PROPERTIES AND MICROSTRUCTURAL EVOLUTION IN HOT ROLLING SIMULATION OF Nb AND C-Mn STEELS

BY

A. R. Morgridge*

*Dr. Morgridge is in the Mechanical Engineering Department of the University of Ibadan, Ibadan, Nigeria

Abstract

Hot simulation has been carried out on the Gleeble 1500 on C-Mn and Nb steels, using 1,2 3 and 5 stage hot compression tests. Test temperatures were varied between 875°C and 1100°C; strain rates between 0.5 and 20s^{-1}; holding times between 0.5 and 30s and strain increments between 0.12 and 0.3 per stage. Metallographic samples were prepared for microstructural evolution measurements.

Maximum stresses obtained varied from 150MPa for Nb steel at 1100°C to 330MPa for C-Mn steel at 875°C.

Effects of variation of Temperature, strain, strain rate, and initial grain size were observed on static, metadynamic and dynamic recrystallisation through measurement of recrystallised grain sizes and observation of shapes of stress-strain curves.

Single peak, non-synchronised stress-strain curves were observed for both C-Mn and Nb steels, after dynamic recrystallisation. Dynamic recrystallisation was also observed to be strain rate and temperature sensitive.

Microstructures of C-Mn steel after static recrystallisation for increasing holding times between passes reveal grain boundary migration, recrystallisation and progressive grain growth characteristics. It was found, however, to be temperature and strain insensitive in contrast to dynamic recrystallisation. Metadynamic recrystallisation reveal strain independence, since strain had exceeded the value of the critical strain. Grain growth behaviour in C-Mn steel was observed metallographically and grain size measurements agreed to a large extent with the parabolic law governing grain growth behaviour in materials, proposed by Roberts [1]. Microstructural evolution in C-Mn and Nb steels was observed through measurement of austenite grain sizes at the end of each of the same 5 stage compression tests, for both steels. Models proposed by other workers have also been applied to present work and results analysed.

Nomenclature

σ	–	stress (MPa)
ε	–	strain
$\dot{\varepsilon}$	–	strain rate (s^{-1})
T	–	Temperature (^{o}C)
ε_c	–	critical strain
ε_s	–	saturation strain
H.T.	–	Holding time (s)
D_o	–	Initial Grain size (μm)
f.c.c.	–	face centred cubic
Cu	–	Copper
Ni	–	Nickel
D_{rex}	–	Recrystallised grain size (μm)
D	–	current grain size (μm)
Fig.	–	Figure
Eq^{n}	–	Equation

1. Introduction

Many hot forming processes involve deformation increments with short time intervals between each step during which some recovery and recrystallisation occurs and the subsequent yield stress level is reduced. The level of yield stress reduction is dependent upon whether recrystallisation is partial or full. Hence, the most improtant factor for mcrostructural evolution during hot forming is the control of recrystallisation which is ultimately responsible for grain refinement, especially where the hot-worked condition represents the final product microstructure. In some cases, recrystallisation during hot forming is deliberately retarded through the use of suitable alloying additions e.g. in controlled rolling of HSLA steels, where grain refinement of ferrite is achieved by virtue of transformation from heavily deformed unrecrystallised austenite [1]

Other important controlling parameters govening microstructural evolution include

a) Degree of deformation associated with each pass
b) Temperature at each pass or stage
c) Deformation rate at each stage
d) Holding time between passes
e) Cooling behaviour after completion of deformation
f) Degree of recovery and grain growth during holding time and during cooling after completion of deformation.

Recrystallisation can be static,metadynamic and dynamic in nature depending on the degree of prior deformation and the temperature of deformation. Grain growth of freshly recrystallised microstructures occurs in two stages (a) fast growth for a short time and (b) slow growth for a longer time.

Both stages can best be described by a parabolic law with different proportionality constants for the short and long times [2].

Theoretical microstructural evolution models sited in Roberts work [1] will be used to calculate evolving microstructural parameters and results compared with actual experimantal results obtained in the present work, wherein incremental hot compression tests have been performed using the Gleeble 1500.

2. Experimentation

Specimens of 2 steels: Nb and Plain carbon steels were machined to length 30mm and diameter 8mm for the tests. They were then resistance heated and subjected to 2, 3 and 5 stage hot compression tests at temperatures between 875°C and 1100°C with strain rate varied between 0.5 and 20s-1 at holding times between 0.5 and 30s. Strain increments for the 2 - stage compression test was 0.3 for each stage. Holding times were varied between 0.5 and 30s for both tests at 875°C and 950°C.

