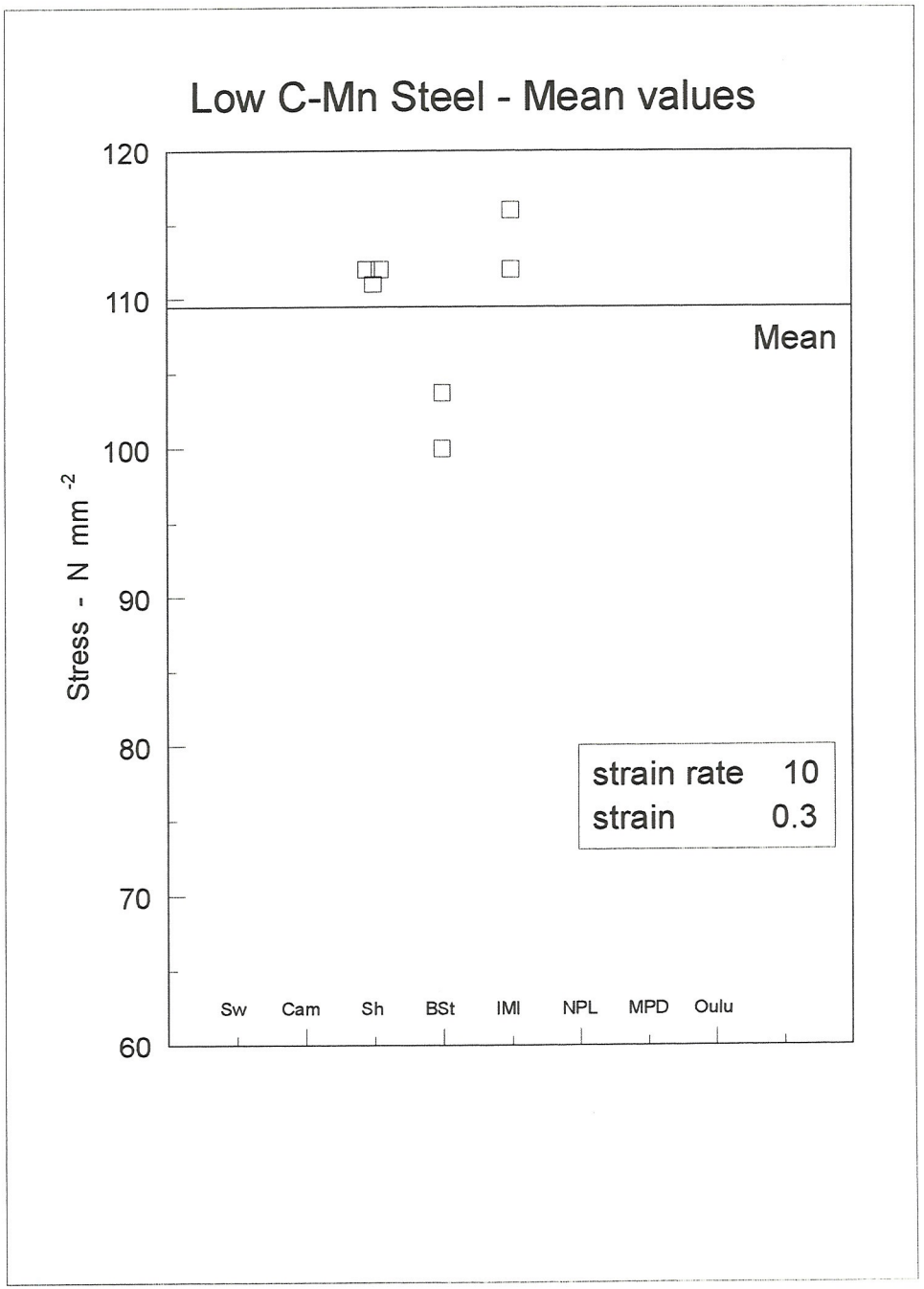

Low C-Mn Steel - Mean values
strain rate 0.1
strain 0.1
Mean
Stress - N mm -2
90
80
70
60
50
40
30
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu


Low C-Mn Steel - Mean values
strain rate 0.1
strain 0.3
Mean
Stress - N mm -2
90
80
70
60
50
40
30
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu


Low C-Mn Steel - Mean values
strain rate 1
strain 0.1
Mean
Stress - N mm -2
90
80
70
60
50
40
30
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu


Low C-Mn Steel - Mean values
strain rate 1
strain 0.3
Mean
Stress - N mm -2
120
110
100
90
80
70
60
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu


Low C-Mn Steel - Mean values
strain rate 10
strain 0.1
Mean
Stress - N mm -2
120
110
100
90
80
70
60
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu


Low C-Mn Steel - Mean values
Mean
strain rate 10
strain 0.3
Stress - N mm -2
120
110
100
90
80
70
60
Sw
Cam
Sh
BSt
IMI
NPL
MPD
Oulu

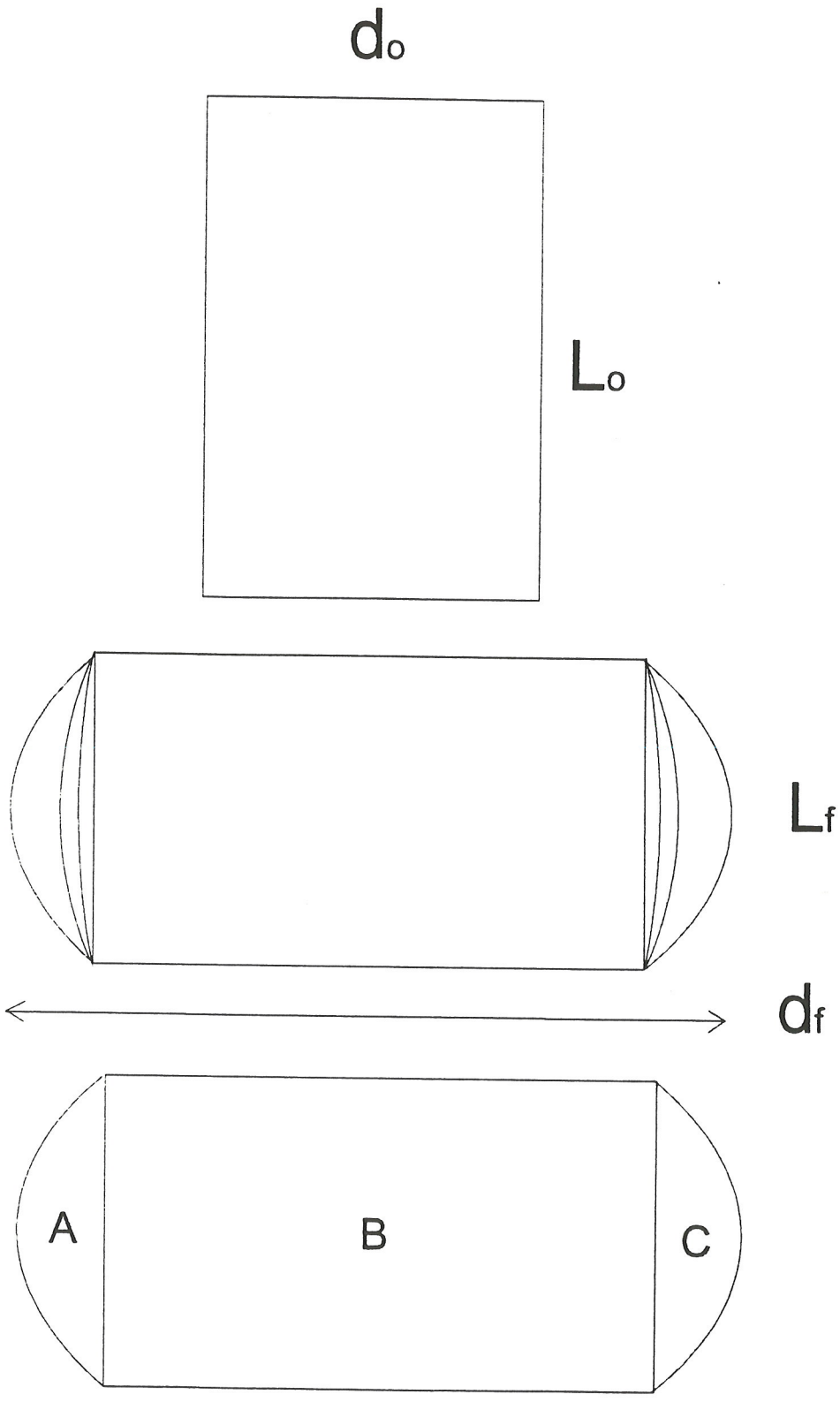


Fig 8 Schematic diagrams of barrelling.

APPENDIX A

Interlaboratory Exercise

Hot Axisymmetric Compression

Representative Force - Displacement (Diameter) Curves

Machine Output

Nimonic 901	1000 °C
Low C-Mn Steel	1100 °C

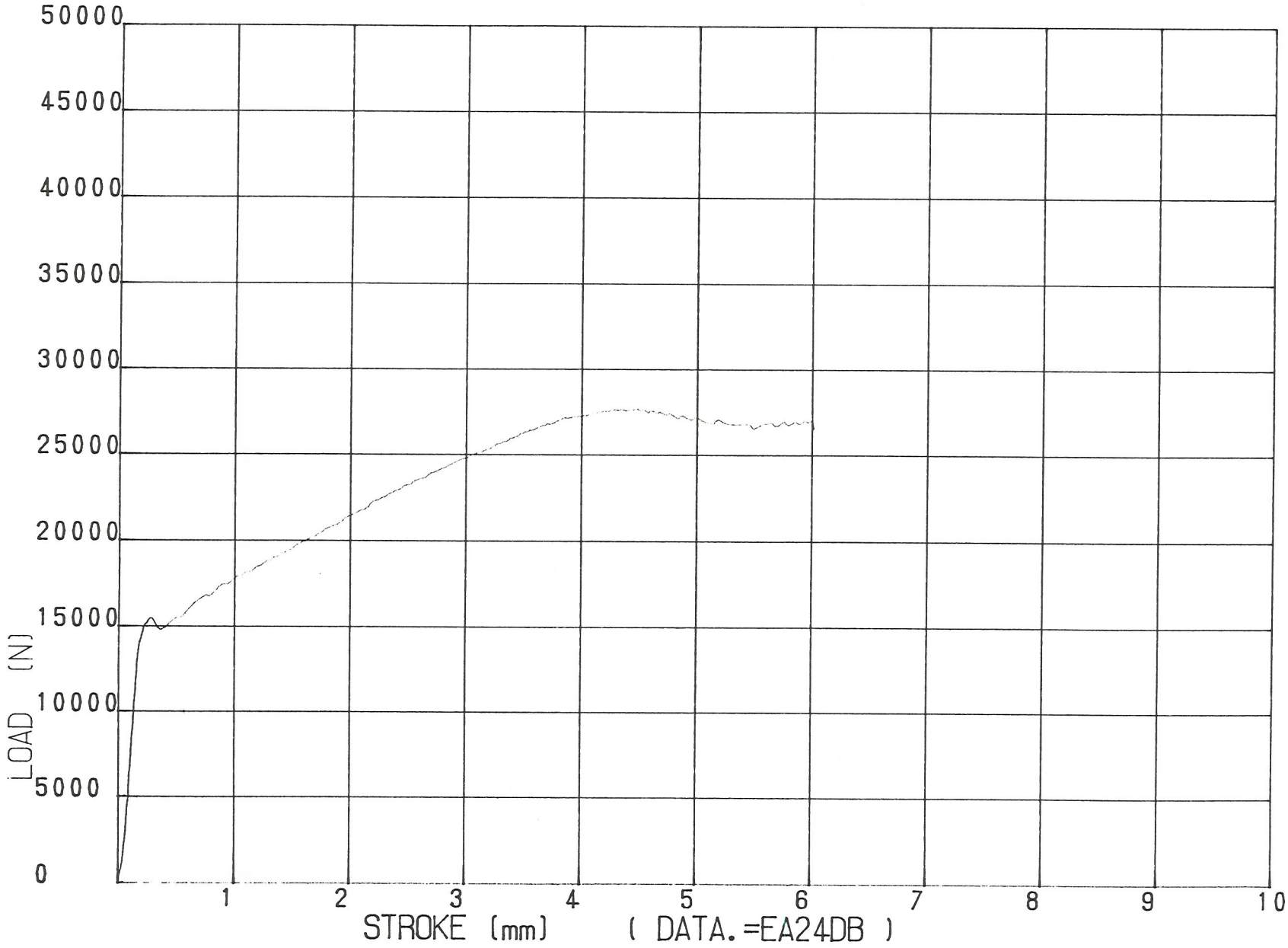
Strain Rates	0.1, 1, 10	s^{-1}

Nimonic 901

Strain Rate 0.1 s^{-1}

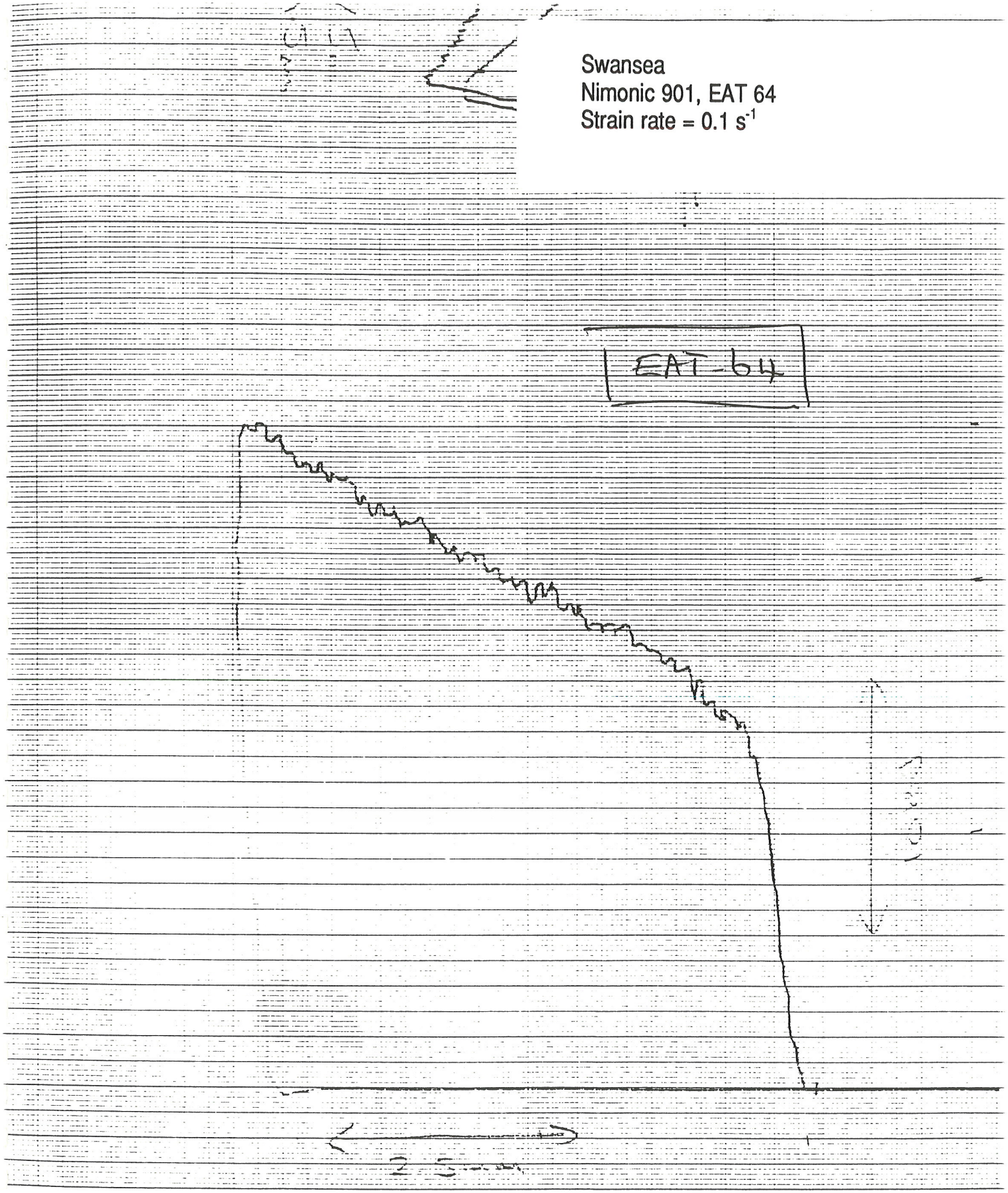
Cambridge	EAT 24
Swansea	EAT 64
British Steel	EAT 76
NPL	EAT 55
MPD	EAT 25
Oulu [diametral strain]	EAT 66,69 (plus EAT 70,75 1 s^{-1})

Cambridge
Nimonic 901
0.1 s^{-1}



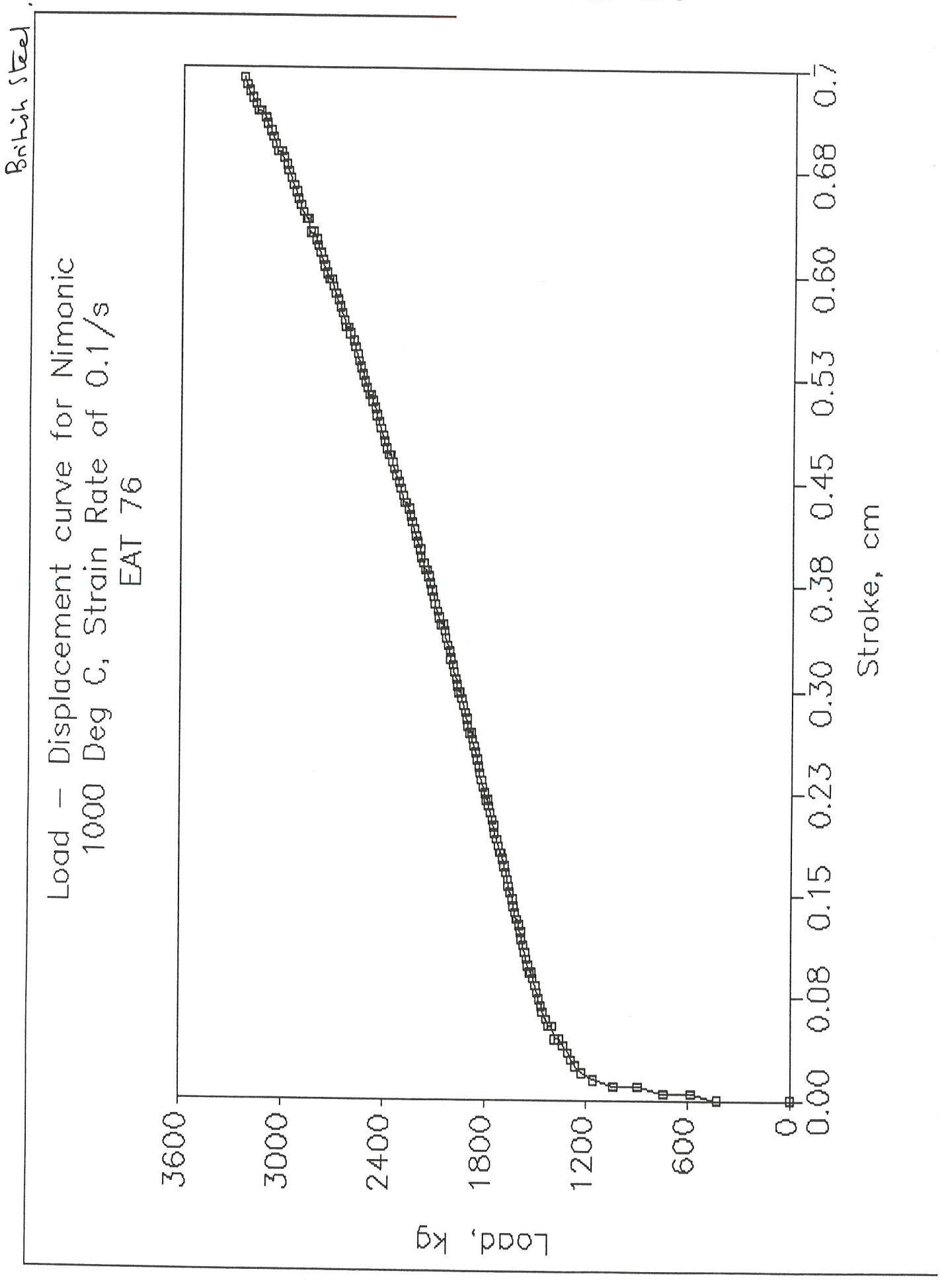
Cambridge
Nimonic 901, EAT 24
Strain rate = 0.1 s^{-1}