Tests were carried out on the Gleeble 1500, a computer controlled machine capable of performing diverse thermomechanical tests and simulations, under vacuum conditions. Gleeble computer programmes to effect 2 and 5-stage compression tests were developed, filed and used to carry out the tests. 1-stage compression programme was also developed to obtain continuous stress-strain curves for comparison with the stress-strain curves of the 2, 3 and 5-stage compression tests.

Tests were often repeated and found to give the same results showing the accuracy of the Gleeble. During testing, force, holding times, and lengthwise strain measurements were automatically recorded and stored in the computer. These were retrieved after each test through the computer plotter system in the form of force-strain diagrams. Specimens were allowed to cool to room temperature at the rate of 40°C/s after tests. Metallographic samples from the deformed specimens were prepared and analysed.

Composition of the 2 steels are presented in Table 1. Summary of experimental results are presented in Tables 2-5. Micrographs from metallographic examinations are presented in Fig. 3.

3. Discussion

3.1 Dynamic recrystallisation (strains

For the plain carbon and the alloy steels, the stress-strain curves exhibit maximum peak stress (between = 0.8 (Fig. 1). The slowness of recovery during continuous deformation allows a driving force large enough for full dynamic recrystallisation to be achieved. The shapes of these curves typify what obtain for f.c.c. metals and alloys with intermediate or low stacking fault energy e.g. Cu, Ni, austenitic steels. High initial grain boundary mobility and high nucleation rate, associated with high strain rate, may also be an additional factor contributing to the occurrence of dynamic recrystallisation. Dynamic recrystallisation occurs through a process of repeated nucleation and limited growth of new grains. Nucleation of recrystallised grains along the grain boundaries, occurs at the critical strain c. Continued straining beyond c creates new nuclei at additional grain boundaries, until all these have been exhausted. Subsequent nucleation occurs at the boudary between the recrystallised and

unrecrystallised sections until eventually the recrystallised sections impinge at the centre of the original grains. This concurrent straining eventually reduces the driving force for grain boudary migration, leading to limited growth of newly recrystallised grains (Drex). Drex varies very little as fraction of recrystallised section increases [3].

The critical strain ε_c varies from one boundary to the next giving rise to the typical single peak, non synchronised stress-strain curves [4]. The rate of dynamic recrystallisation is, however, very sensitive to the initial grain size (Do) as has been observed by many workers [3] [5].

At temperatures above the recrystallisation temperature Tr, steels have undergone continuous large pass strains above $\varepsilon = 0.7$, hence dynamic recrystallisation. Values of the critical strain ($\varepsilon_c = \varepsilon_{max}$ corresponding to position of maximum stress) and the saturation or steady state stress ε_s are found to be very sensitive to the strain rates applied during deformation. This is shown in Fig. 2. Values of ε_s increased from 0.76 to 0.96 for a strain rate increment from 1.0 to 12s-1 for C-Mn at 875°C. Similar results are observed for Nb steel at the same temperature.

3.2 Static recrystallisation (Strains $\varepsilon \leq \varepsilon_c$)

This occurs during the holding time, after prior deformation, through a process of repeated nucleation at pre-existing grain boundaries, and continuous growth of all newly recrystallised grains. Differential dislocation density drives grain boundary migration during the latter stages of static recrystallisation, hence rapid grain growth [1].

Fig. 3 shows a sequence of micrographs of C-Mn steel illustrating typical features of static recrystallisation after prior hot compression to $\varepsilon = 0.3$. Temperature was 950°C and prior strain rate of $12s^{-1}$. Grain boundary migration, recrystallisation and progressive grain growth could be observed with increase in holding times i.e. 10s and 30s. Static recrystallisation kinetics depend strongly on strain (driving force) and on pre-existing grain size [6]. It does not seem to be strain rate or temperature dependent in contrast with dynamic recrystallisation. This is illustrated by Fig. 4. Statically recrystallised grain size for Nb varies very little (23 to 25um) as temperature increases from 875°C to 950°C. Similar result is observed for C-Mn steel at the same temperature. Large reduction in grain size can however be observed for strain increment 0 to 0.2 for both steels. Initial grain size (Do) also affects the final statically recrystallised grain size. (Fig. 4.).

3.3 Metadynamic recrystallisation ($\varepsilon_c < \varepsilon < \varepsilon_s$)

Metadynamic recrystallisation proceeds in two stages

a) Recrystallisation of regions not previously recrystallised dynamically (if $\varepsilon < \varepsilon_s$)

b) Reaction of remaining areas as a result of the residual dislocation density in the dynamically formed grains [1].