Swansea
Nimonic 901, EAT 64
Strain rate = 0.1 s^{-1}



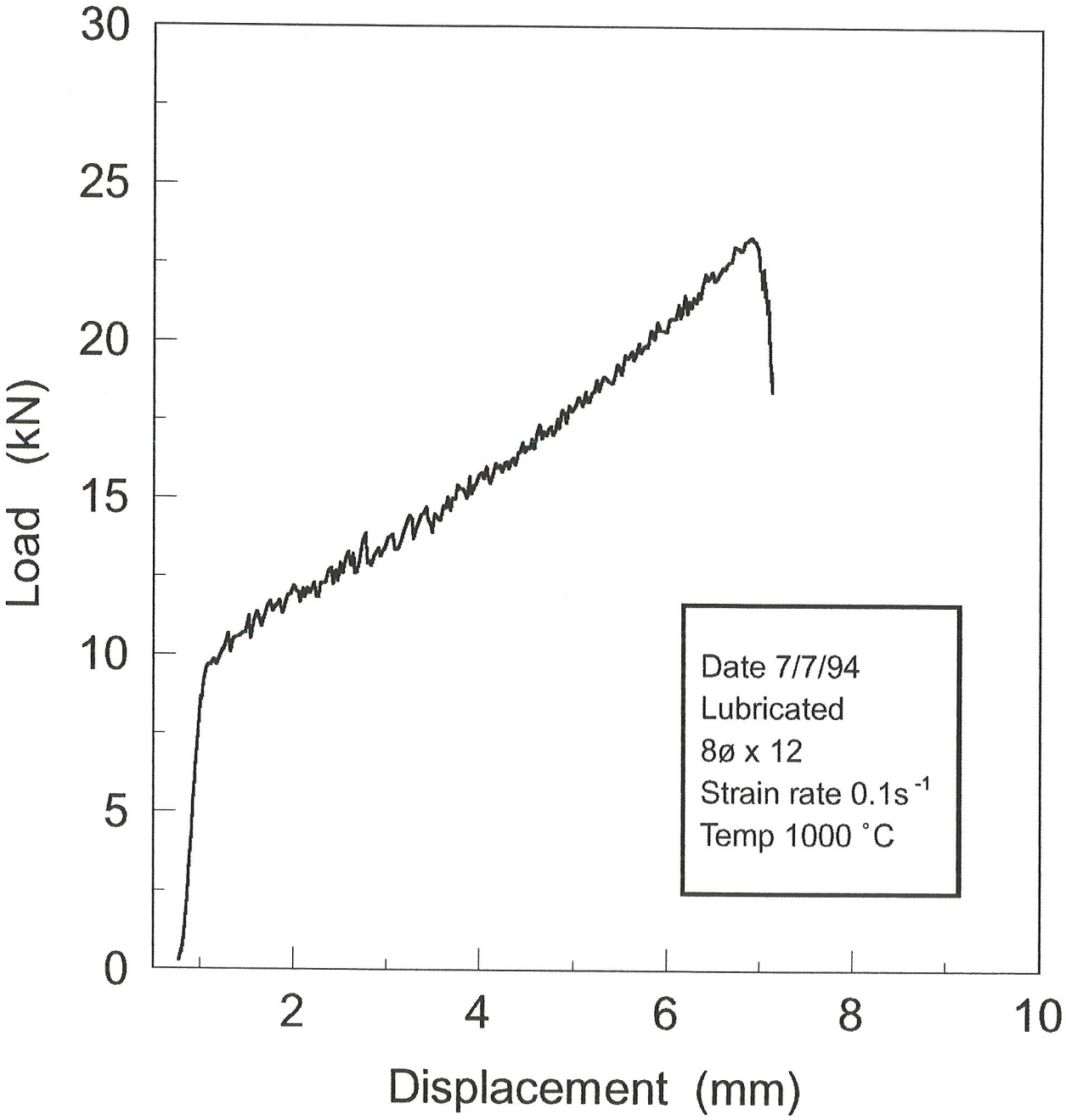
Swansea
Nimonic 0.1 s^{-1}

British Steel
Nimonic 901, EAT 76
Strain rate = 0.1 s^{-1}

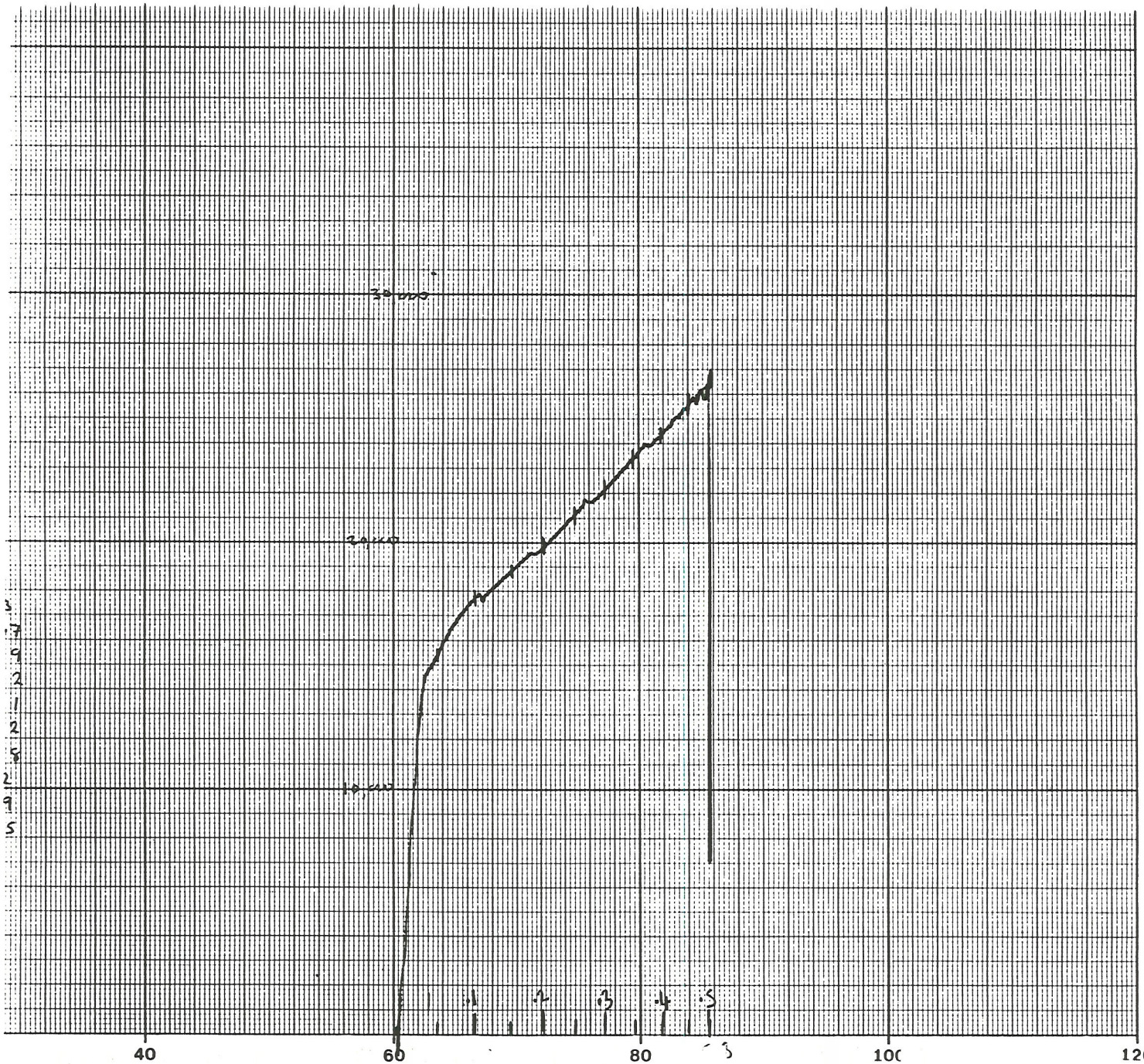


NPL
Nimonic 901, EAT 55
Strain rate = 0.1 s^{-1}

EAT55 : Load - displacement



Nimonic 0.1 s⁻¹
MPD



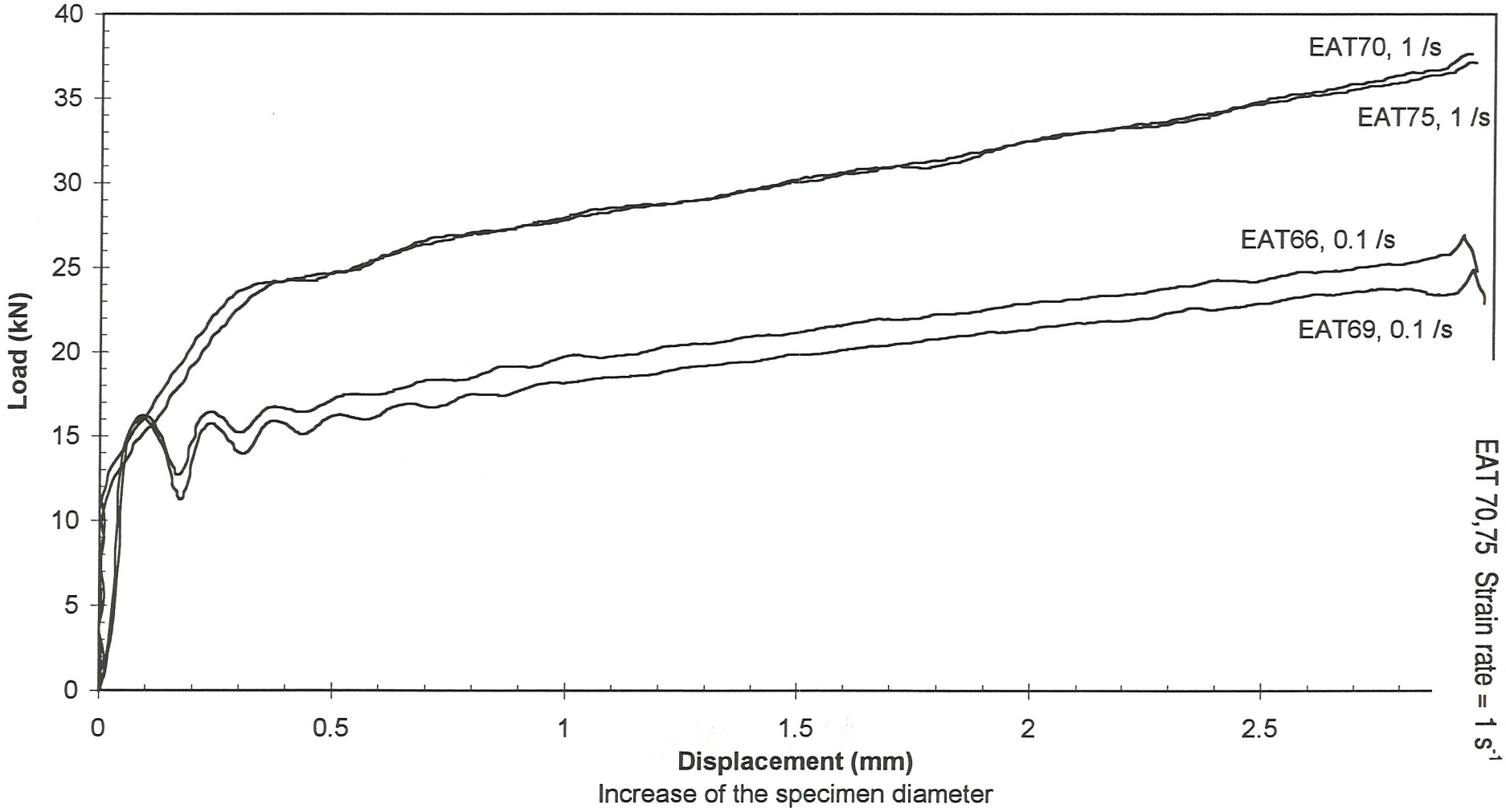
Test System Test Machine Type No. Zwick	
Sample Grips	
Load Cell	200 kN
Extensometer	
Sample Material	NPL N901
Sample Type (Standard)	
Width/Diameter	9.98 mm ϕ
Thickness	
Initial Gauge Length L_o	15.0
Grip Separation	
Test Paramet Crosshead Sp	
Co-ordinates	
Load Ratio kN	
Extension Co-	
Extension Rati	
Time Co-ordin	
Time Ratio t/1	
Notes	10
Date Tested by	

MPD
Nimonic 901, EAT 25
Strain rate = 0.1 s^{-1}

Order ... Ger ZI
Orde... Frei ZN

Oulu

Nimonic 901, 1000°C

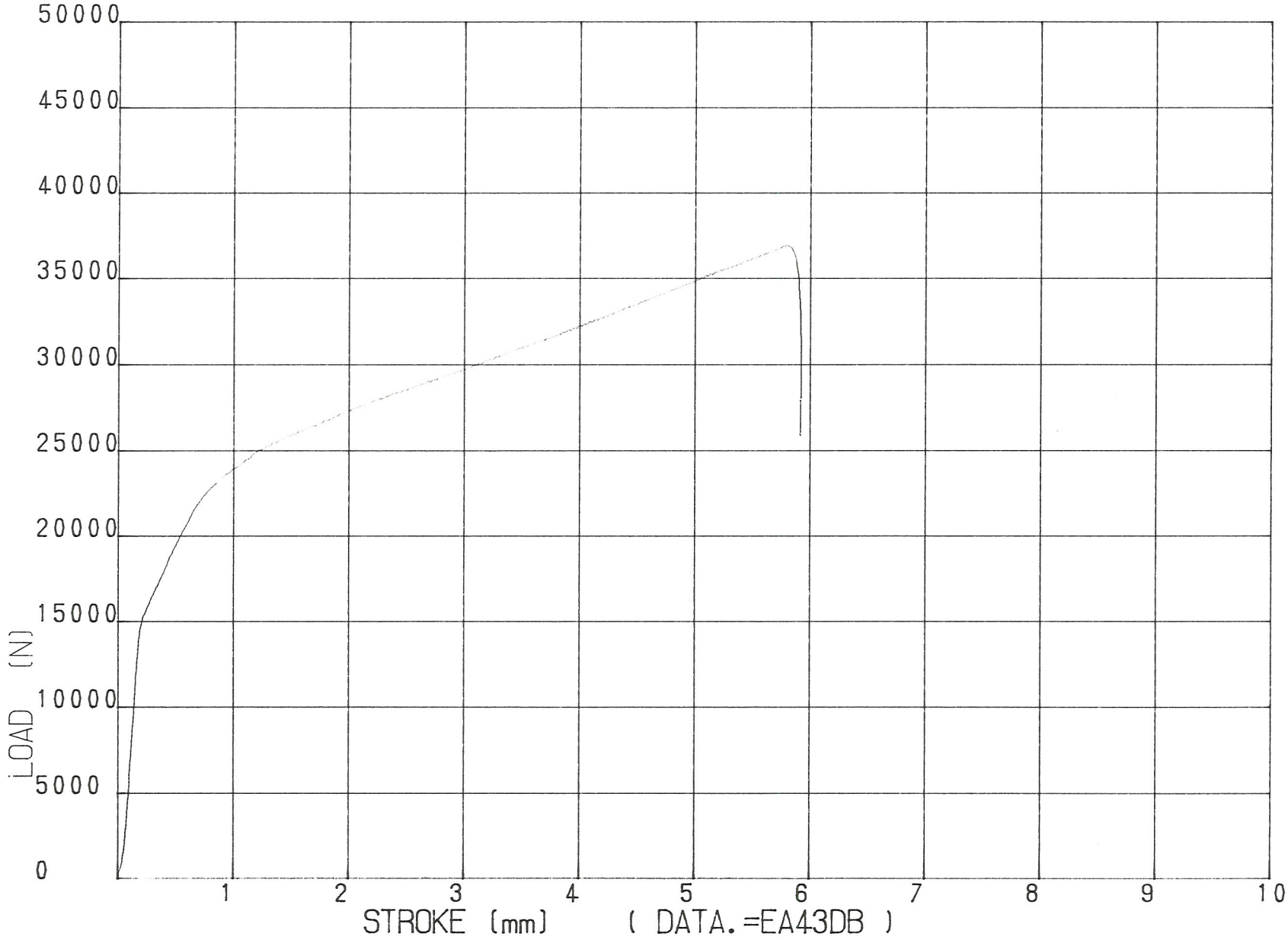


Nimonic 901

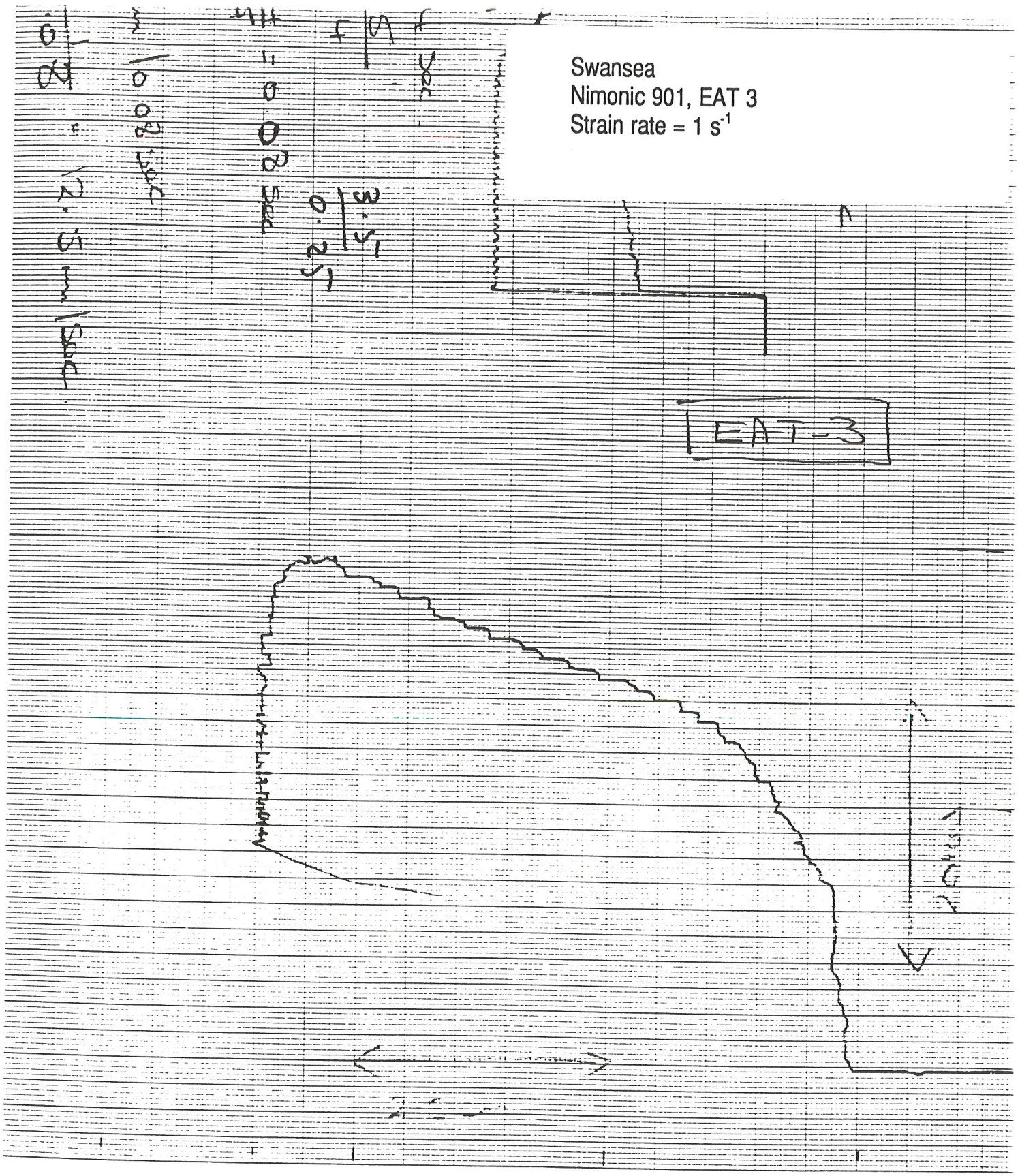
Strain Rate 1 s^{-1}

Cambridge	EAT 43
Swansea	EAT 3
Sheffield	EAT 66
British Steel	EAT 73
NPL	EAT 30
MPD	EAT 19

Cambridge Nimonic 901
1 s⁻¹



Cambridge
Nimonic 901, EAT 43
Strain rate = 1 s^{-1}

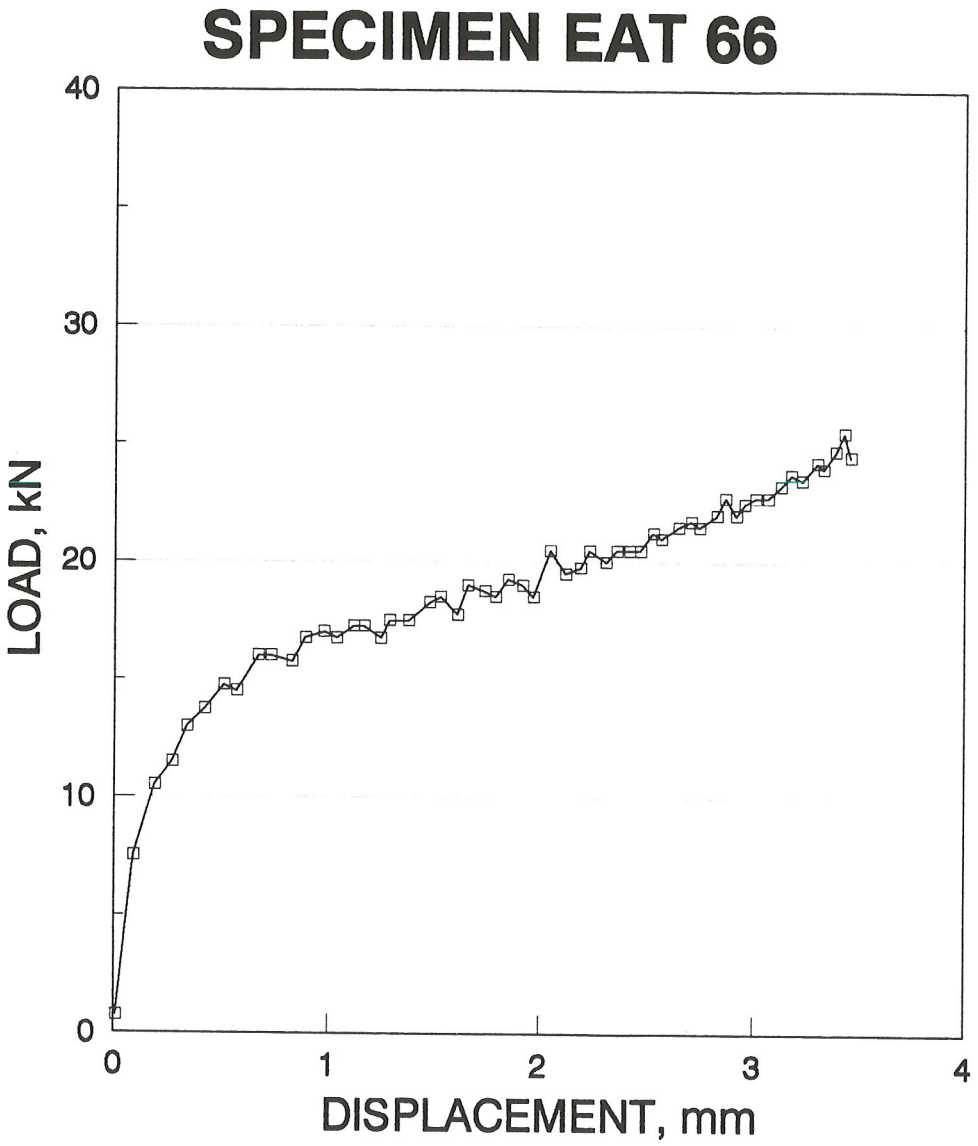


Y..... mV/cm Datum Nr:

Name:

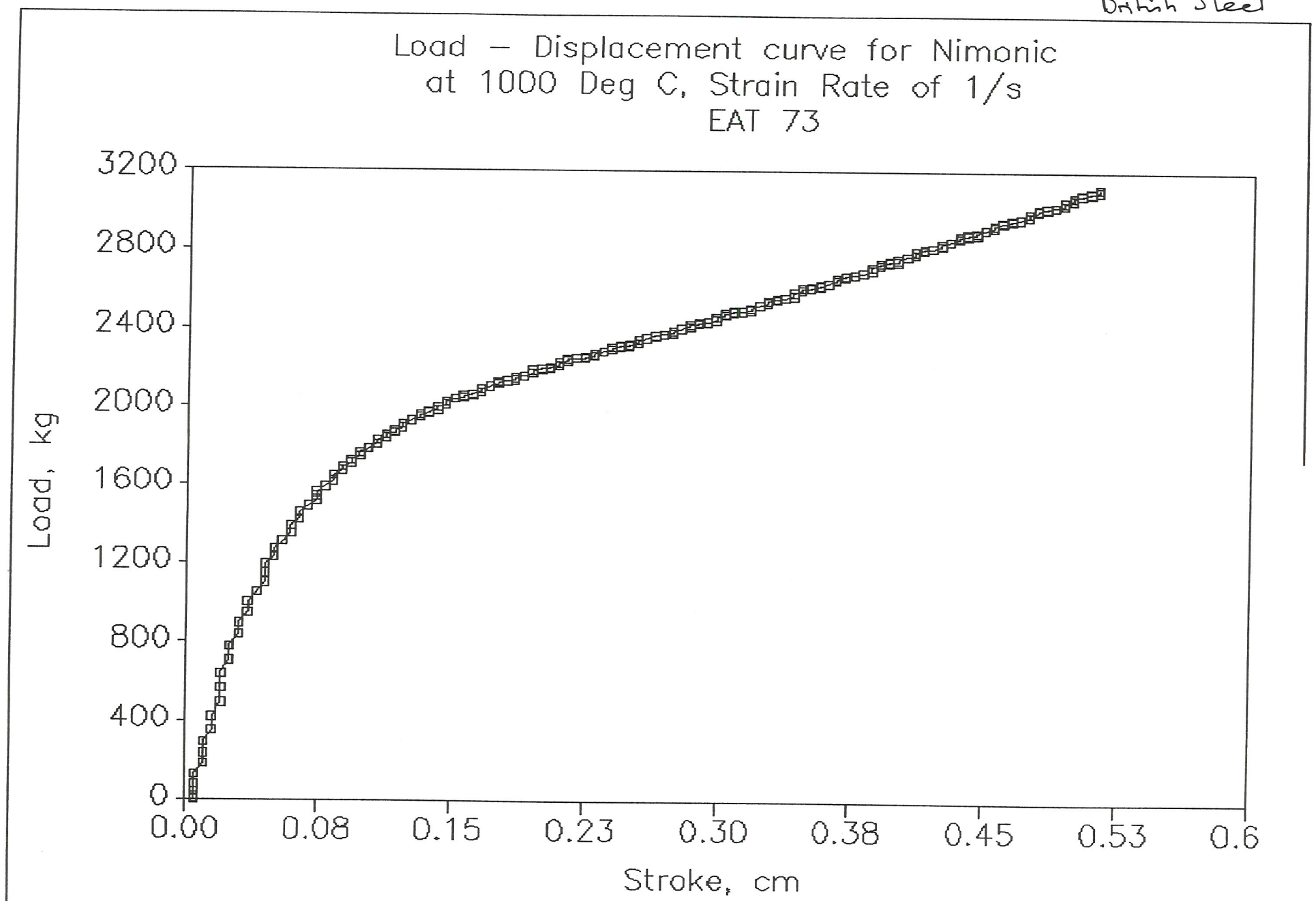
Swansea
Nimonic 1 s-1

Sheffield
Nimonic 901, EAT 66
Strain rate = 1 s^{-1}



Sheffield
Nimonic 1 s^{-1}

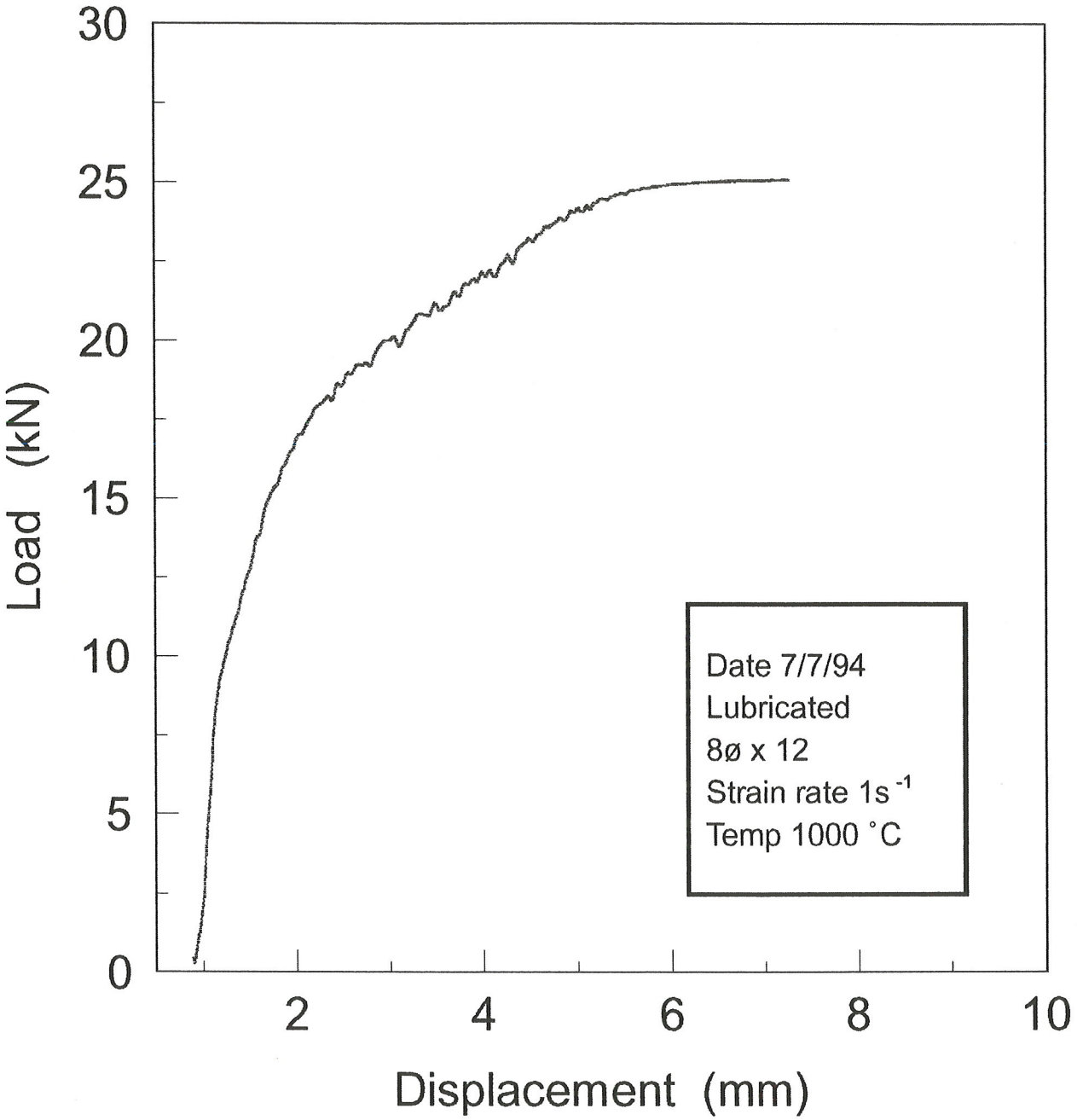
British Steel



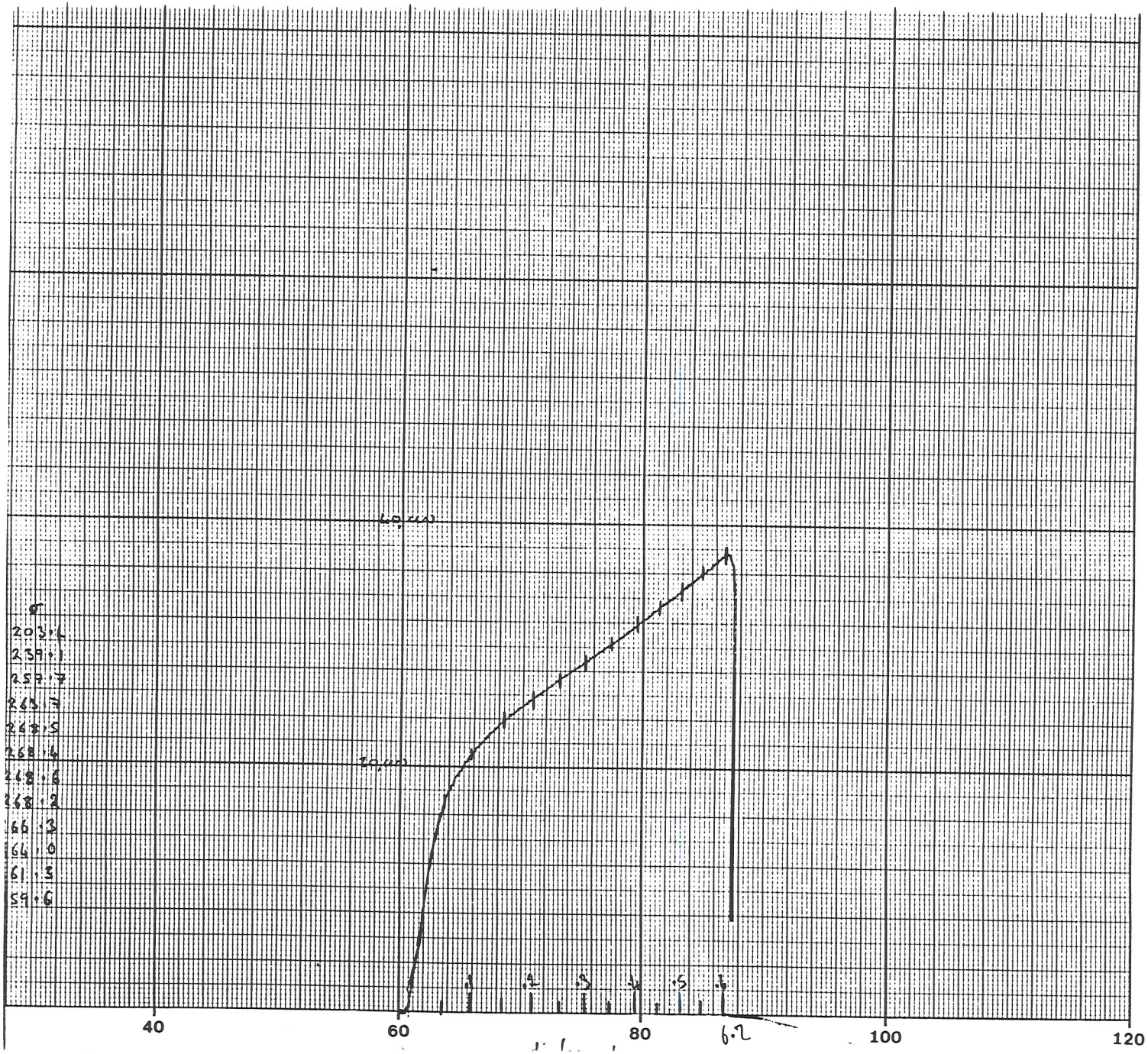
British Steel
Nimonic 901, EAT 73
Strain rate = 1 s^{-1}