Metadynamically recrtystallised structures will therefore be heterogeneous since stages (a) and (b) will result in different recrystallised grain sizes. Reaction here proceeds over a longer relative interval than does static recrystallisation because of the decrease in driving force involved with the transition from stage (a) to (b).

It has been observed by several workers that the size of the metadynamically recrystallised grains (Drex) becomes almost strain independent once $\varepsilon > \varepsilon_c$ [1][5]. Value of Drex after static, metadynamic and dynamic recrystallisation have been shown in Fig. 5. With increase in temperature from 875°C to 950°C, Drex values for both metadynamic and dynamic recrystallisations however remain strain insensitive since ε_c had been exceeded, even though slightly more temperature dependent as mentioned earlier (Fig. 5).

3.4 Grain Growth

Roberts [2] suggested that the grain growth behaviour of freshly recrystallised microstructure is best described by a parabolic law with different proportionality constants for short and long times i.e.

$$D^2 = D_{rex}^2 + k_1 t \quad (t < t_{bp}) \qquad (1)$$

and

$$D^2 = D_{bp}^2 + k_2 t \quad (t > t_{bp}) \qquad (2)$$

where $k_1 >> K_2$ and where the breakpoint for transition from fast to slow growth ($t_{b.p}$) decreases with increased temperature. For C-Mn austenite, he further evaluated the temperature dependence of k_1, k_2 ($in\ \mu m^2 \cdot s^{-1}$) as

$$\log k_1 = 6.6 - 6200/T$$

and

$$\log k_2 = 8.1 - 9000/T$$

Fig. 6 compares the experimental and calculated (according to equations 1-4) grain growth characteristics following static recrystallisation of

C-Mn austenite; $\varepsilon = 0.2$, $\dot{\varepsilon} = 12s^{-1}$, Temperature 950°C. The suggested equations appear to fit well with experimentally observed points except for the initial point (t = 0) where calculated Drex is slightly less than experimentally observed Drex.

It can be postulated thus that newly formed, recrystallised grains have a shape far from the equilibrium one, with pronounced local variations in curvature. This promotes a high growth rate until an equilibrium shape is attained; the growth rate then drops to a level characteristics of annealing experiments [2].

Fig. 7 shows observed values of austenite grain sizes in Nb and C-Mn steel at the end of each of the 5 passes. Holding time between each pass was 3s at 950°C using strain rate of $\dot{\varepsilon} = 3.0s^{-1}$. Initial grain size of Nb (Do) was 48um, while that of C-Mn was 37um. The C-Mn steel is seen to grain refine continuously throughout the 5 passes. Grain size of the Nb steel initially slightly increased after the first pass due to recrystallisation but grain refines progressively thereafter. Grain refinement in C-Mn steel was from 37um while it was from 48um down to 20um in the Nb steel. The figure represents the microstructural evolution in the two steels dirung hot deformation.

Grain growth, during cooling, at the end of the five passes was however much more rapid in the C-Mn steel than the Nb steel.

4. Conclusions

4.1 To ensure more confidence in experimental results, variations in temperature (875°C - 1100°C); strain rate (0.5 - 20s^{-1}); Holding time (0.5 - 30s); strain increments (0.12 - 0.3) have been carefully chosen to reflect actual conditions that exist during typical hot working processes e.g. open die forging, plate rolling and strip rolling.

4.2 Results may serve as basis for more accurate calculations of load/stress requirements for hot working, which in turn are prerequisite for improved process control in industrial plants.

4.3 Recrystallisation in association with hot working is an important controlling factor for microstructural evolution, level of flow stress and hot workability.

4.4 Models following a parabolic law utilised in the present work have accurate predictive capabilities.

4.5 Dynamic recrystallisationis both strain rate and temperature sensitive.

4.6 Static recrystallisation is both strain and temperature insensitive.

4.7 Metadynamic recrystallisation reveal strain independence once critical strain value is exceeded.

Acknowledgement

My sincere thanks go to Oulu University, Finland for the financial assistance provided and Prof. P. Karjalainen, Head of Materials Testing Laboratory of the same University for the provision of research facilities.

References

1) W. Roberts (1986). Strength of Metals and Alloys (edited by J.J. McQueen et al), p. 1859. Pergamon Press, Oxford.

2) W. Roberts et al. (1984). In HSLA steels: Technology and Applications, p. 67, ASM, Metals Park, OH.

3) J.P. Sah et al, (1974). Met. Sci. 8. 325.