NPL
Nimonic 901, EAT 30
Strain rate = 1 s^{-1}

EAT30 : Load - displacement



Nimonic
MPD 1 s-1



Test System
Test Machine Type No.
Zwick

Sample Grips

Load Cell 100kN

Extensometer

Sample
Material NR N901

Sample Type (Standard)

Width/Diameter 10.06 min ø

Thickness

Initial Gauge Length L_o 13.9

Grip Separation

Test Parameters
Crosshead Spe

Co-ordinates

Load Ratio kN/

Extension Co-c

Extension Ratio

Time Co-ordin

Time Ratio t/10

Notes

1 s

Date

Tested by

Order No. German ZN
Order No. French ZN

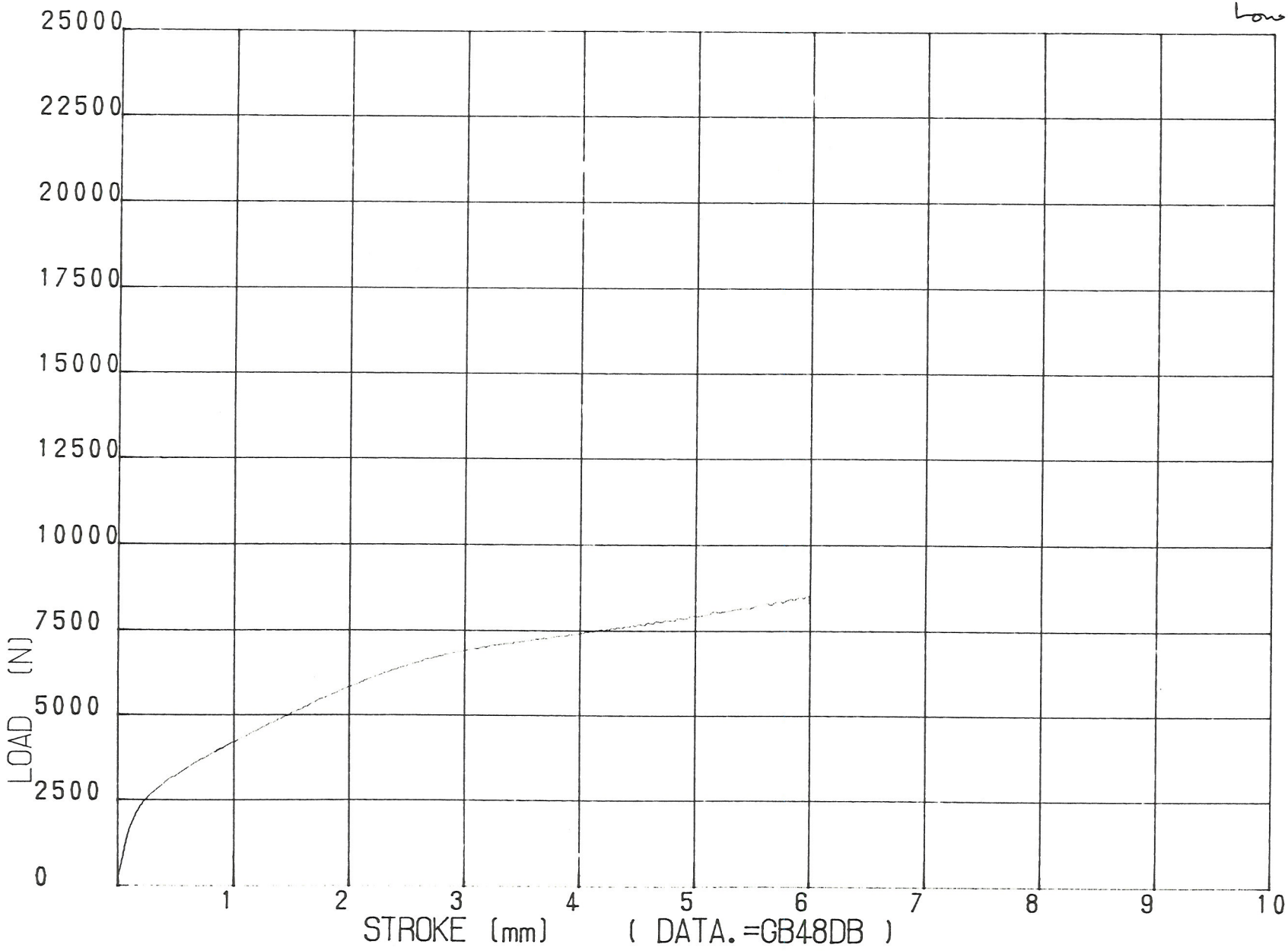
MPD
Nimonic 901, EAT 19
Strain rate = 1 s^{-1}

Low C-Mn Steel

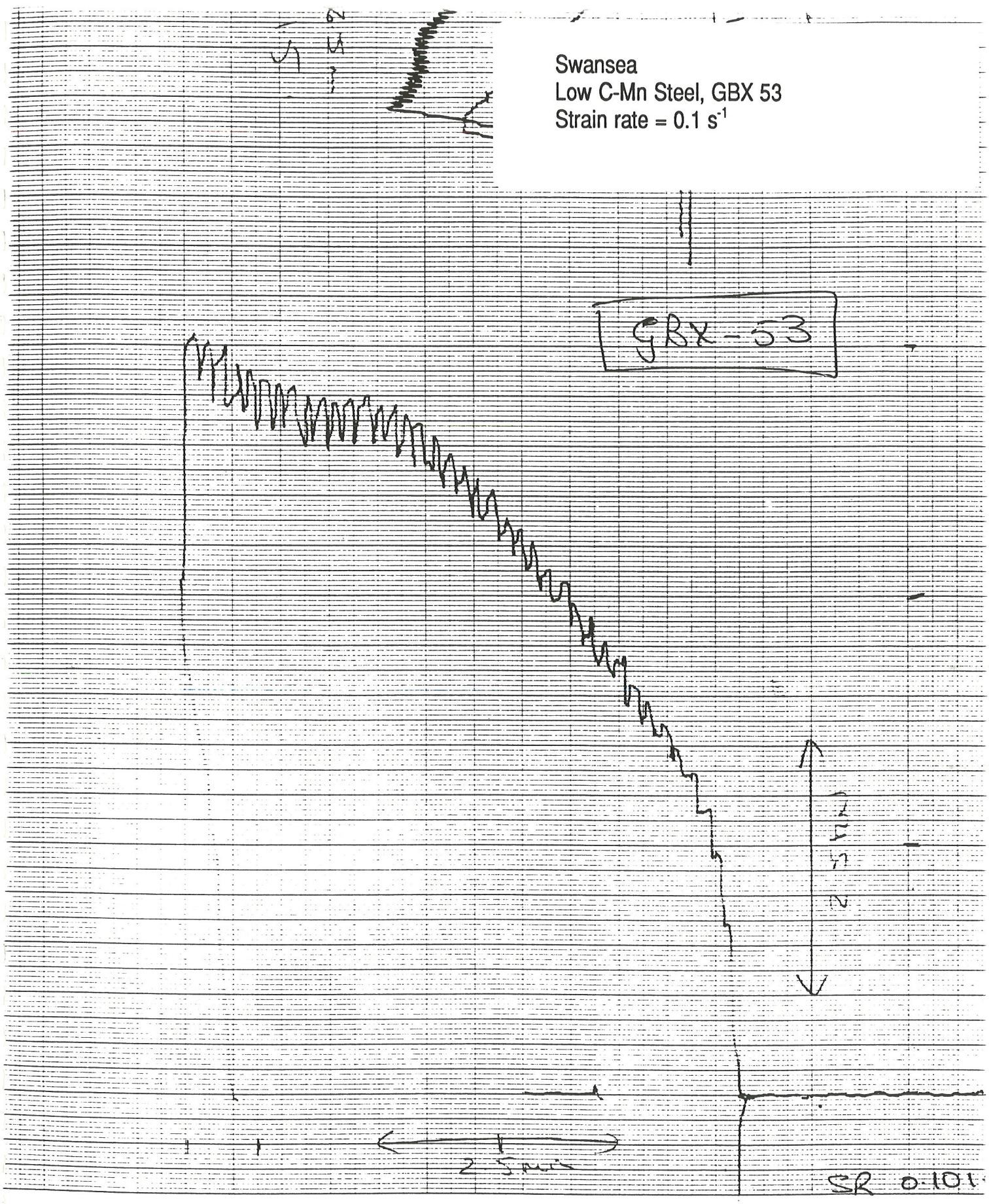
Strain Rate 0.1 s^{-1}

Cambridge	GBX 48
Swansea	GBX 53
MPD	GBX 59
Oulu	8 x 12 mm 0.1 and 1 s^{-1} [longitudinal strain] 10 x 15 mm 0.1 and 1 s^{-1} [diametral strain]

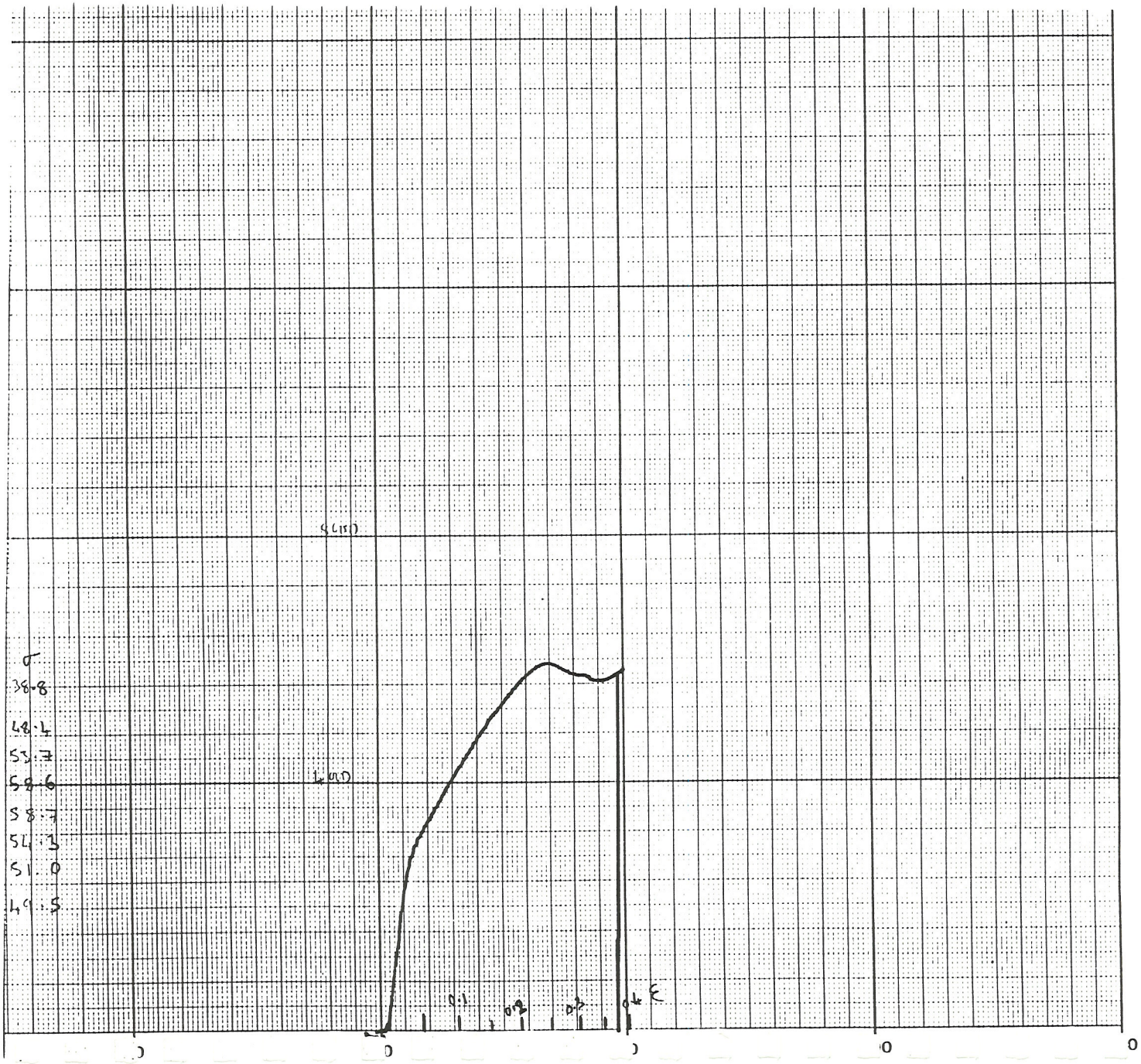
Cambridge 0.1 s^{-1}
Low C-Mn steel



Cambridge
Low C-Mn Steel, GBX 48
Strain rate = 0.1 s^{-1}


Swansea
Low C-Mn Steel, GBX 53
Strain rate = 0.1 s-1
GBX-53
2 5mm
SR 0.101

MPD
Low C-Mn steel
0·1 s^{-1}



Test System
Test Machine Type No
Zwick

Sample Grips

Load Cell 200kN

Extensometer

Sample
Material NPL Steel sample

Sample Type (Standard)

Width/Diameter 10.0 mm

Thickness

Initial Gauge Length L_o 14.99

Grip Separation

Test Parameters
Crosshead Speed v

Co-ordinates

Load Ratio kN/10

Extension Co-ord

Extension Ratio l

Time Co-ordinate

Time Ratio t/10 m

Notes

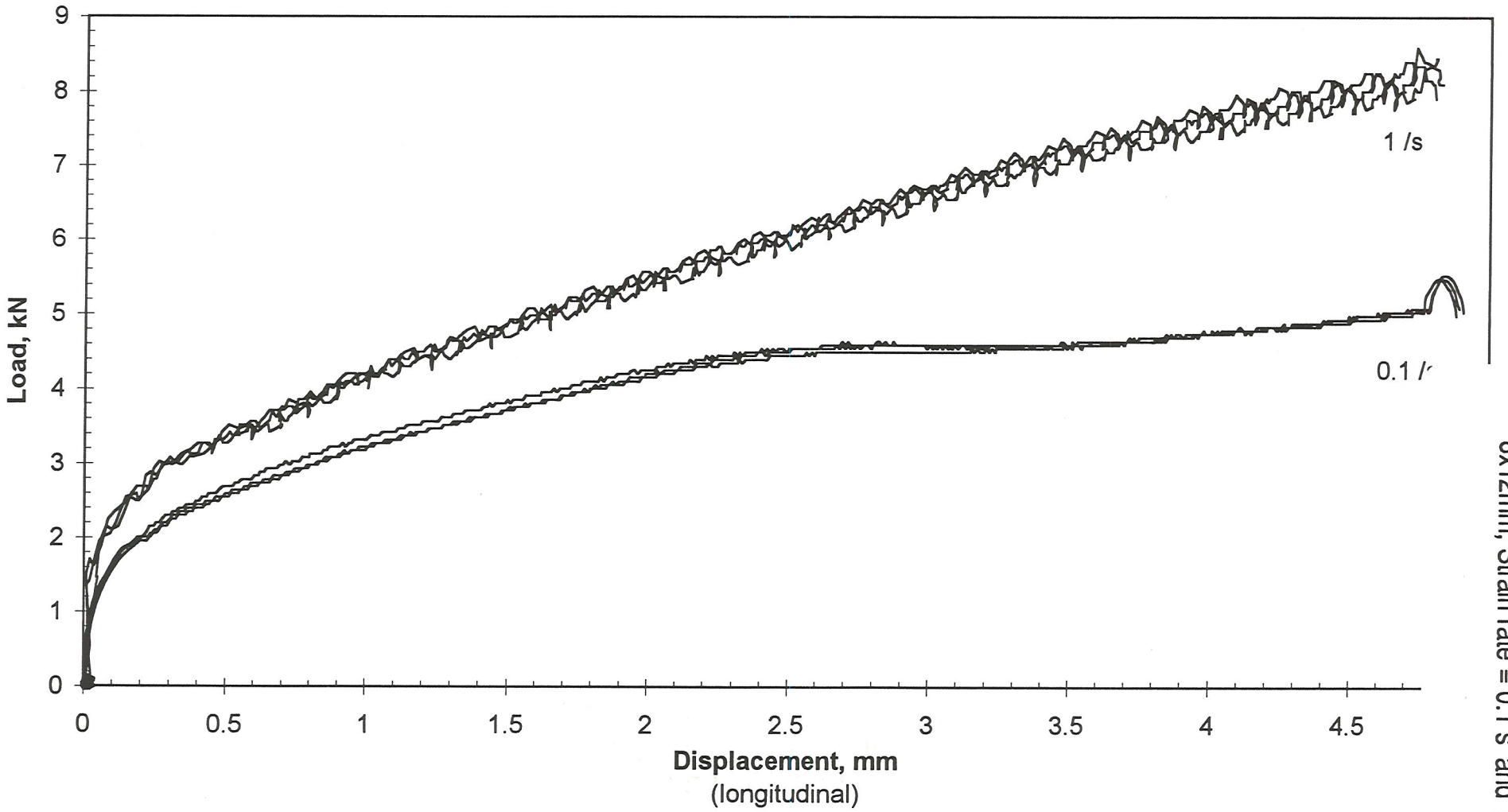
Date 20
Tested by

MPD
Low C-Mn Steel, GBX 59
Strain rate = 0.1 s^{-1}

Oulu

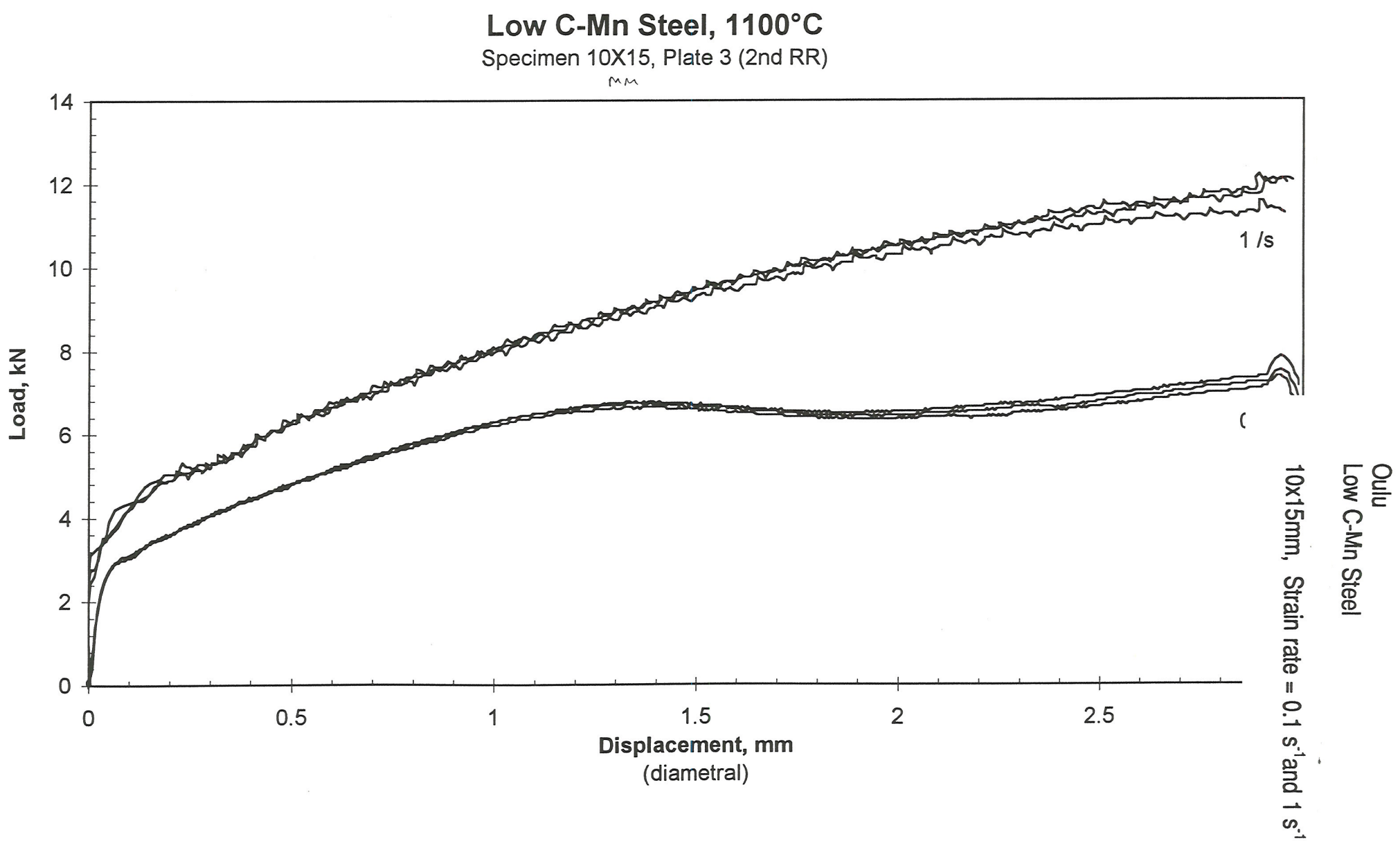
Low C-Mn Steel, 1100°C

Specimen 8X12, Material Code GBX...



Oulu
Low C-Mn Steel
8x12mm, Strain rate = 0.1 s^{-1} and 1 s^{-1}

Oulu

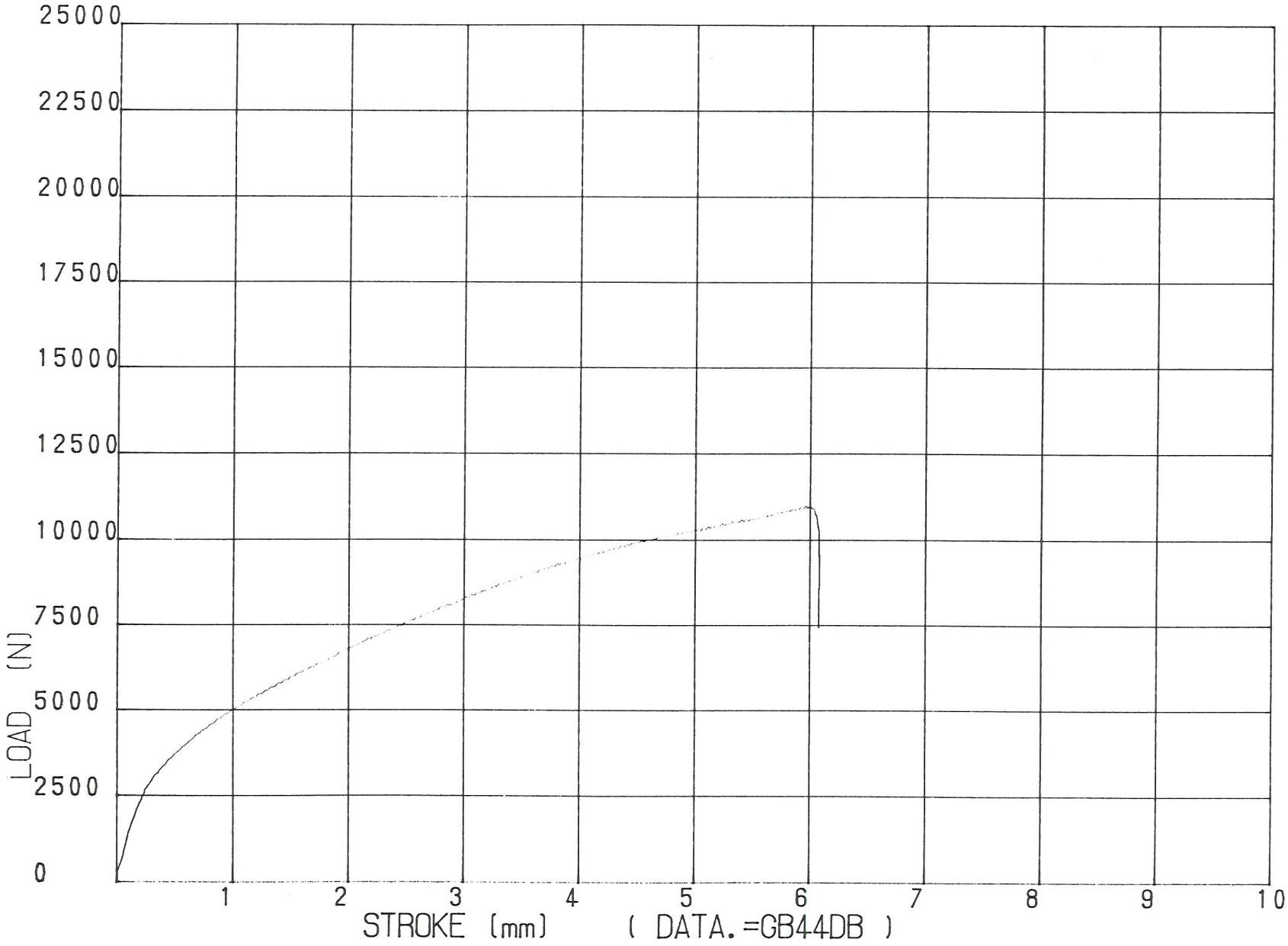

Low C-Mn Steel, 1100°C
Specimen 10X15, Plate 3 (2nd RR)
mm
Load, kN
14
12
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
Displacement, mm
(diametral)
1 /s
Oulu
Low C-Mn Steel
10x15mm, Strain rate = 0.1 s-1 and 1 s-1

Low C-Mn Steel

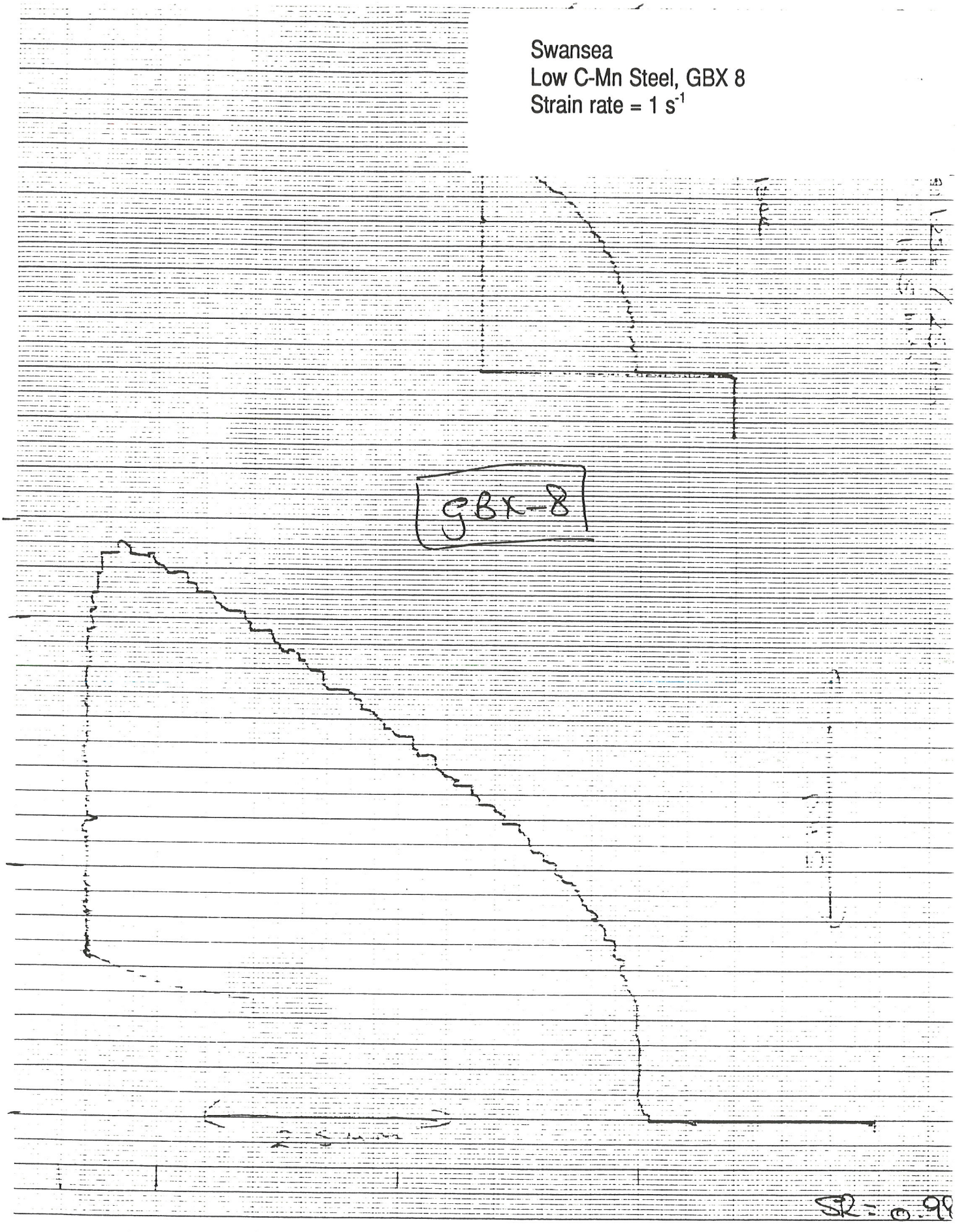
Strain Rate 1 s^{-1}

Cambridge	GBX 44
Swansea	GBX 8
Sheffield	GBX 67
British Steel	GBX 33
MPD	GBX 15

Cambridge 1 s⁻¹
Low C-Mn Steel

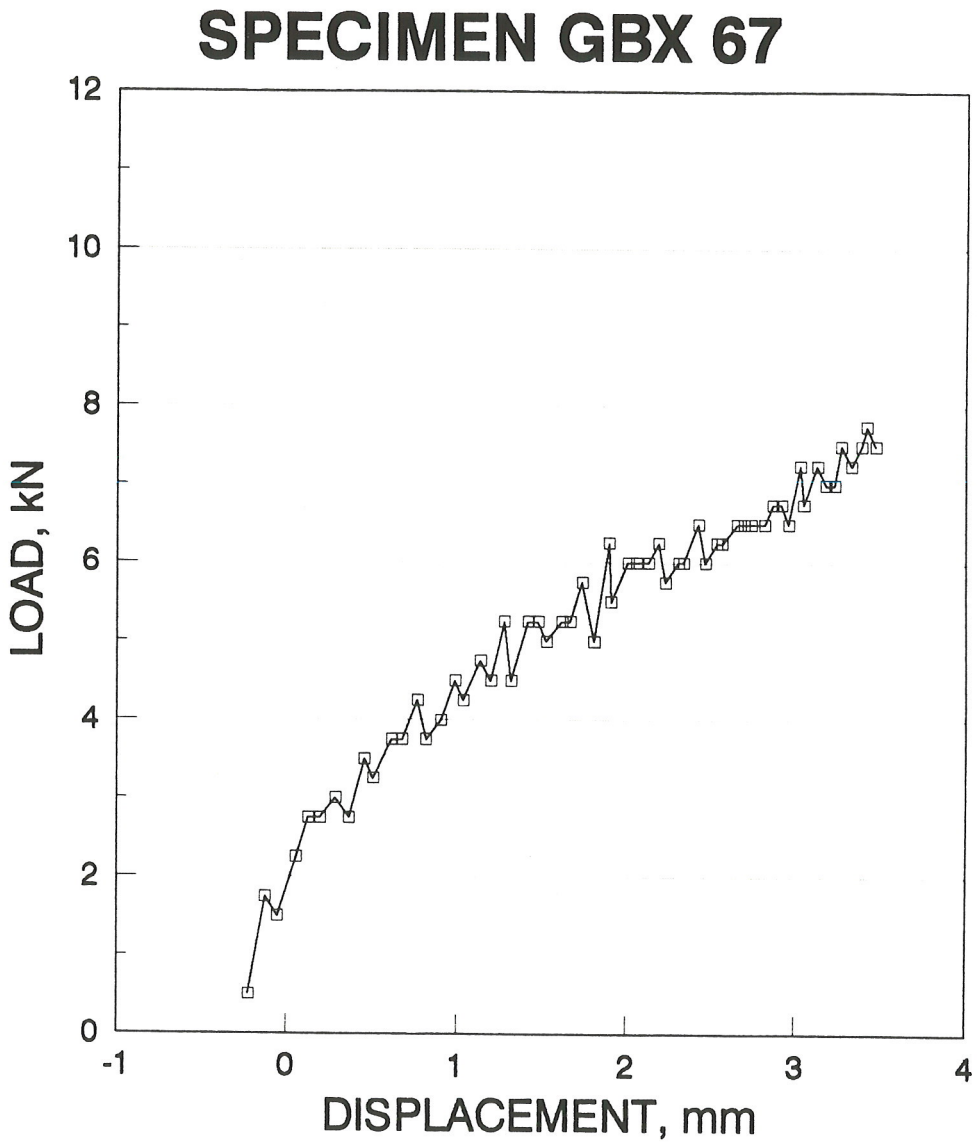


Cambridge
Low C-Mn Steel, GBX 44
Strain rate = 1 s^{-1}



Swansea
Low C-Mn Steel
1 s^{-1}

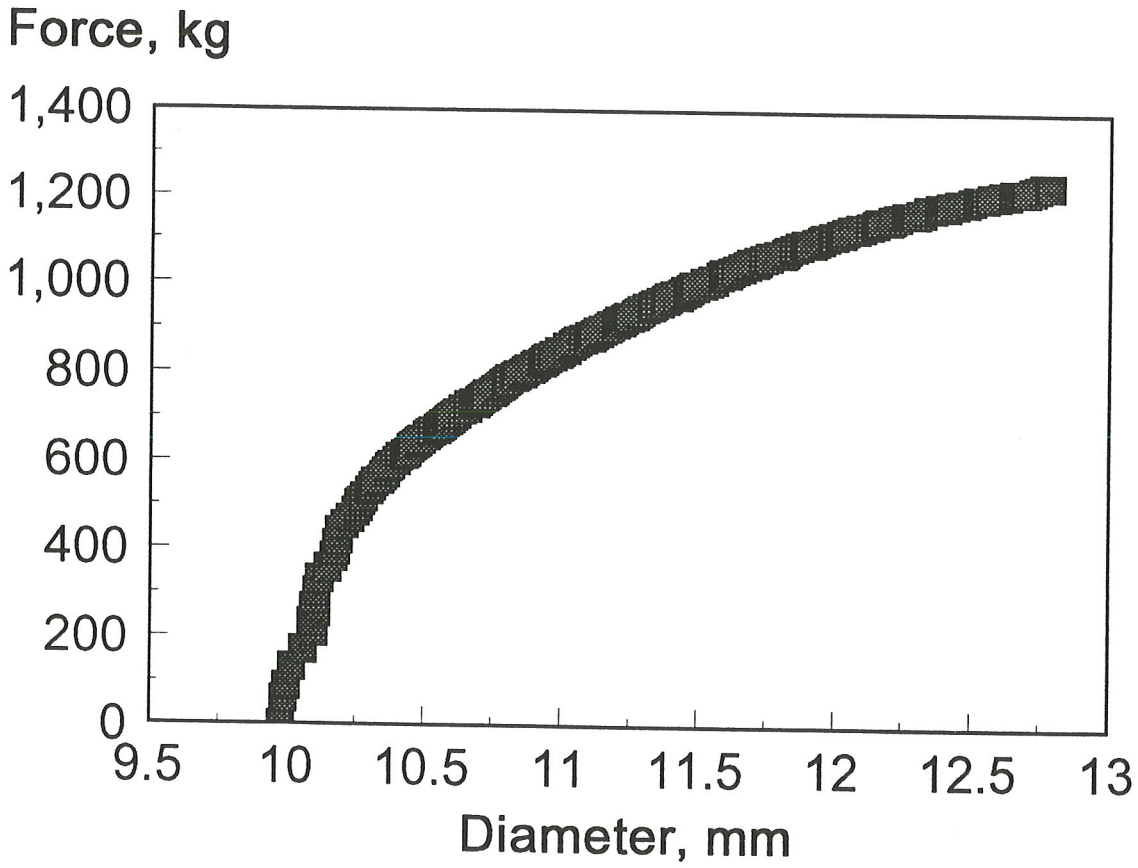
Sheffield
Low C-Mn Steel, GBX 67
Strain rate = 1 s^{-1}



Sheffield 1 s-1
Low C-Mn Steel

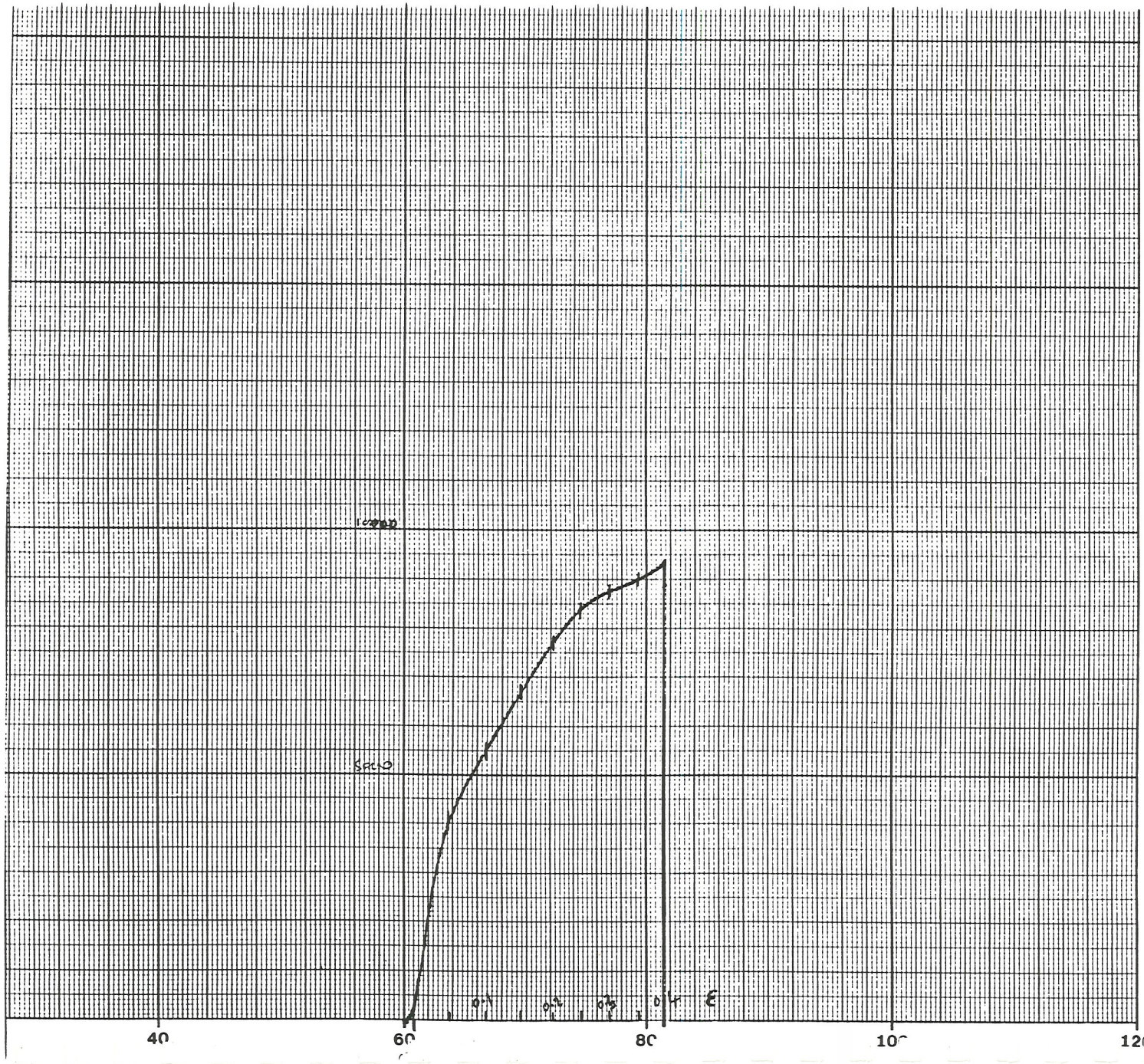
British Steel
Low C-Mn Steel, GBX 33
Strain rate = 1 s^{-1}

Force-Diameter Curve for Carbon Steel at 1 s^{-1} -GBX33



British Steel
Low C-Mn Steel
1 s^{-1}

MPD
Low C-Mn Steel
1 s-1



Test System Test Machine Type No. Zwick	
Sample Grips	> 1
Load Cell	200kN
Extensometer	
Sample Material	NPL Steel
Sample Type (Standard)	
Width/Diameter	9.99mm ø
Thickness	
Initial Gauge Length L_o	13.95mm
Grip Separation	
Test Parameters Crosshead Spe	
Co-ordinates	
Load Ratio kN	
Extension Co-(	
Extension Rati	
Time Co-ordin	
Time Ratio t/1(	
Notes	1 s
	11 c
Date Tested by	

MPD
Low C-Mn Steel, GBX 15
Strain rate = 1 s^{-1}

Order No. German ZN
Orde , Fre ZN

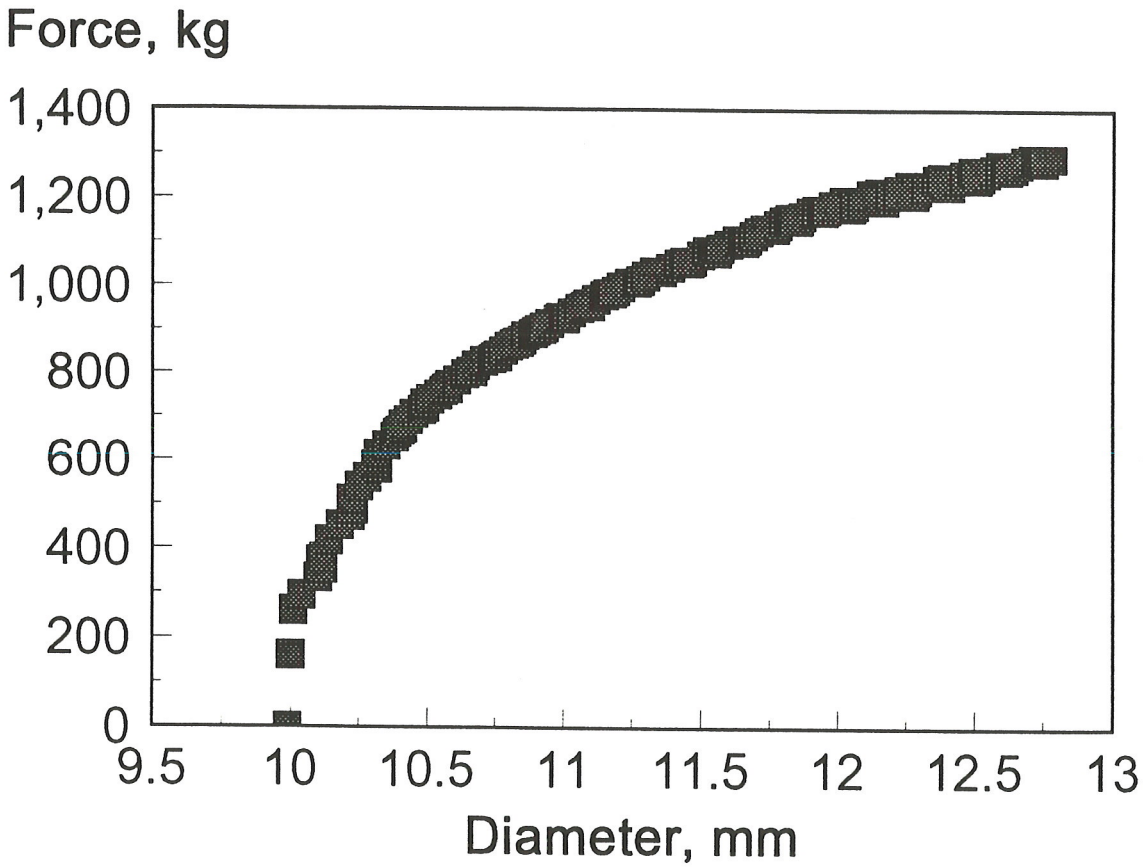
Low C-Mn Steel and Nimonic 901

Strain Rate 10 s^{-1}

British Steel	Low C-Mn steel	GBX 55
Sheffield	Nimonic	EAT 70
Sheffield	Low C-Mn steel	GBX 72

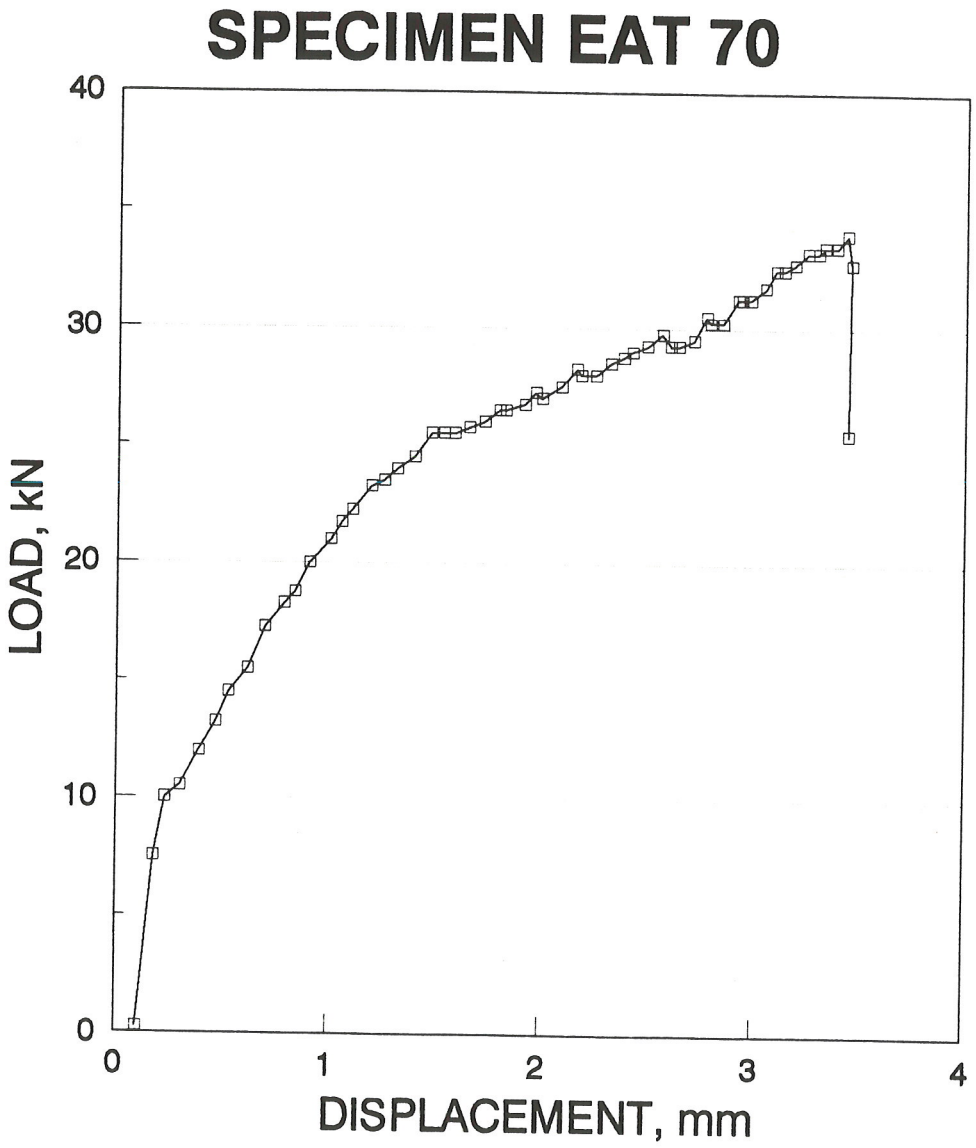
British Steel
Low C-Mn Steel, GBX 55
Strain rate = 10 s^{-1}