4) J.J. Jonas and T. Sakai (1983). in Defor mation, Processing and structure (edited by G. Krauss, p. 185, ASM, Metals Park, OH.

5) R.W. Pethen and R.W.K. Honeycombe, (1973). Reprints of Int. Conf. on Recrystallisation in the control of micro structure, Iron and steel Institute/Institute of Metals, London.

6) C.M. Sellars and J.A. Whiteman, (1979). Met. Sci., 13, 187.

Table 1

Composition of steels

Steel Designation	Weight Percentage									
	C	Si	Mn	P	S	V	T_1	Nb	Cr	Mo
C-Mn	0.18	0.2	0.8	0.04	0.045	0.09				
Nb	0.081	0.26	0.43	0.014	0.003	0.009	0.003	0.03	0.021	0.003

Table 2

Summary of results of Continuous or 1-stage Compression tests

Temp. °C	Strain rate $\dot{\varepsilon}$ (s^{-1})	Stress values at ε=0.3, 0.6 and 0.9					
		C-Mn			Nb		
		ε=0.3	ε=0.6	ε=0.9	ε=0.3	ε=0.6	ε=0.9
875	1.0	263	240	210	212	194	185
	9.5	318	296	267	230	233	228
	12.0	324	330	288	245	244	234
950	9.5	265	259	231	224	209	200
	12.0	270	262	240	220	216	190
	20.0	268	287	271	225	224	214

Table 3

Summary of results of '2 stage' compression tests

Temp. (°C)	Strain rate $\dot{\varepsilon}$ (s^{-1})	Holding time (s)	Peak stresses (MPa)			
			C-Mn		Nb	
			ε=0.3	ε=0.6	ε=0.3	ε=0.6
875°C	1.0	0.5	264	240	212	183
	9.5	0.5	315	290	224	209
		1.0	321	258	235	221
	12.0	0.5	326	296	238	229
		1.0	322	255	245	215
		3.0	322	252	242	203
		10.0	326	254	252	210
		30.0	324	253	248	210
950°C	9.5	0.5	264	239	225	215
		1.0	273	219	222	199
		3.0	265	213	224	184
		10.0	271	210	226	199
	12.0	0.5	268	239	215	205
		1.0	279	222	219	196
		3.0	268	210	214	184
		10.0	274	214	229	189
		30.0	271	210	228	189
	20.0	1.0	264	223	227	200
		3.0	270	210	226	189
		10.0	270	211	220	190

Table 4

Summary of results of '3 stage' compression tests

Temp. (°C)	Strain rate $\dot{\varepsilon}$ (s^{-1})	Holding time (s)	Peak stresses (MPa) C-Mn steel		
			ε=0.2	ε=0.4	ε=0.6
950	20.0	1.0	243	235	191
1000	20.0	1.0	221	208	171

Table 5

Summary of results '5 stage' Compression Tests

Temp. (^{o}C)	Strain rate $\dot{\varepsilon}$ (s^{-1})	Holding time (s)	Peak stress (MPa)									
			C-Mn					Nb				
			ε=.12	ε=.24	ε=.36	ε=.48	ε=.60	ε=.12	ε=.25	ε=.36	ε=.48	ε=.60
1100	0.5	2.0	120	131	121	100	92	103	112	100	88	82
1100	3.0	2.0	140	152	135	115	106	120	139	126	112	110