Force-Diameter Curve for Carbon Steel at 10 s^{-1}-GBX55



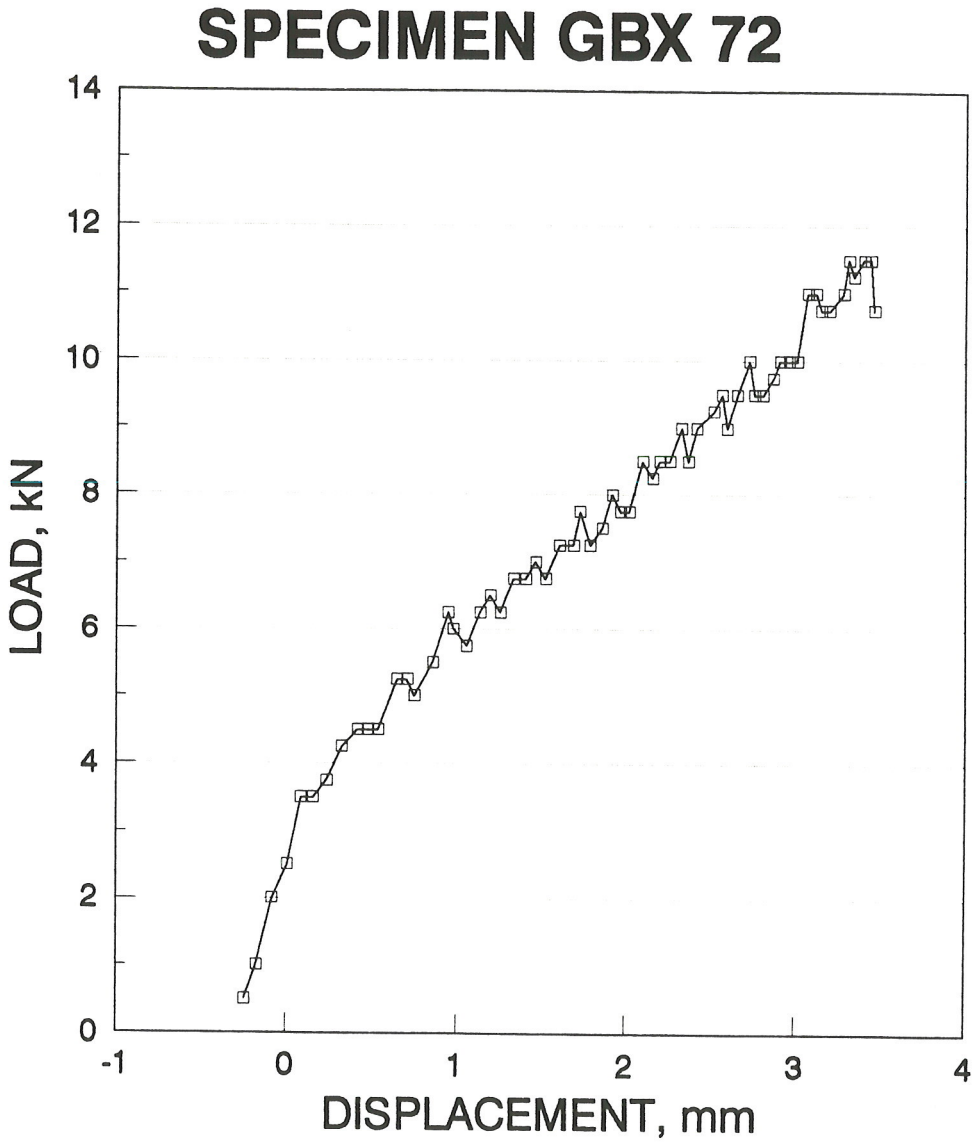
British Steel
Low C-Mn Steel
10 s^{-1}

Sheffield
Nimonic 901, EAT 70
Strain rate = 10 s^{-1}



Sheffield
Nimonic 10[illegible] s^{-1}

Sheffield
Low C-Mn Steel, GBX 72
Strain rate = 10 s^{-1}



Sheffield 10 s-1
low C-Mn steel

APPENDIX B

Interlaboratory Exercise

Hot Axisymmetric Compression

Representative Stress-Strain Curves

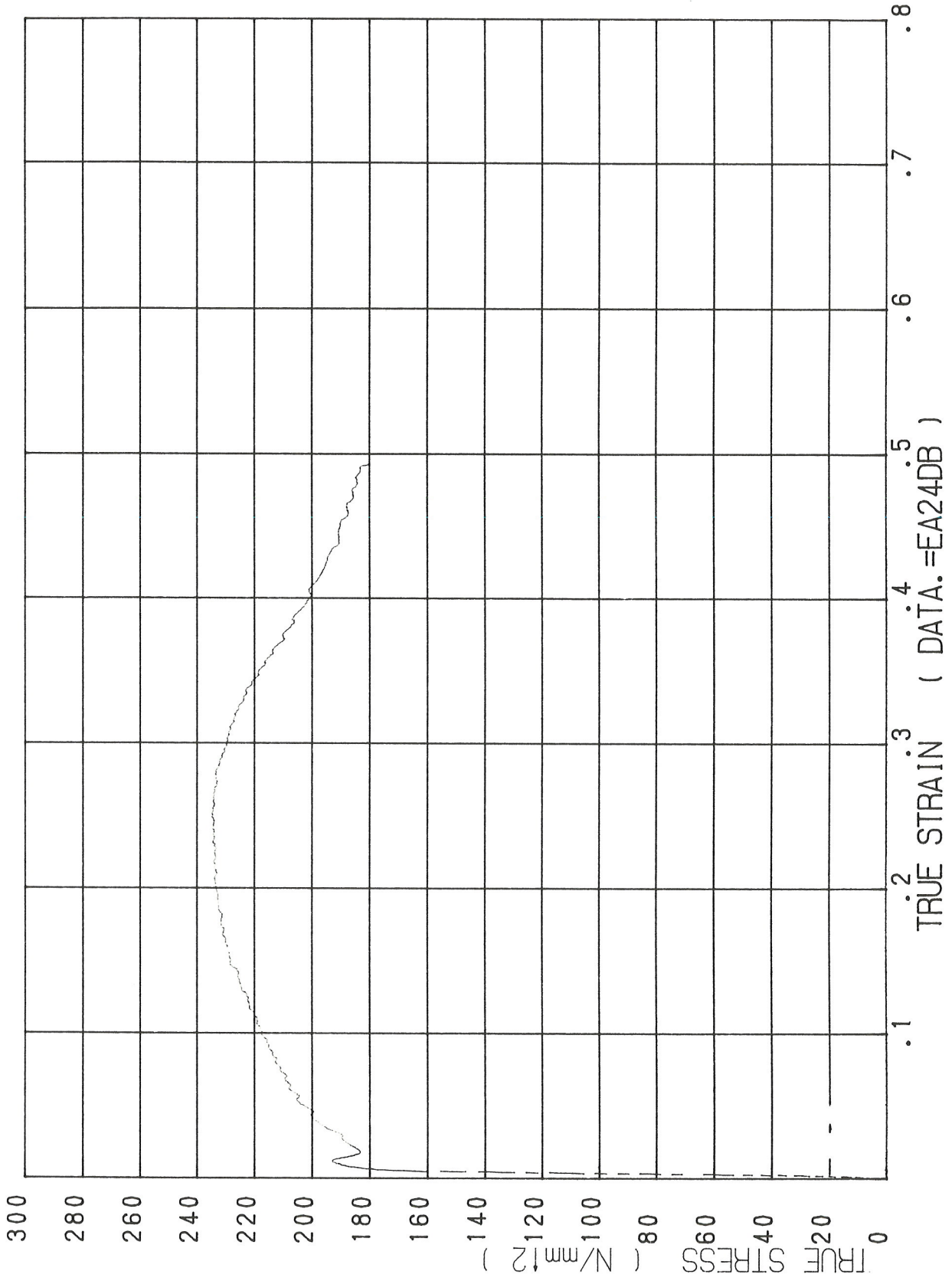
Machine Output

Nimonic 901	1000 °C
Low C-Mn Steel	1100 °C

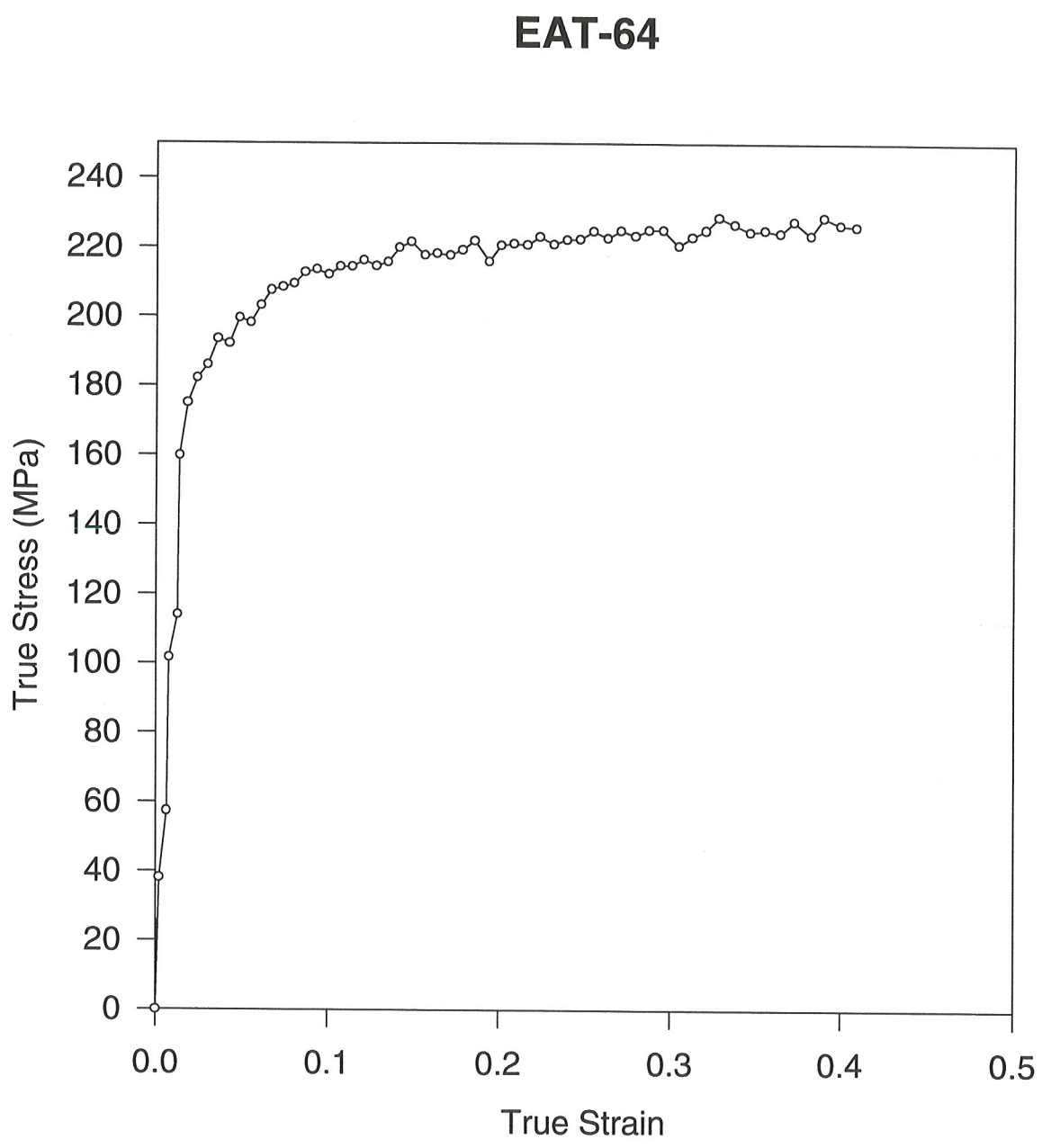
Strain Rates	0.1, 1, 10	s^{-1}

Cambridge
Nimonic 901, EAT 24
Strain rate = 0.1 s^{-1}

Cambridge
Nimonic 901
0.1 s^{-1}

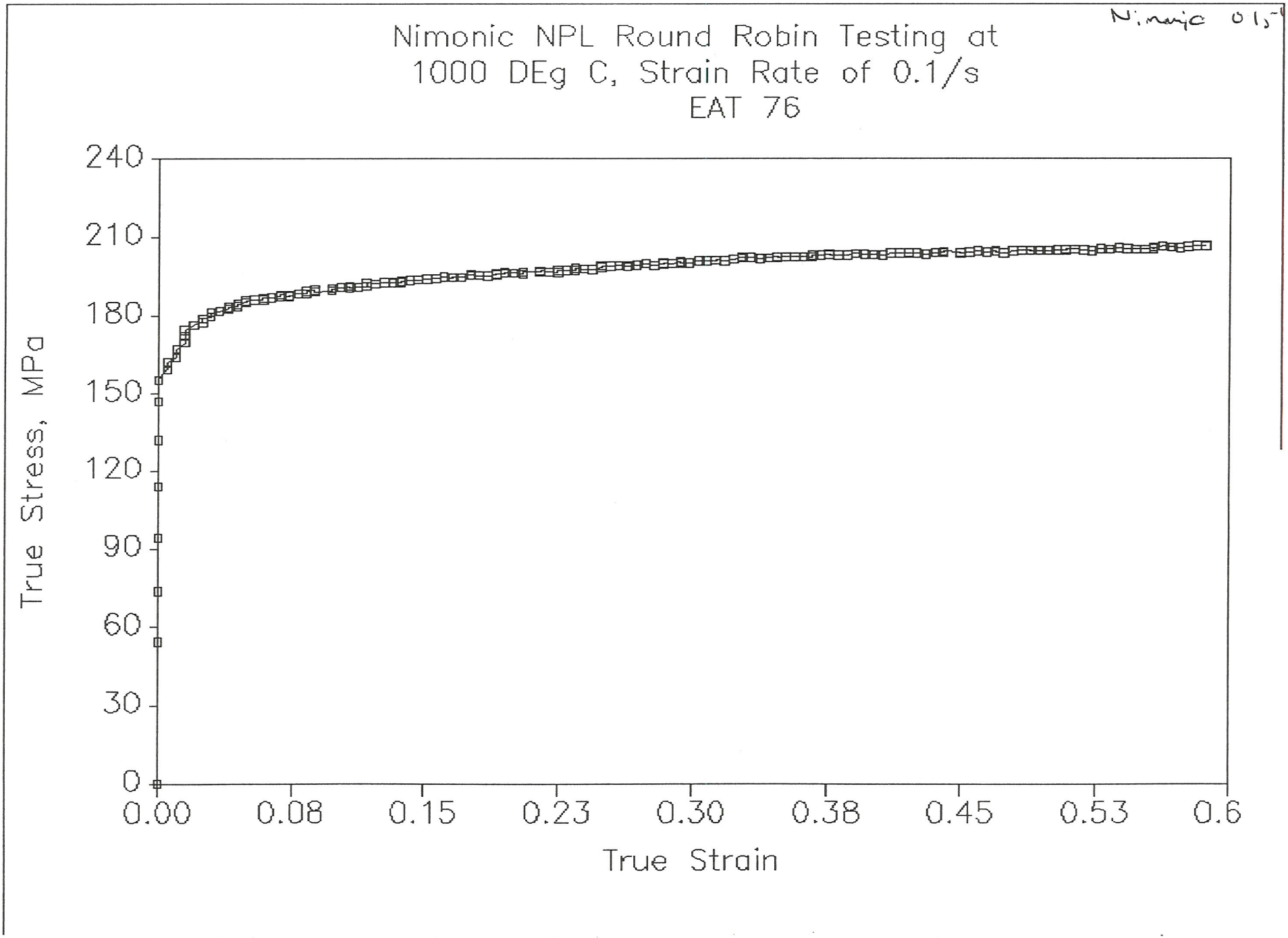


Swansea
Nimonic 901, EAT 64
Strain rate = 0.1 s^{-1}



Swansea Nimonic 901
0.1 s^{-1}
1050°C

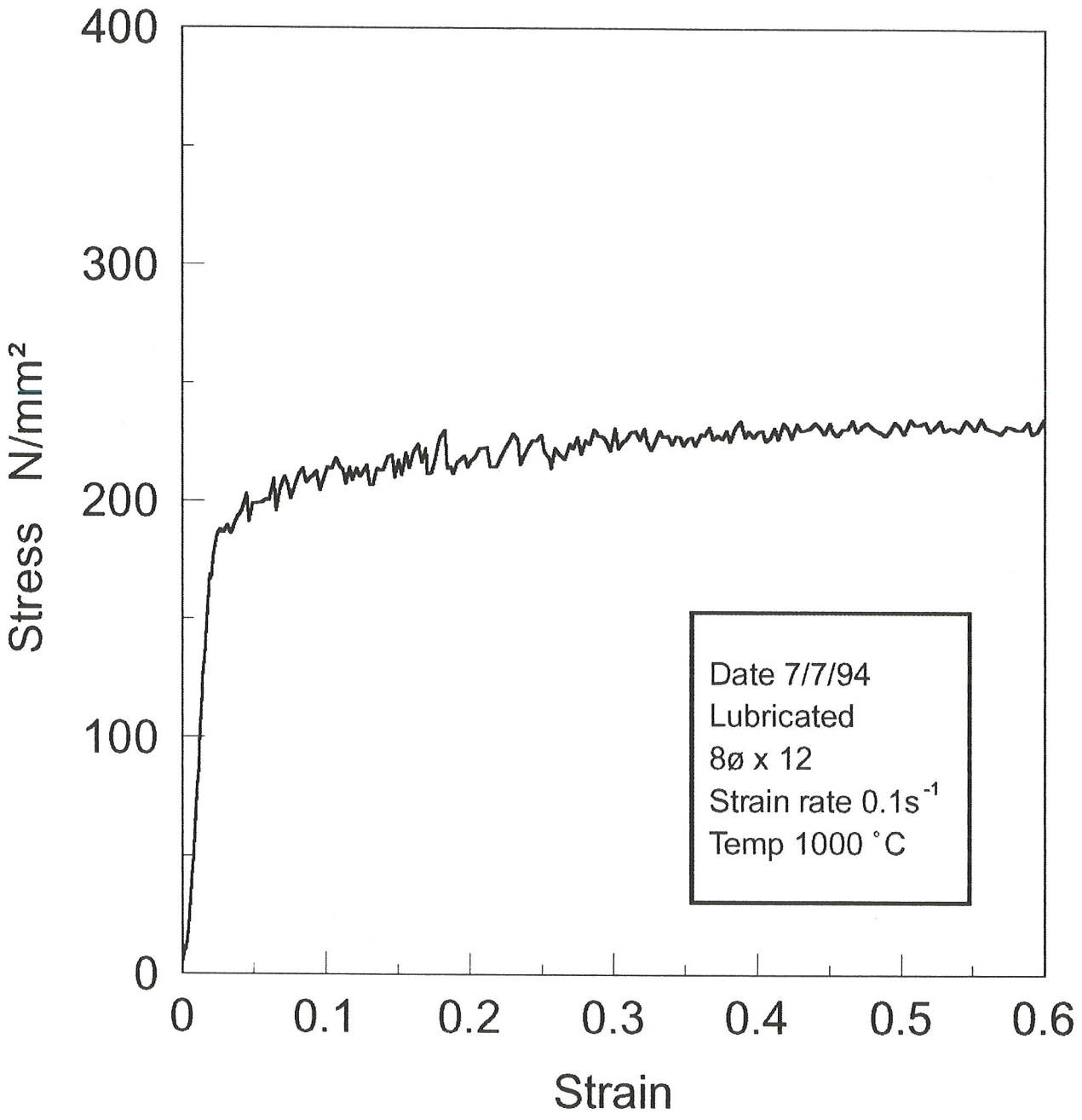
British Steel
Nimonic 0.1 s⁻¹

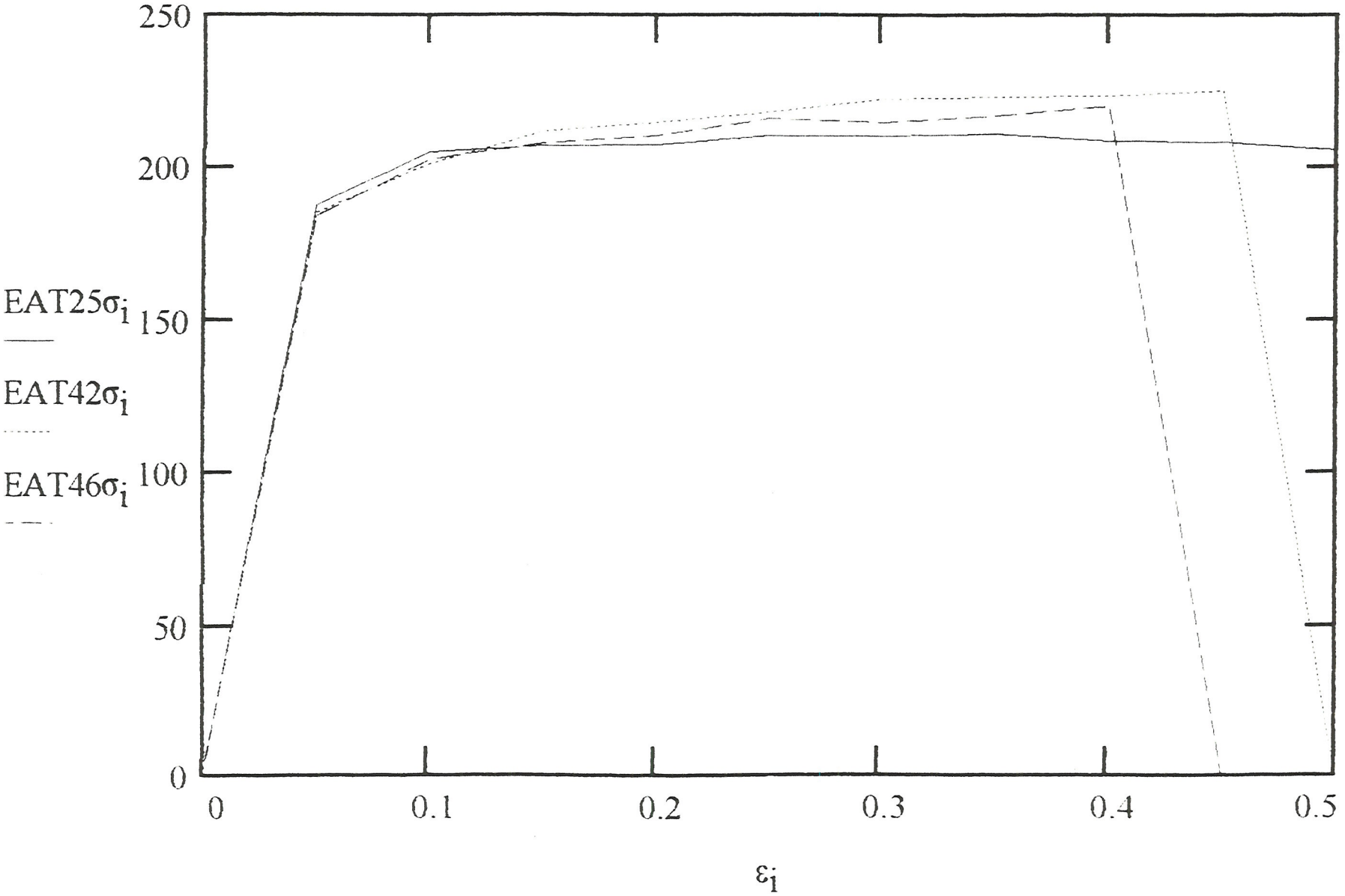


British Steel
Nimonic 901, EAT 76
Strain rate = 0.1 s^{-1}

NPL
Nimonic 901, EAT 55
Strain rate = 0.1 s^{-1}

EAT55 - Nimonic at 1000°C



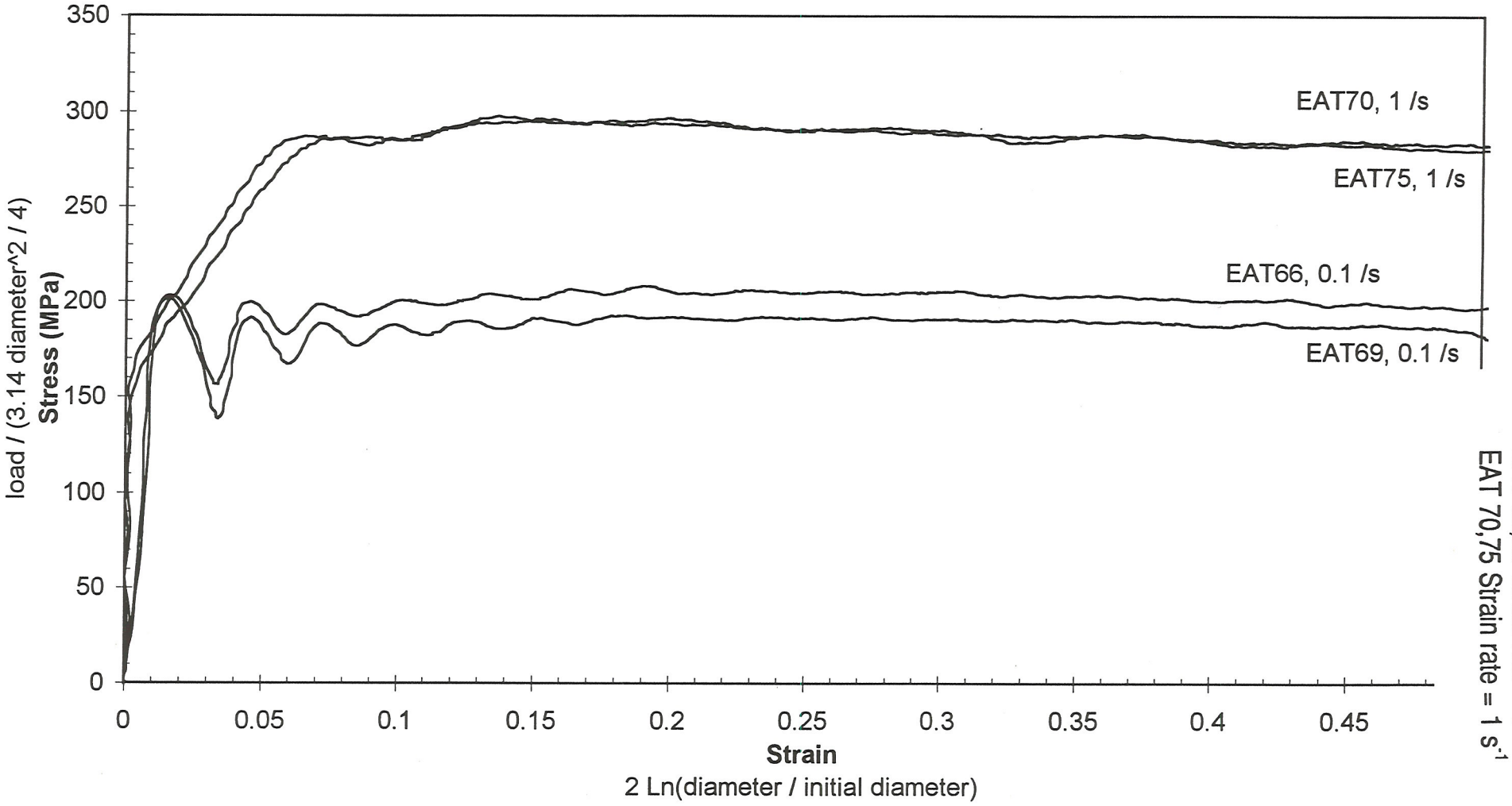


MPD
Nimonic 901, EAT 25
Strain rate = 0.1 s^{-1}

True Strain.

Oulu

Nimonic 901, 1000°C



Nimonic 901

Strain Rate 0.1 s^{-1}

Cambridge	EAT 24
Swansea	EAT 64
British Steel	EAT 76
NPL	EAT 55
MPD	EAT 25
Oulu	EAT 66,69 (plus EAT 70,75 1 s^{-1})

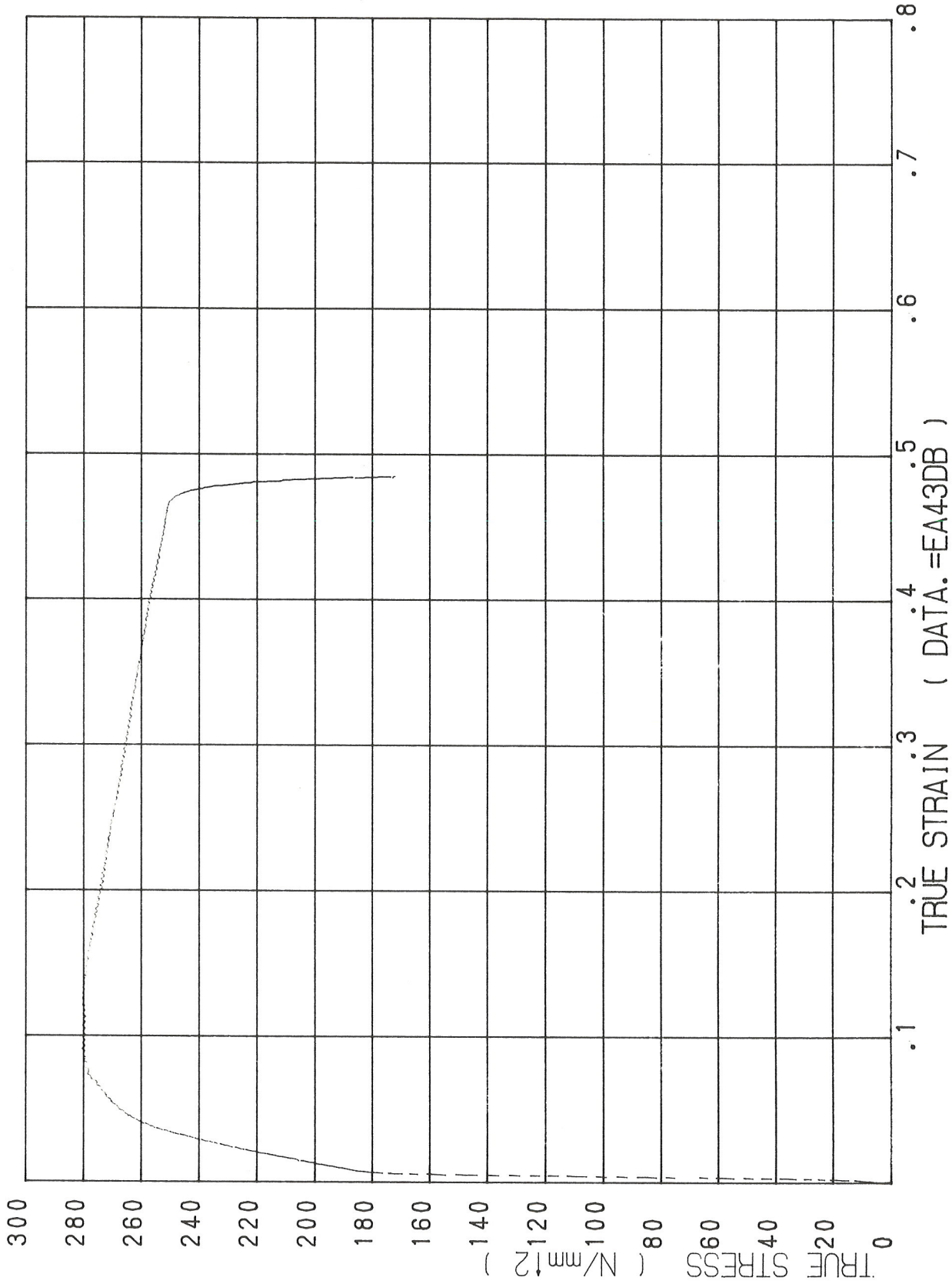
Nimonic 901

Strain Rate 1 s^{-1}

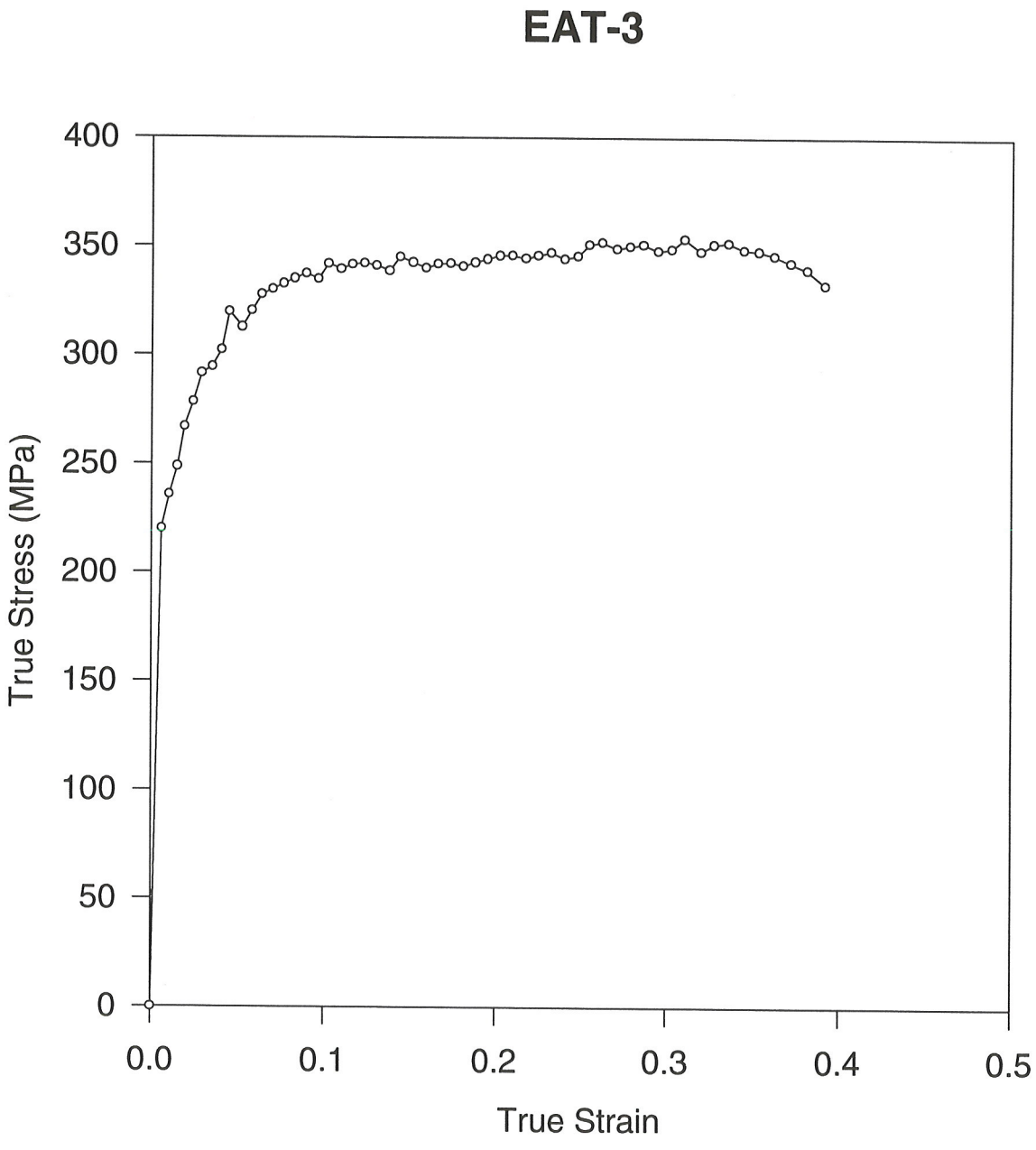
Cambridge	EAT 43
Swansea	EAT 3
Sheffield	EAT 66
British Steel	EAT 73
NPL	EAT 30
MPD	EAT 19
IMI	EAT 17

Cambridge
Nimonic 901, EAT 43
Strain rate = 1 s^{-1}

Cambridge
Nimonic 901
(s^{-1})

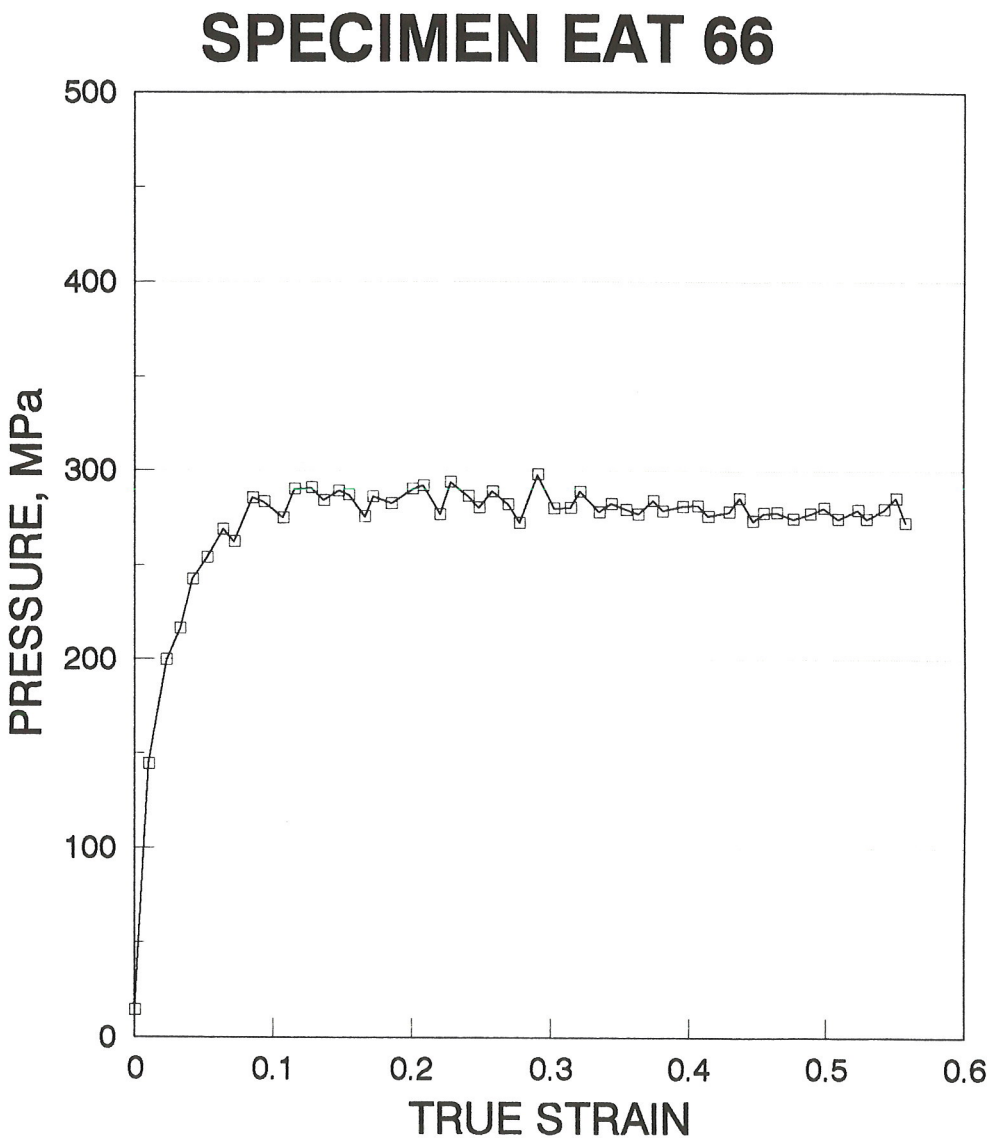


Swansea
Nimonic 901, EAT 3
Strain rate = 1 s^{-1}

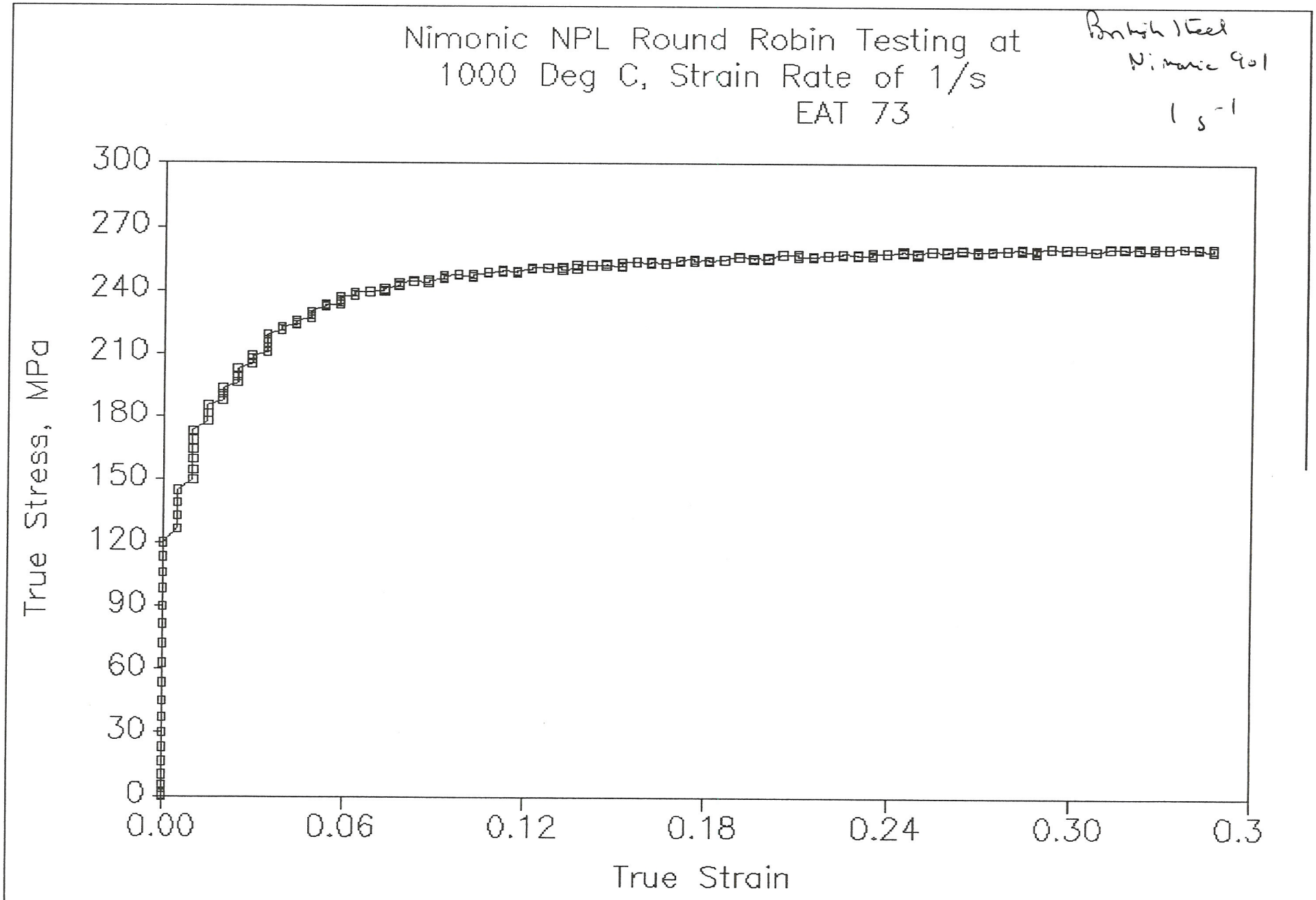


Swansea
1 s^{-1} Nimonic 901
1000°C

Sheffield
Nimonic 901, EAT 66
Strain rate = 1 s^{-1}



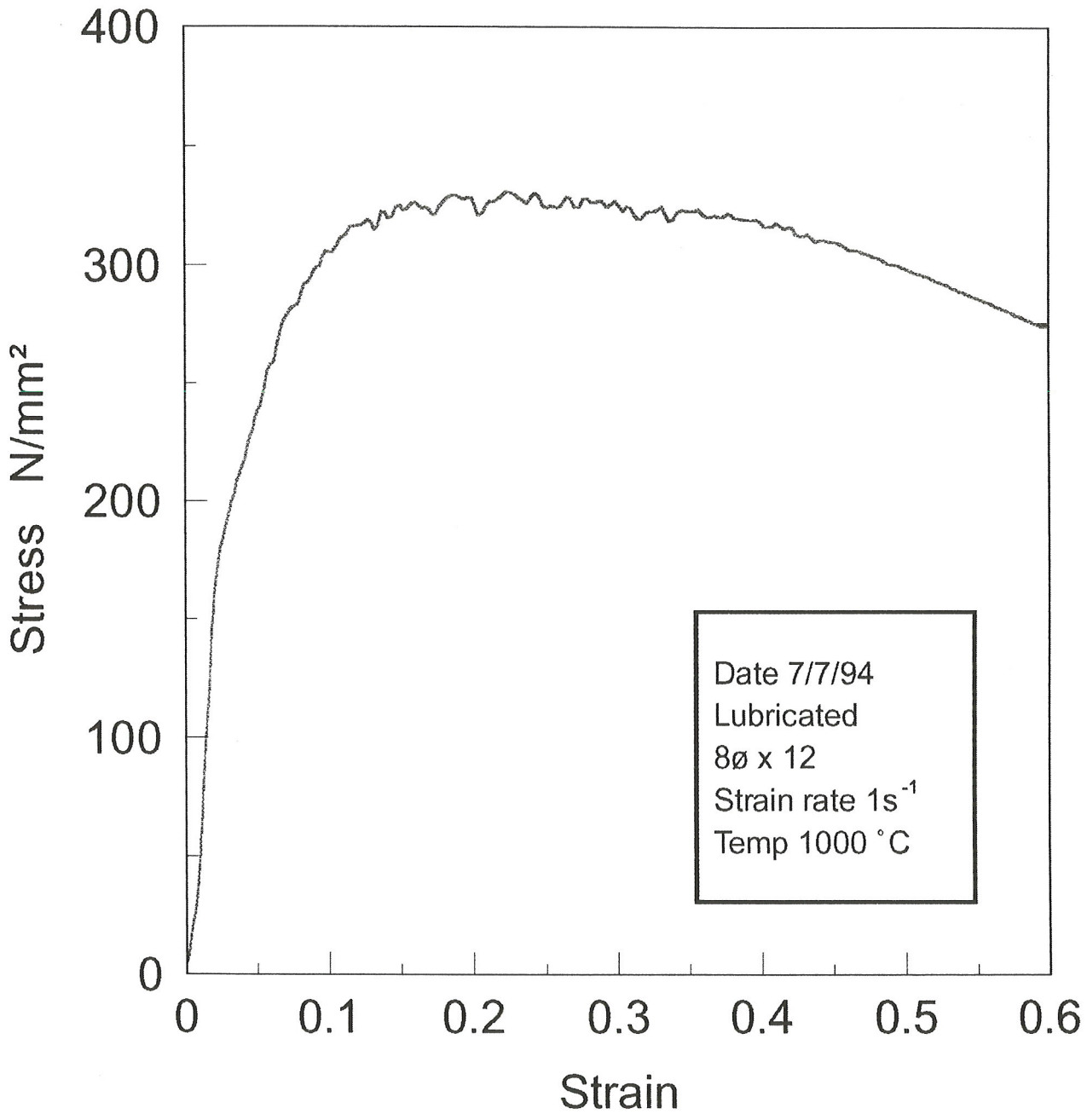
Sheffield
Nimonic 901
1 s^{-1}

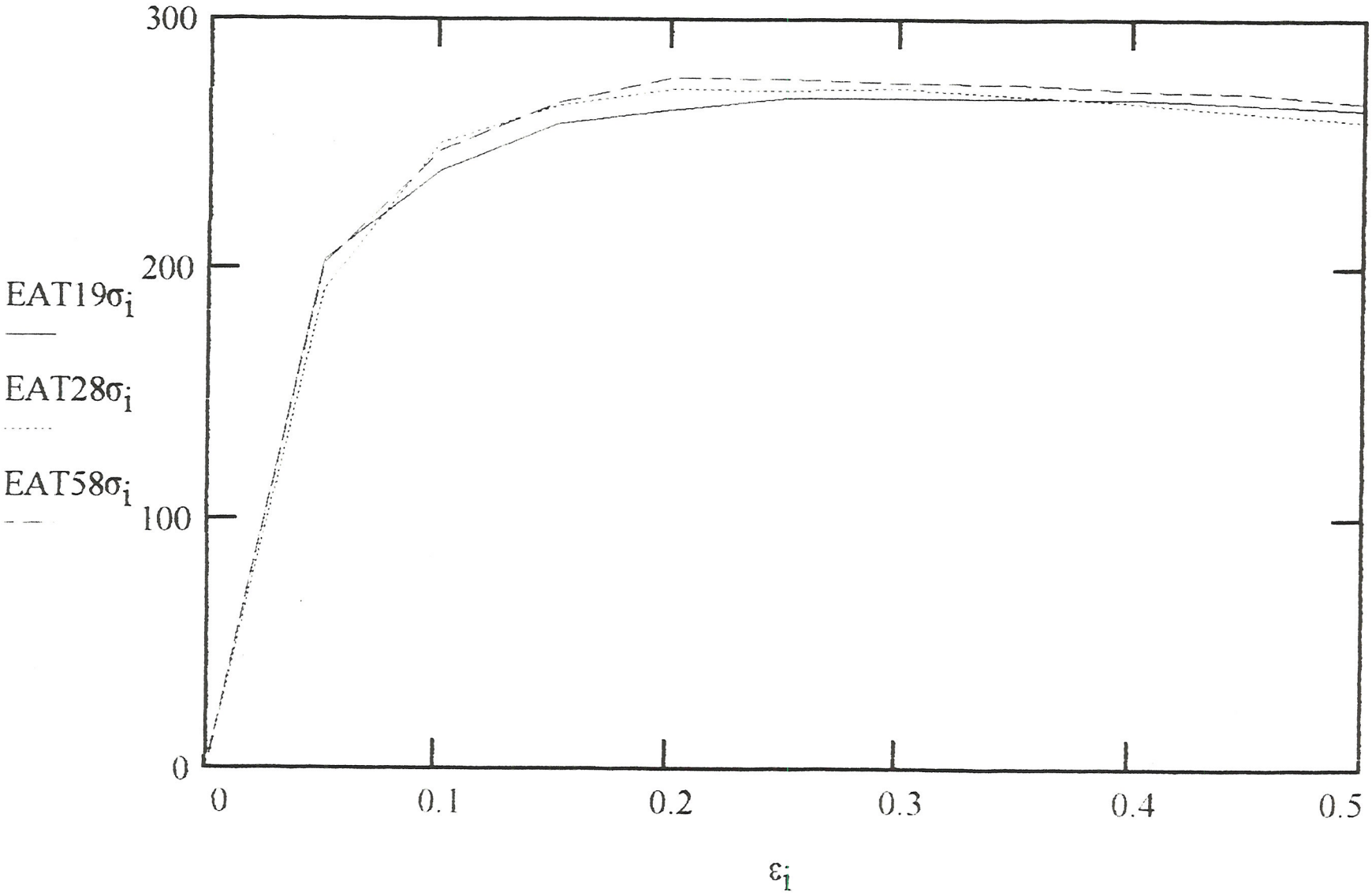


British Steel
Nimonic 901, EAT 73
Strain rate = 1 s^{-1}

NPL
Nimonic 901, EAT 30
Strain rate = 1 s^{-1}

EAT30 - Nimonic at 1000°C





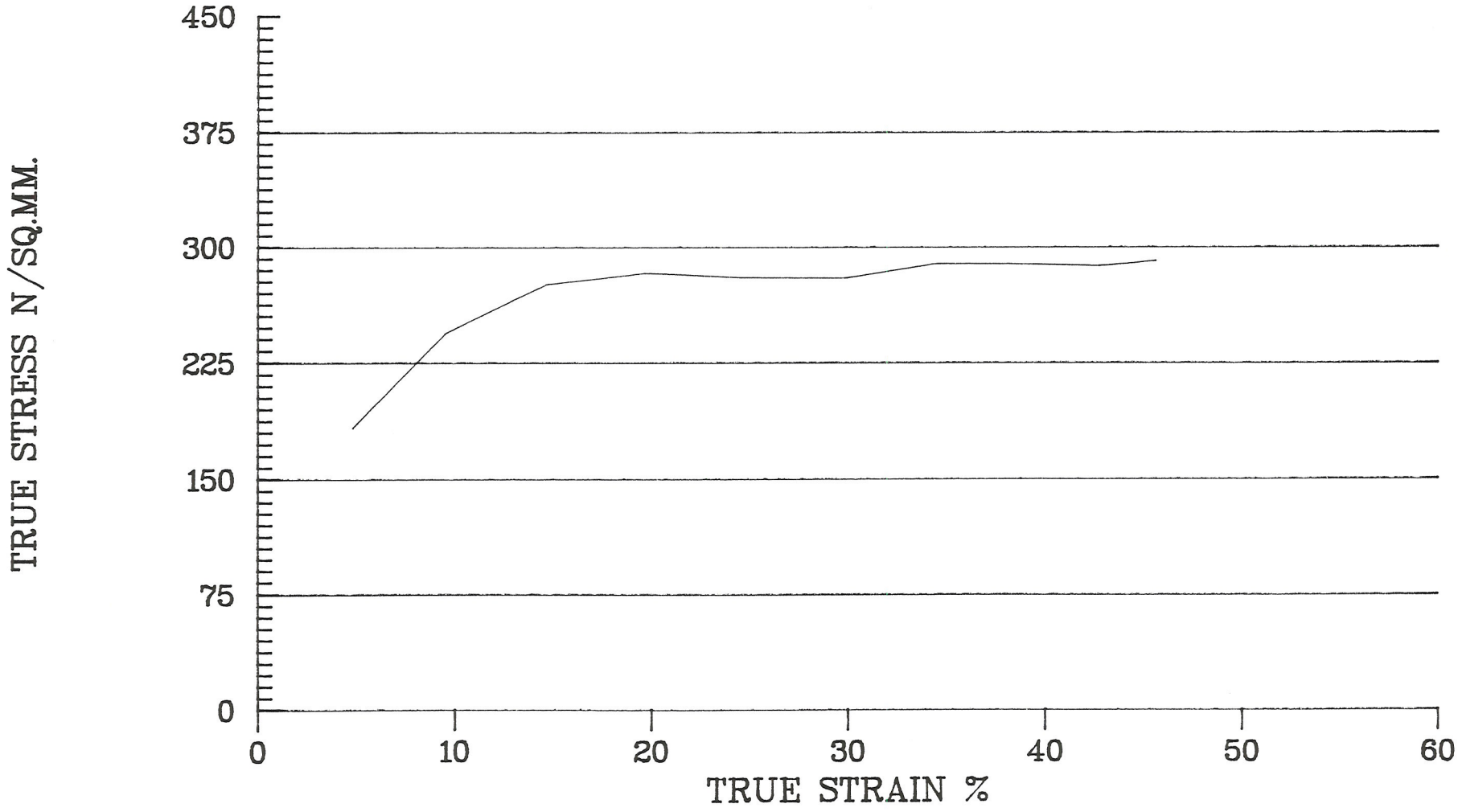
True Strain.

MPD
Nimonic 901, EAT 19
Strain rate = 1 s^{-1}

IMI
Nimonic 901
1 s^{-1}

TRUE STRESS vs TRUE STRAIN %

EAT 17



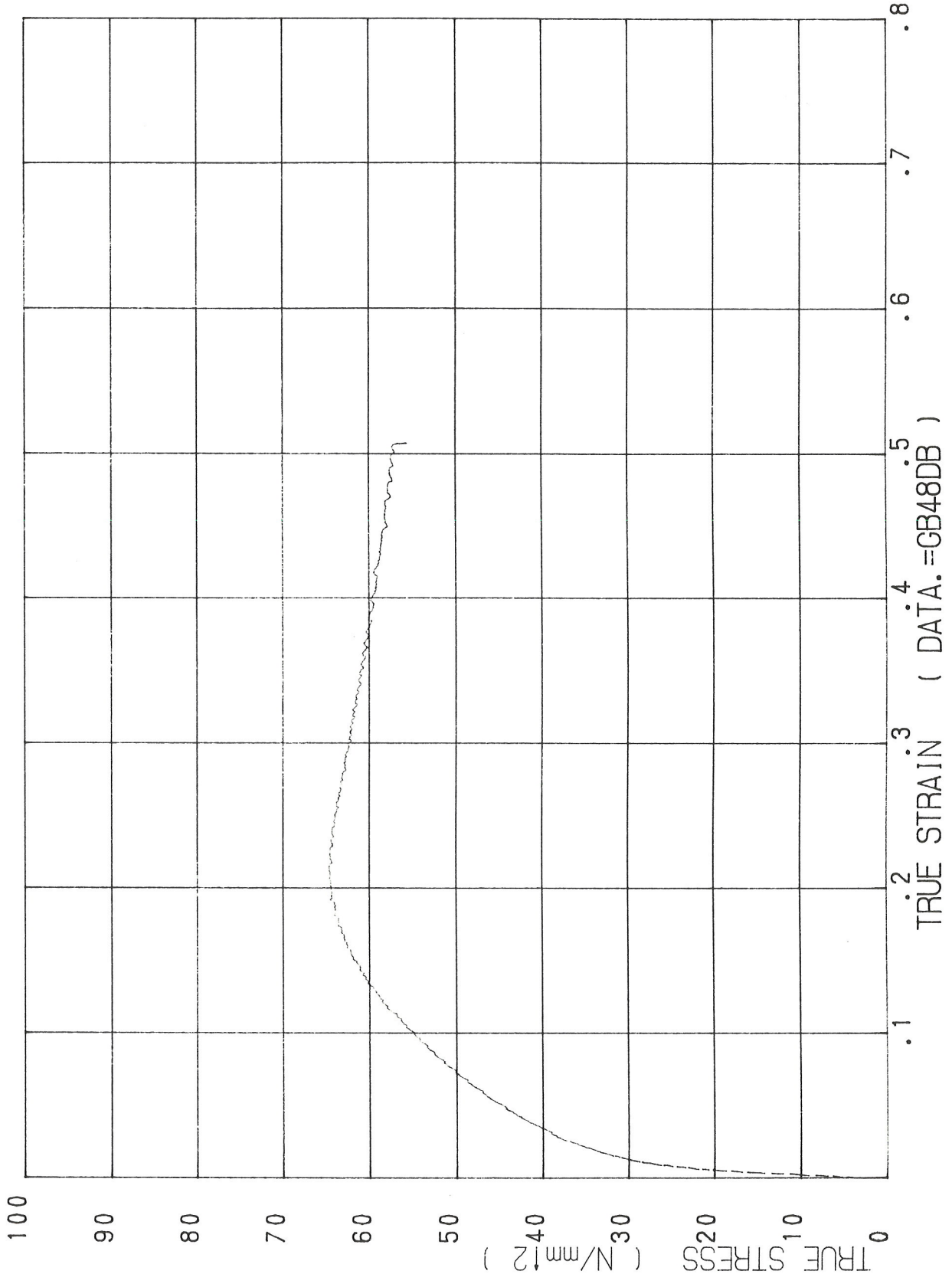
IMI
Nimonic 901, EAT 17
Strain rate = 1 s^{-1}

Low C-Mn Steel

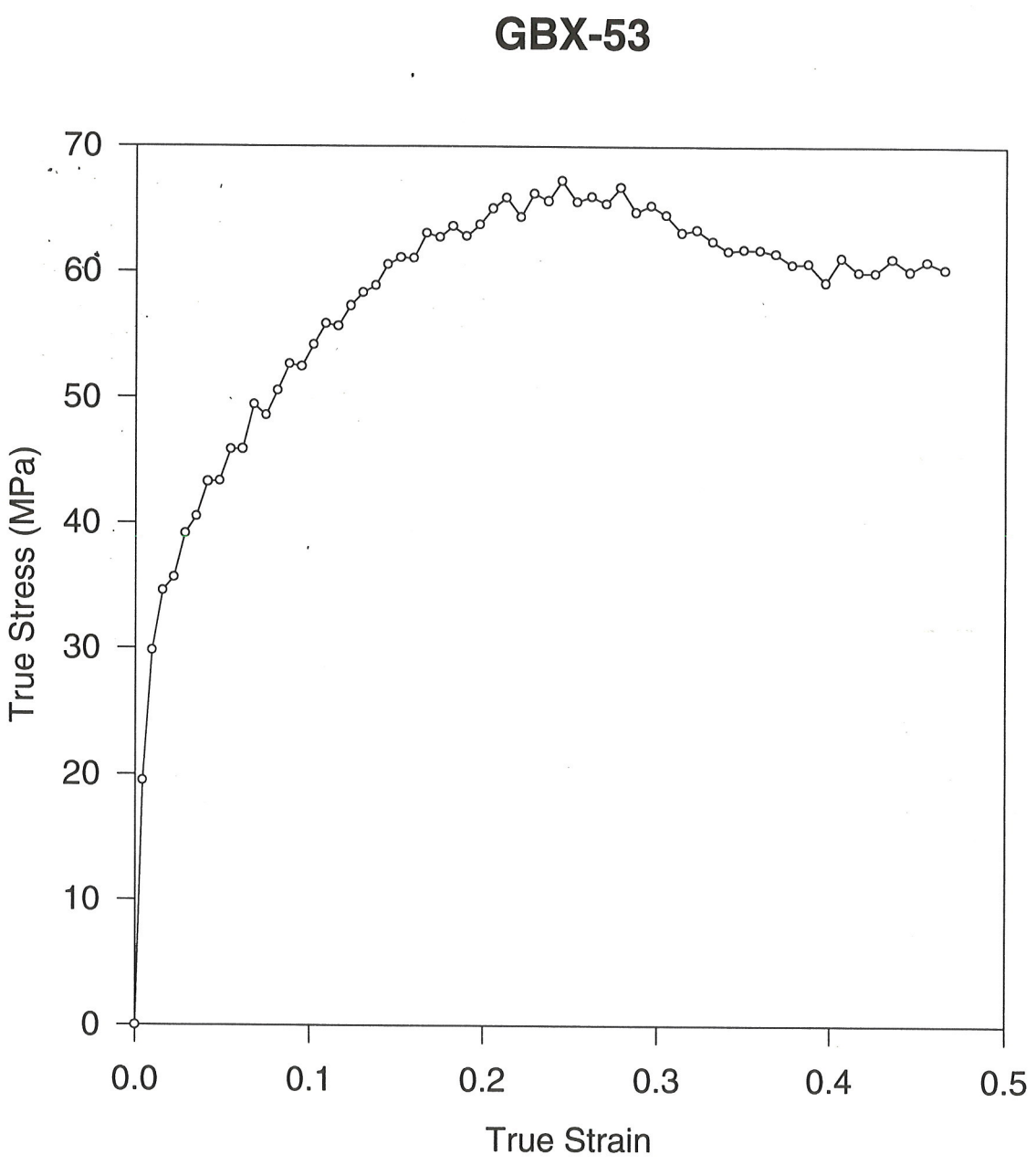
Strain Rate 0.1 s^{-1}

Cambridge	GBX 48
Swansea	GBX 53
MPD	GBX 59
Oulu	8 x 12 mm 0.1 and 1 s^{-1} [longitudinal strain] 10 x 15 mm 0.1 and 1 s^{-1} [diametral strain]

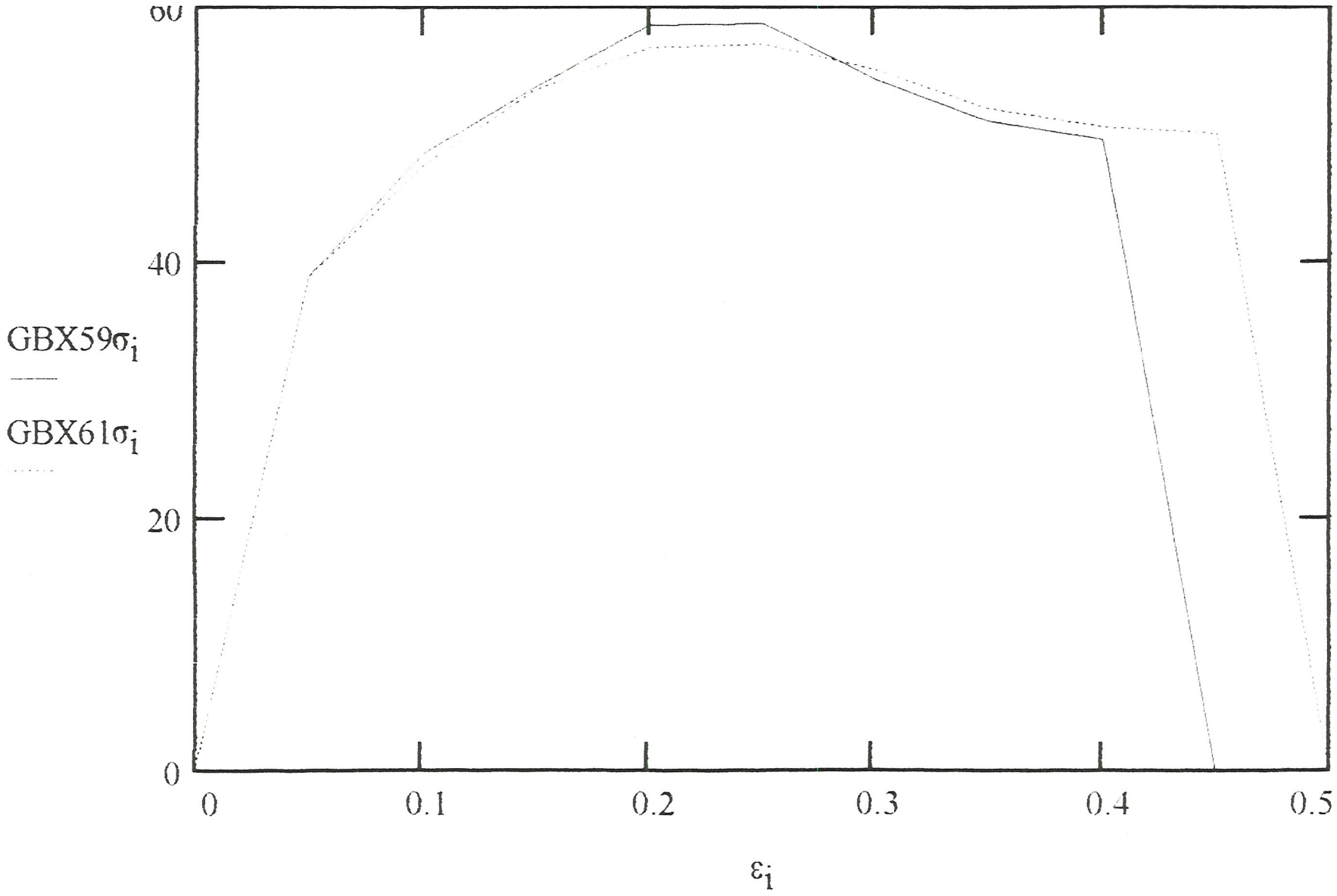
Cambridge
Low C-Mn Steel, GBX 48
Strain rate = 0.1 s^{-1}



Swansea
Low C-Mn Steel, GBX 53
Strain rate = 0.1 s^{-1}



Swansea
Low C-Mn Steel
$0.1 s^{-1}$



MPD
Low C-Mn Steel, GBX 59
Strain rate = 0.1 s^{-1}

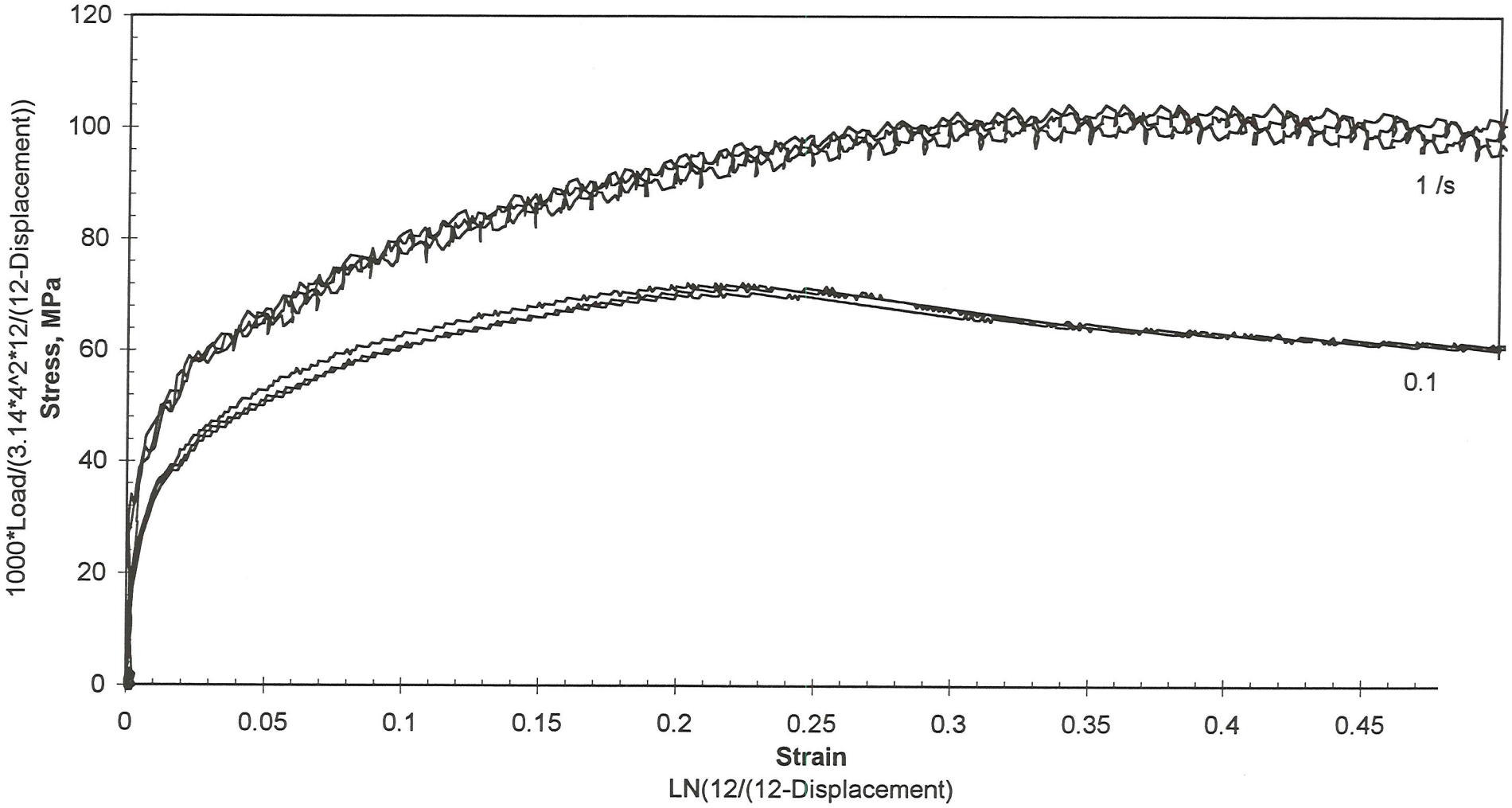
True Strain.

Oulu

Low C-Mn Steel, 1100°C

Specimen 8X12, Material Code GBX...

mm



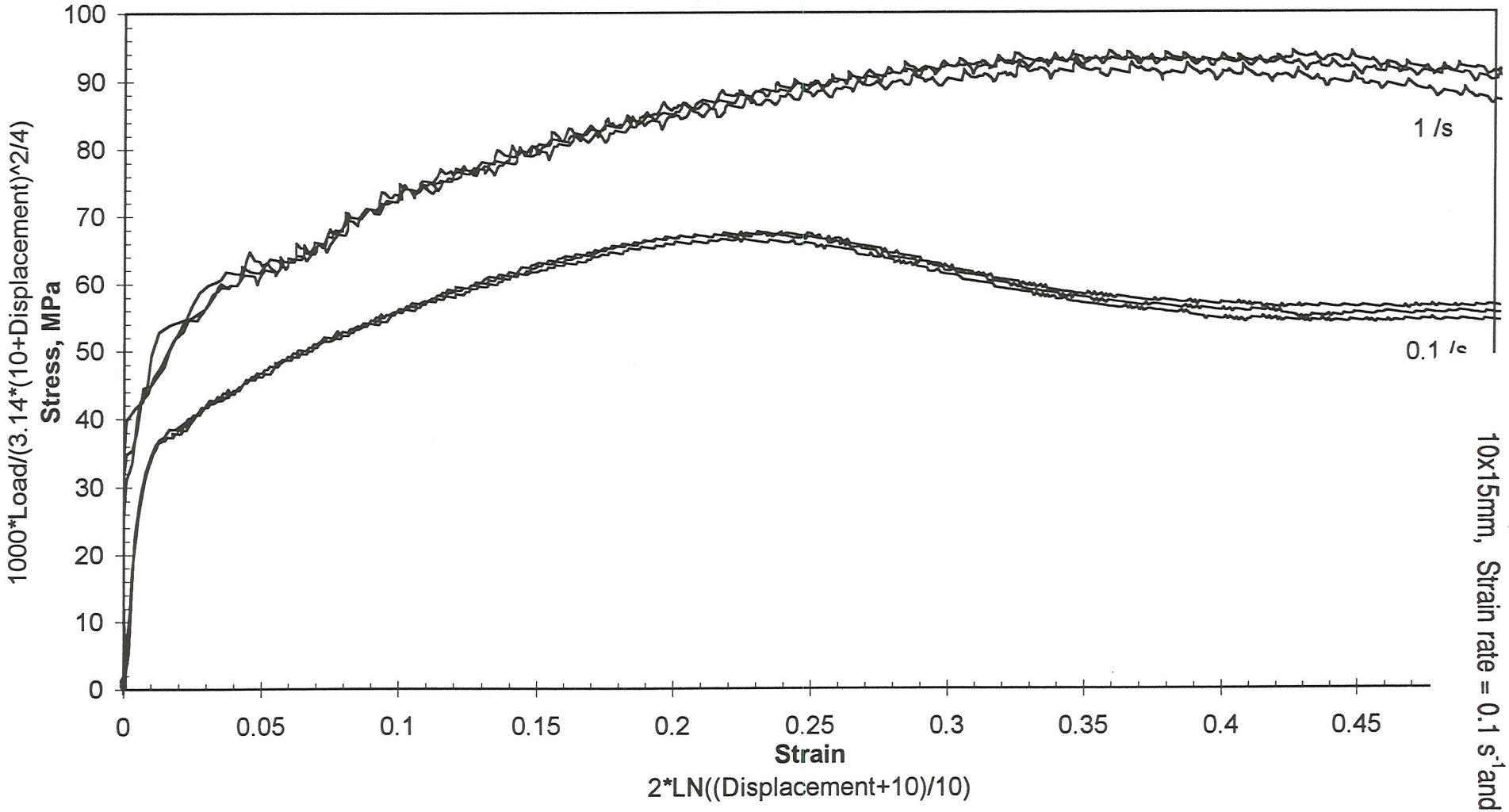
Oulu
Low C-Mn Steel
8x12mm, Strain rate = 0.1 s^{-1} and 1 s^{-1}

Oulu

Low C-Mn Steel, 1100°C

Specimen 10X15, Plate 3 (2nd RR)

mm



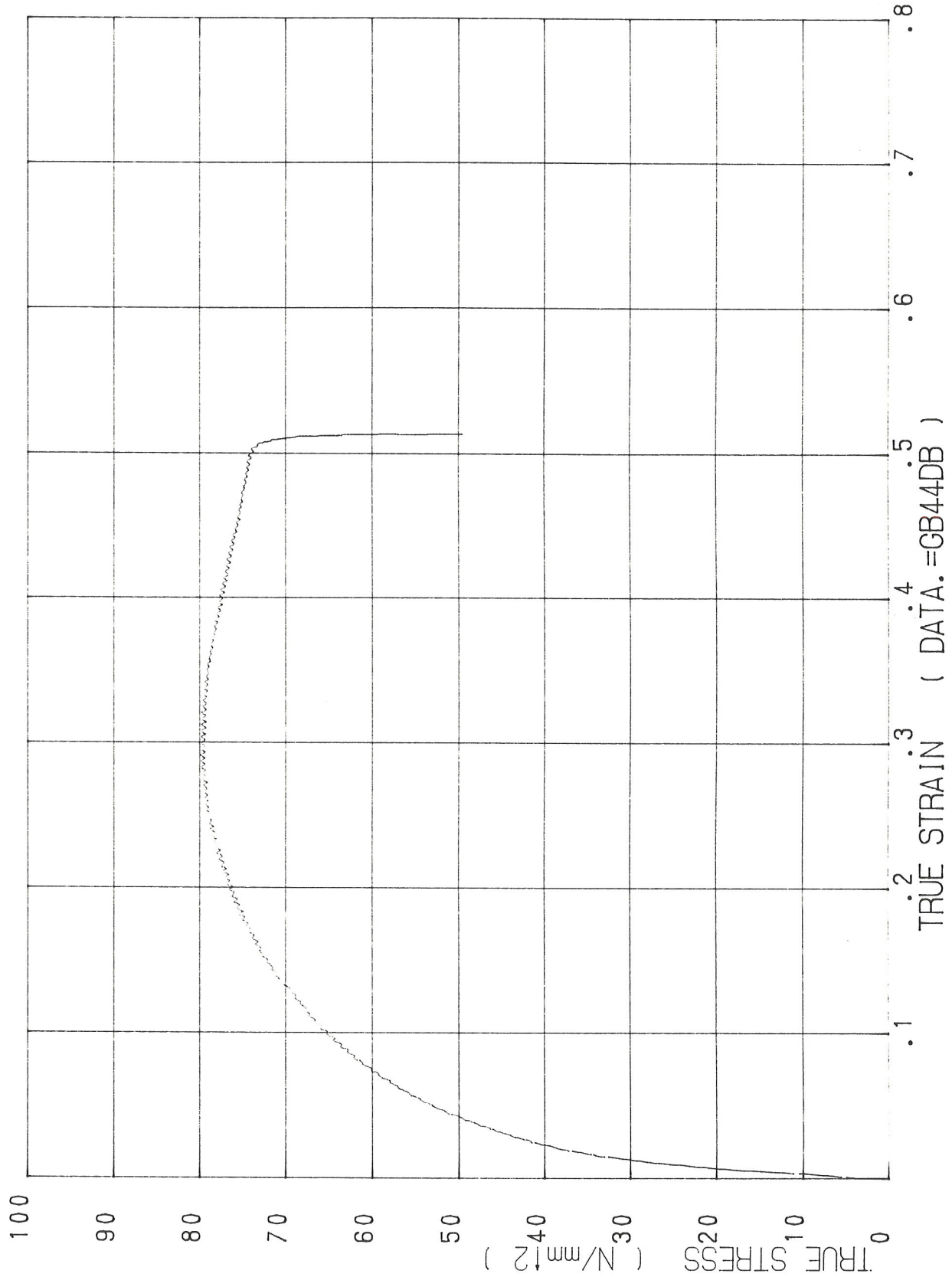
Oulu
Low C-Mn Steel
10x15mm, Strain rate = 0.1 s^{-1} and 1 s^{-1}

Low C-Mn Steel

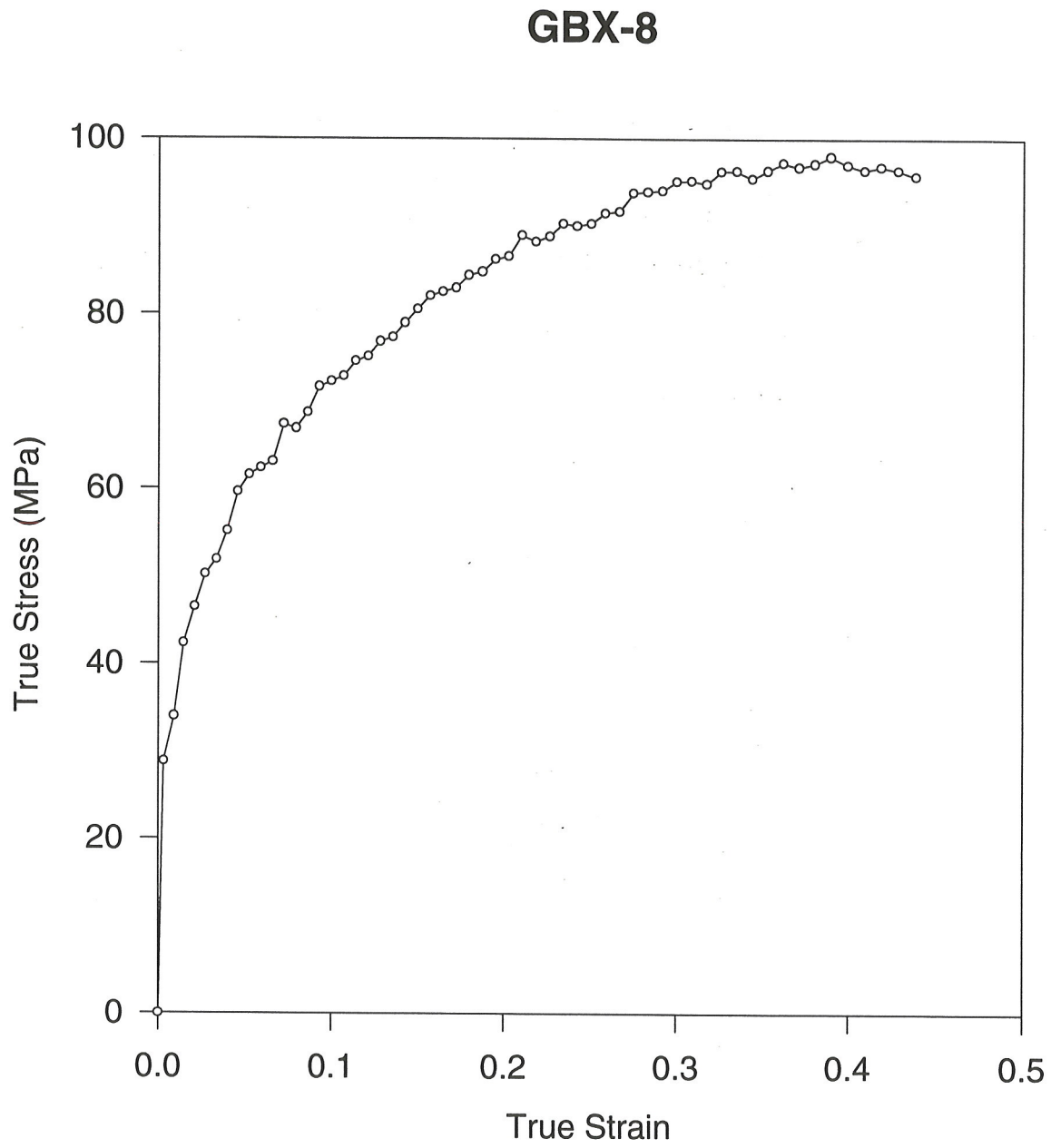
Strain Rate 1 s^{-1}

Cambridge	GBX 44
Swansea	GBX 8
Sheffield	GBX 67
British Steel	GBX 33
MPD	GBX 15
IMI	GBX 13

Cambridge
Low C-Mn Steel, GBX 44
Strain rate = 1 s^{-1}

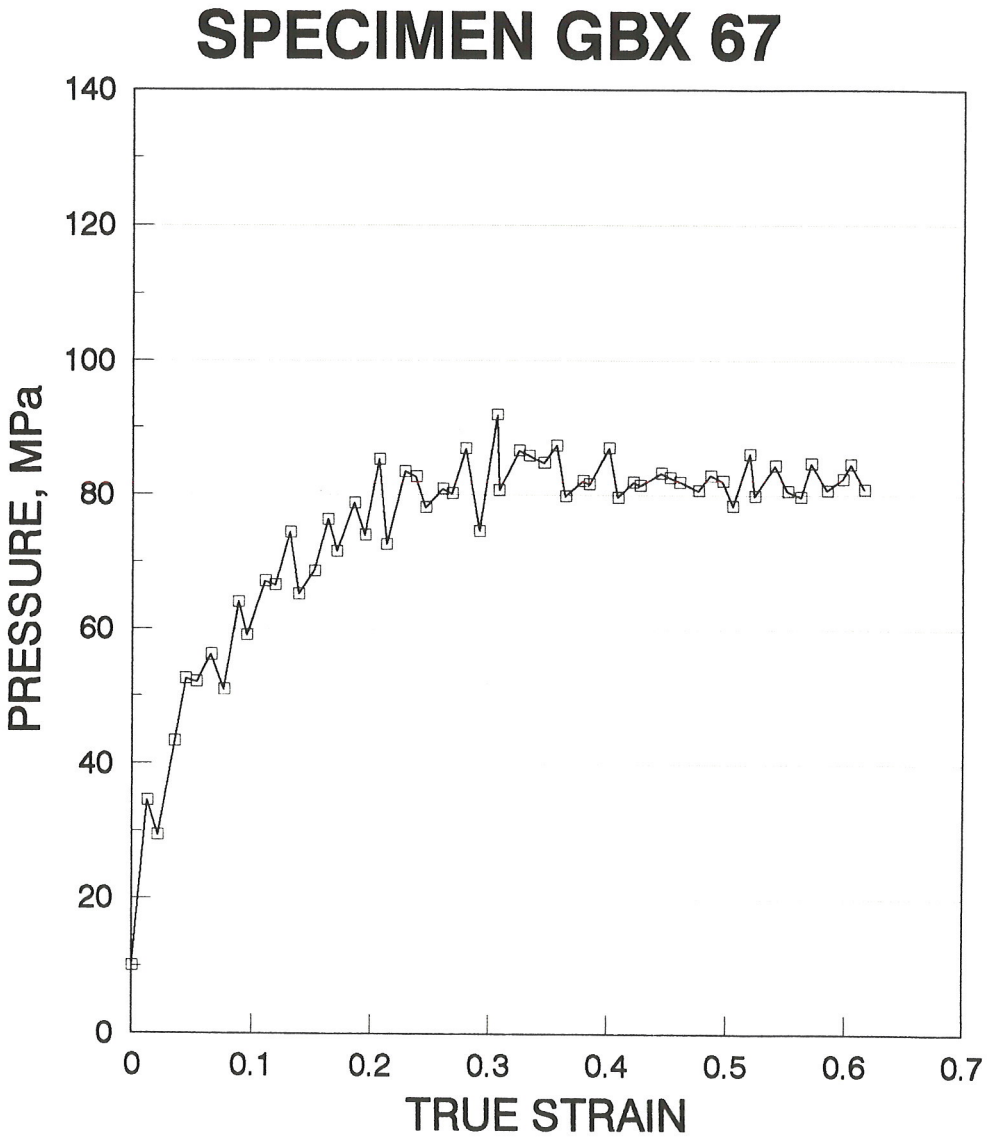


Swansea
Low C-Mn Steel, GBX 8
Strain rate = 1 s^{-1}



Swansea
Low C-Mn Steel
1 s^{-1}

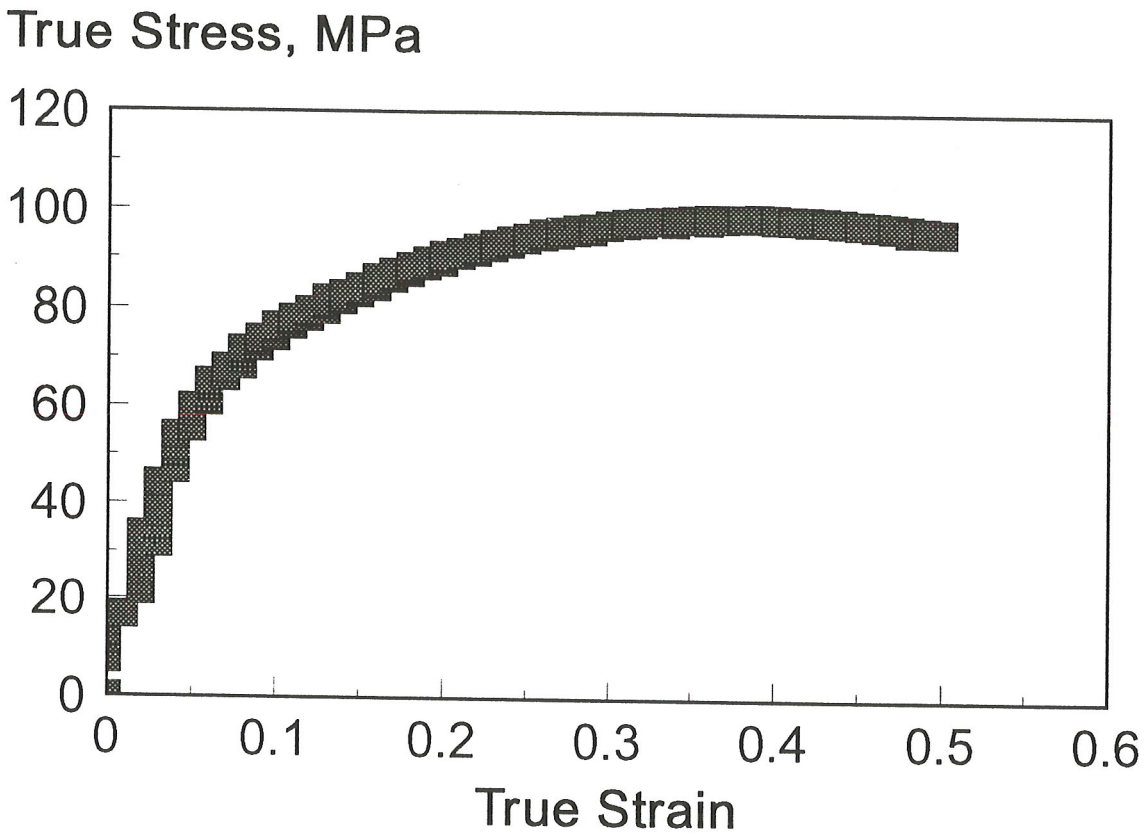
Sheffield
Low C-Mn Steel, GBX 67
Strain rate = 1 s^{-1}



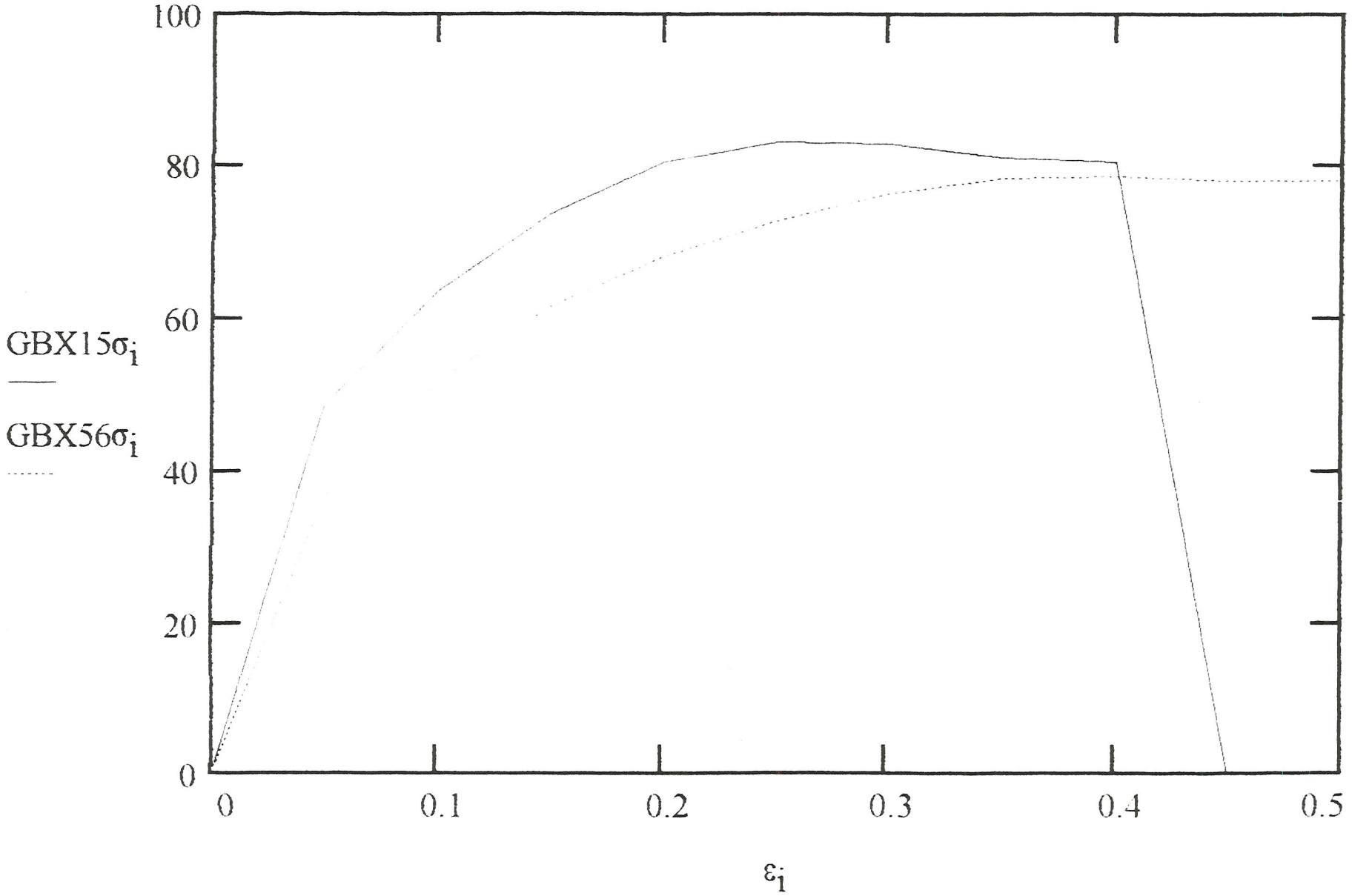
Sheffield
Low C-Mn Steel
1 s-1

British Steel
Low C-Mn Steel, GBX 33
Strain rate = 1 s^{-1}

Flow Curve for Carbon Steel at 1 s^{-1} (GBX 33)



British Steel
Low C-Mn Steel
1 s^{-1}



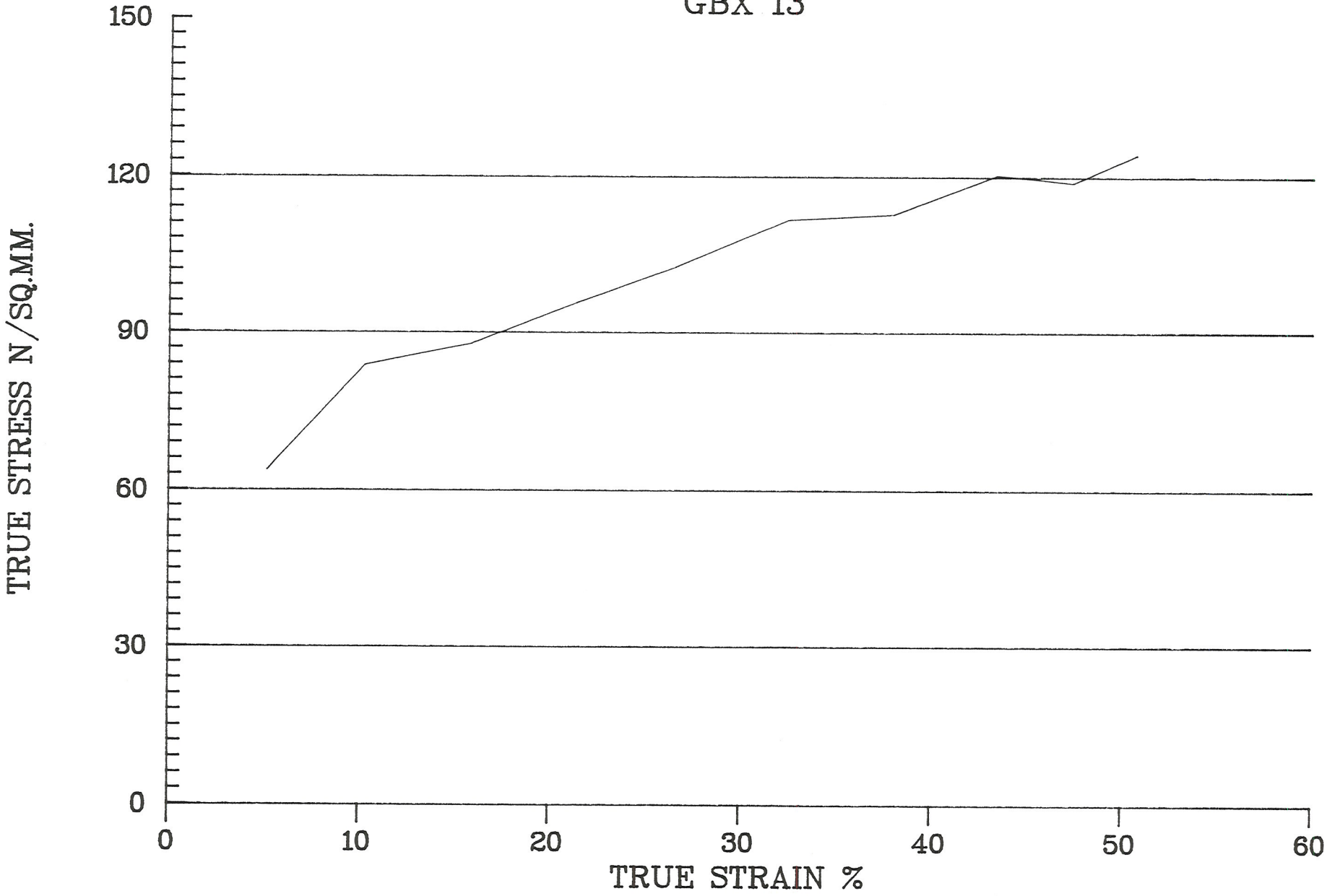
MPD
Low C-Mn Steel, GBX 15
Strain rate = 1 s^{-1}

True Strain.

Low C-Mn Steel tested at 1100 C and 1/second.

TRUE STRESS vs TRUE STRAIN %

GBX 13



IMI
Low C-Mn Steel, GBX 13
Strain rate = 1 s^{-1}

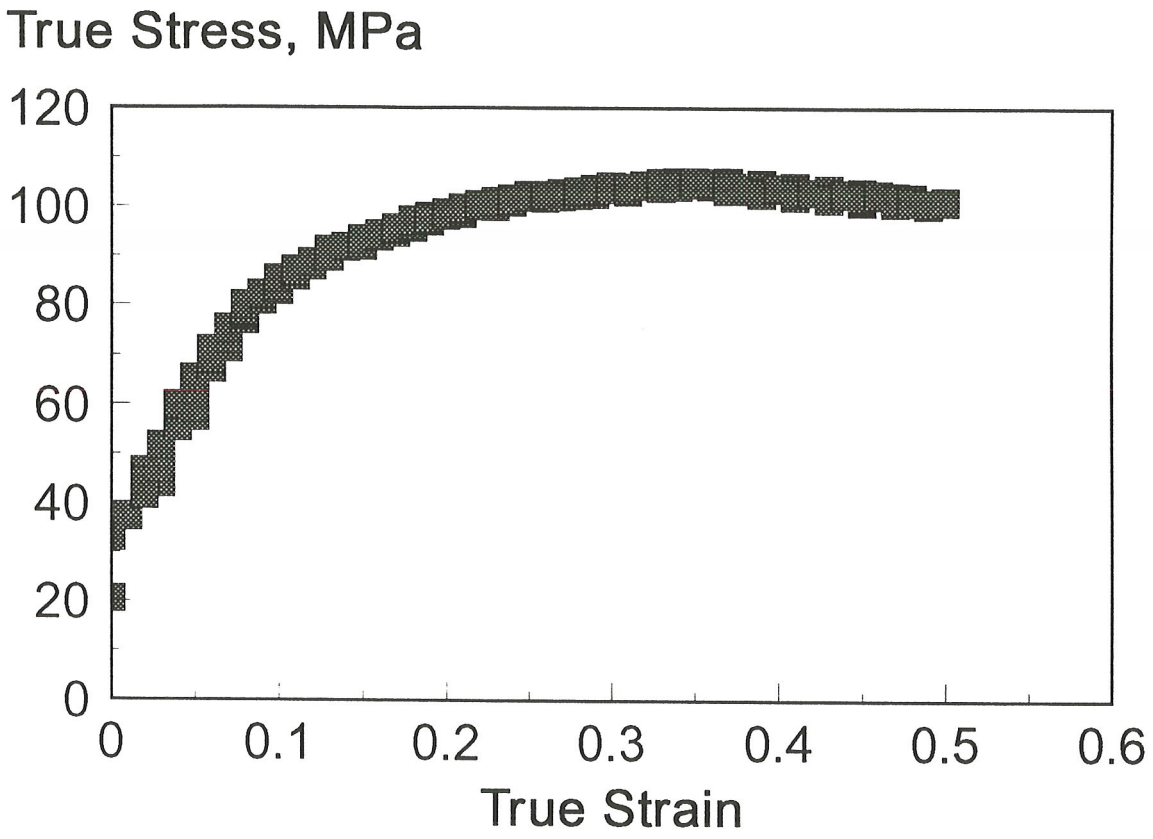
Low C-Mn Steel and Nimonic 901

Strain Rate 10 s^{-1}

British Steel	Low C-Mn Steel	GBX 55
Sheffield	Nimonic 901	EAT 70
Sheffield	Low C-Mn Steel	GBX 72
IMI	Nimonic 901	EAT 62
IMI	Low C-Mn Steel	GBX 60

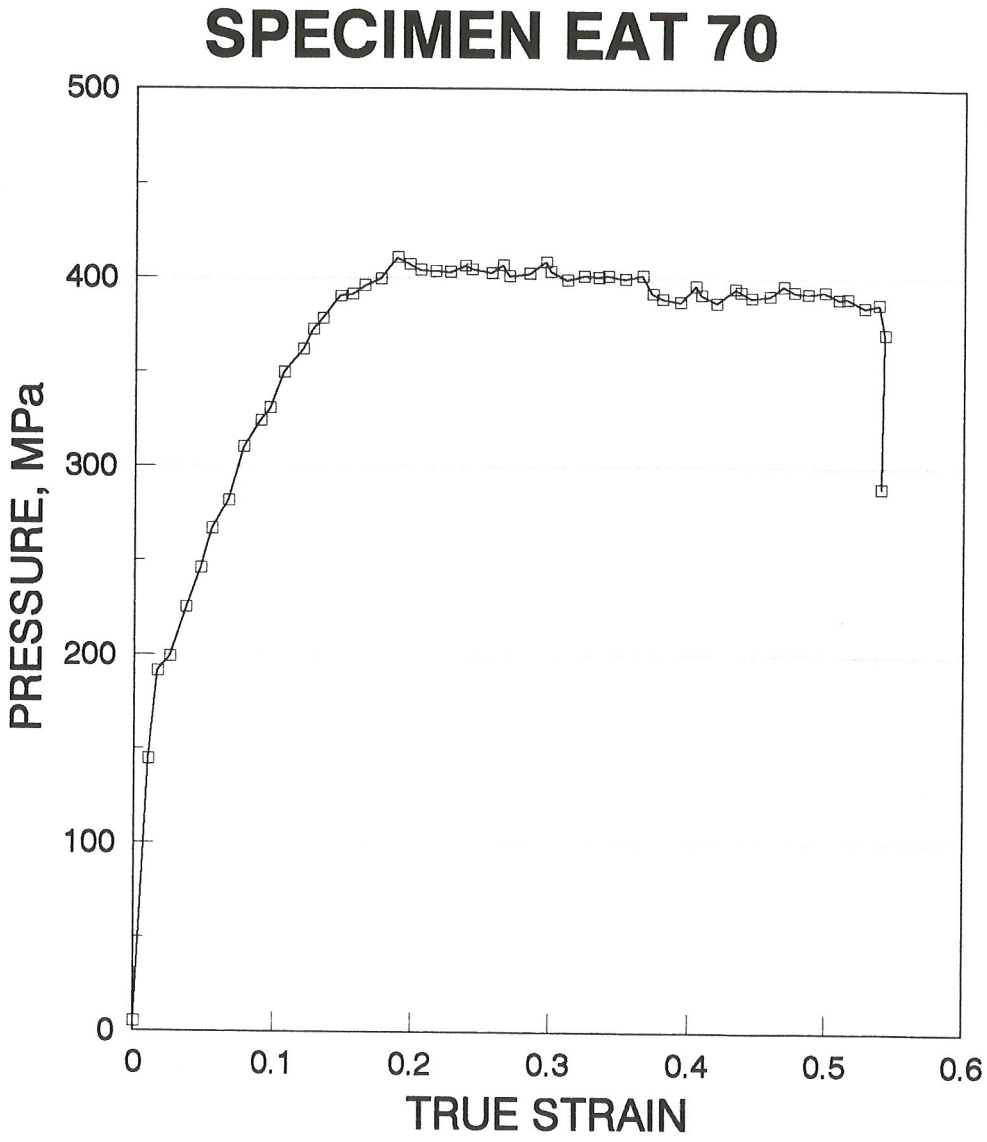
British Steel
Low C-Mn Steel, GBX 55
Strain rate = 10 s^{-1}

Flow Curve for Carbon Steel at 10 s^{-1} (GBX 55)



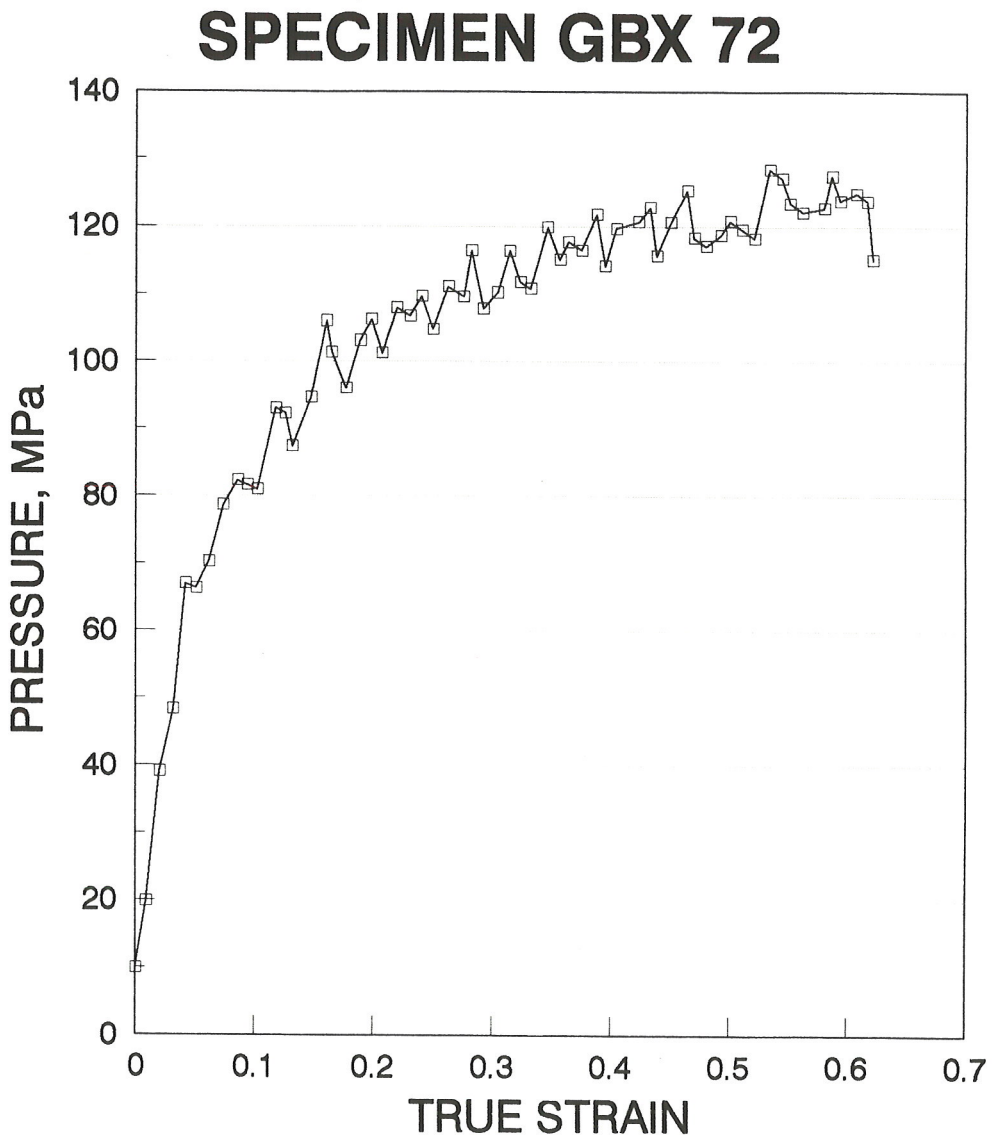
British Steel
Low C-Mn Steel
10 s^{-1}

Sheffield
Nimonic 901, EAT 70
Strain rate = 10 s^{-1}



Sheffield
Nimonic
10 s^{-1}

Sheffield
Low C-Mn Steel, GBX 72
Strain rate = 10 s^{-1}

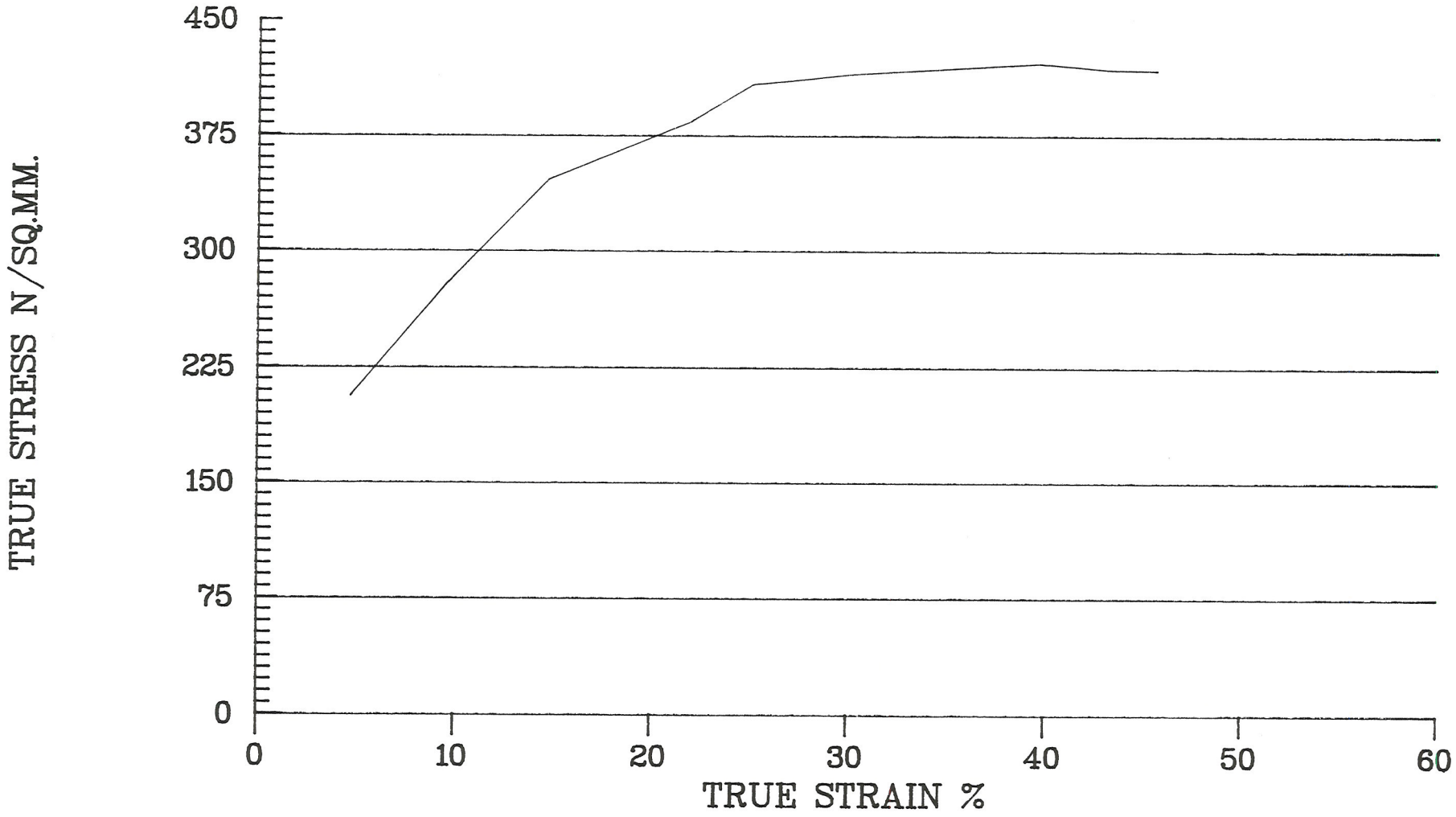


Sheffield
Low C-Mn steel
10 s^{-1}

TRUE STRESS vs TRUE STRAIN %

IMI
Nimonic 901
(nom) 10 s^{-1}

EAT 62

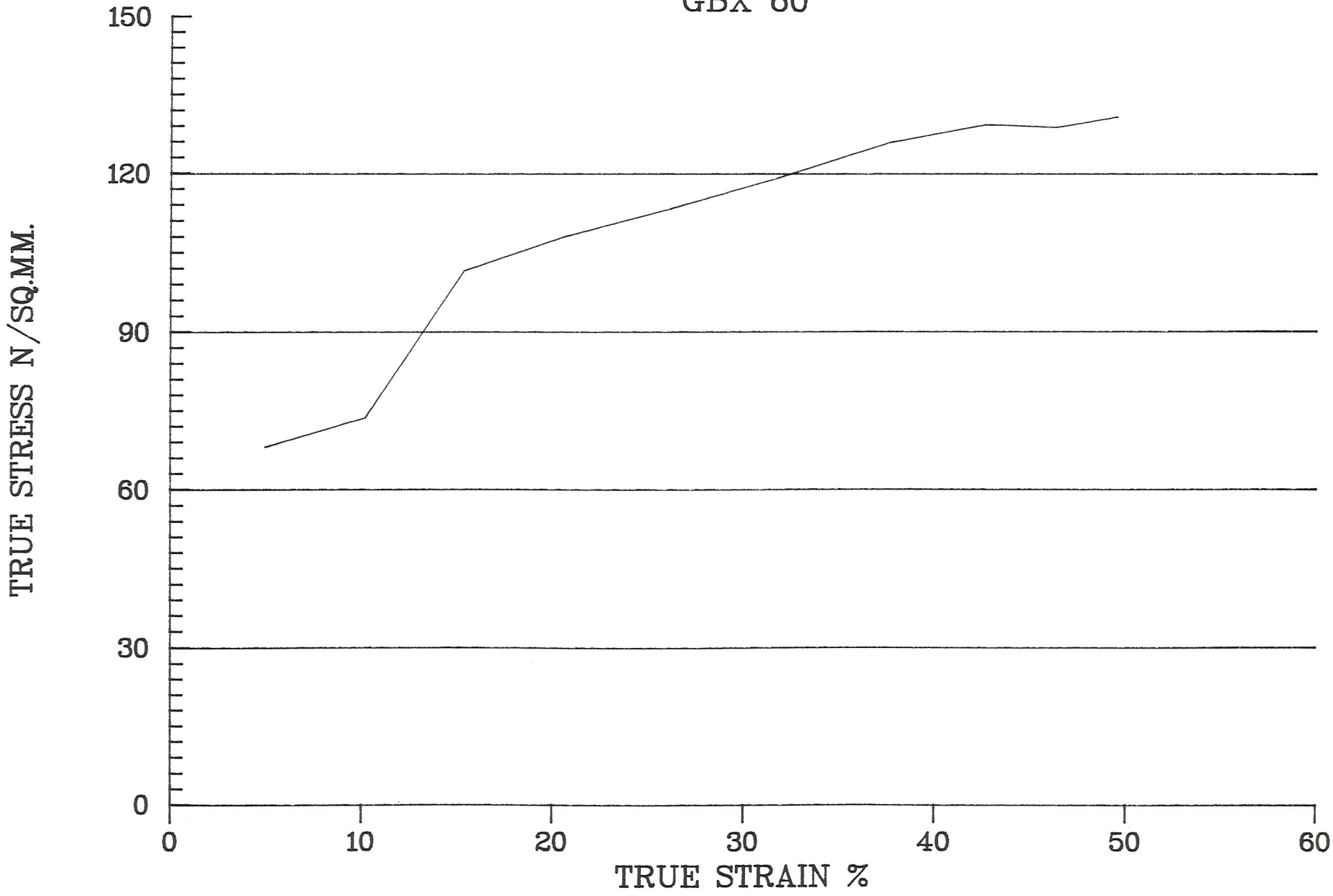


IMI
Nimonic 901, EAT 62
Strain rate = 10 s^{-1}

IMI
Low C-Mn Steel
(nom) 10 s^{-1}

TRUE STRESS vs TRUE STRAIN %

GBX 60



IMI
Low C-Mn Steel, GBX 60
Strain rate = 10 s^{-1}