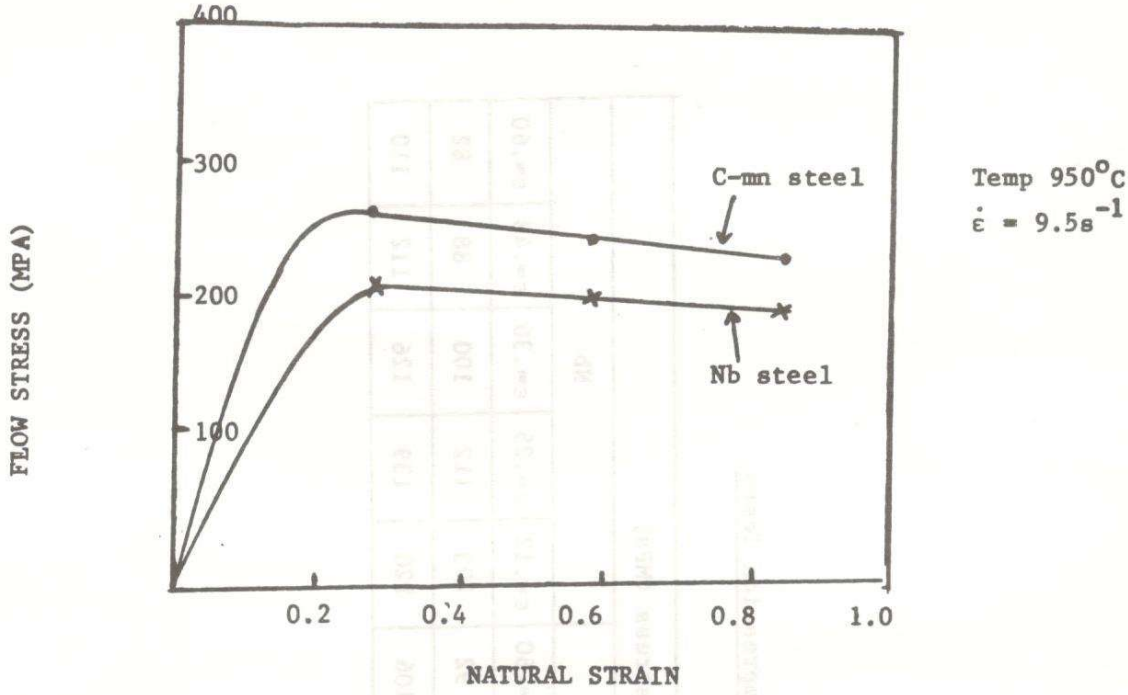


Fig. 1: Shape of σ-ε curve when restoration proceeds through dynamic recovery and recrystallisation.

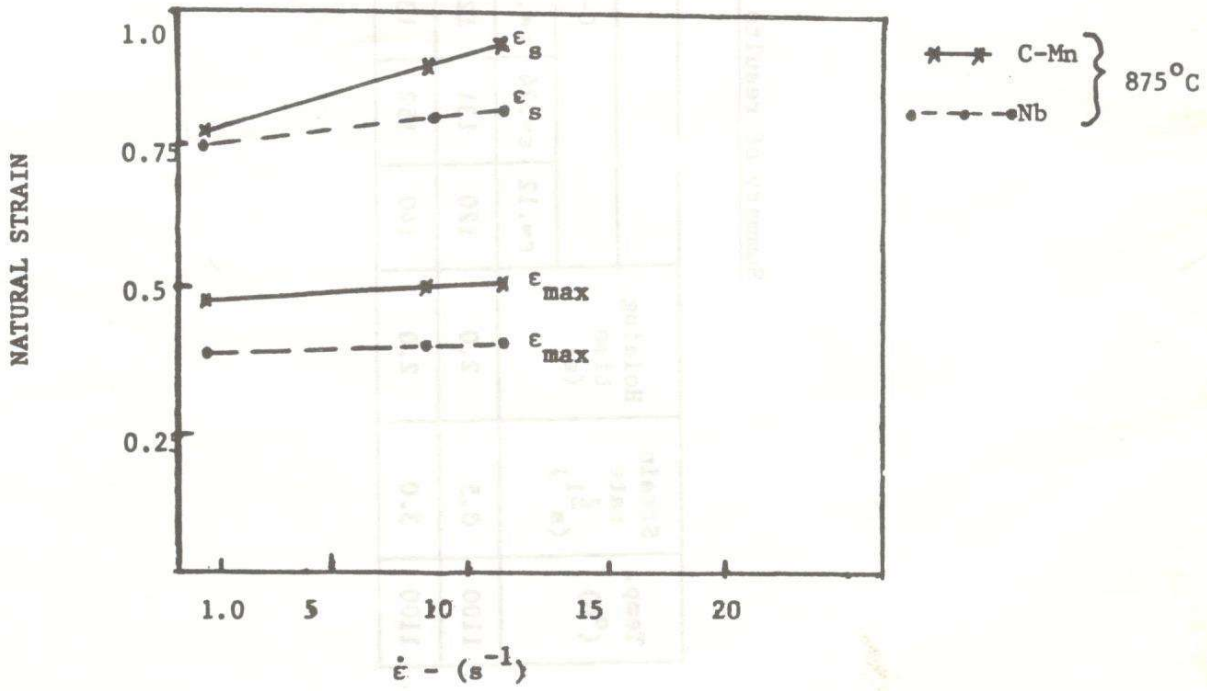


Fig. 2: Dependence of ε_{max} and ε_s on strain rates for two steels Nb and C-Mn. $\dot{\varepsilon}$ varied between 1 and 12s^{-1} at 875°C.

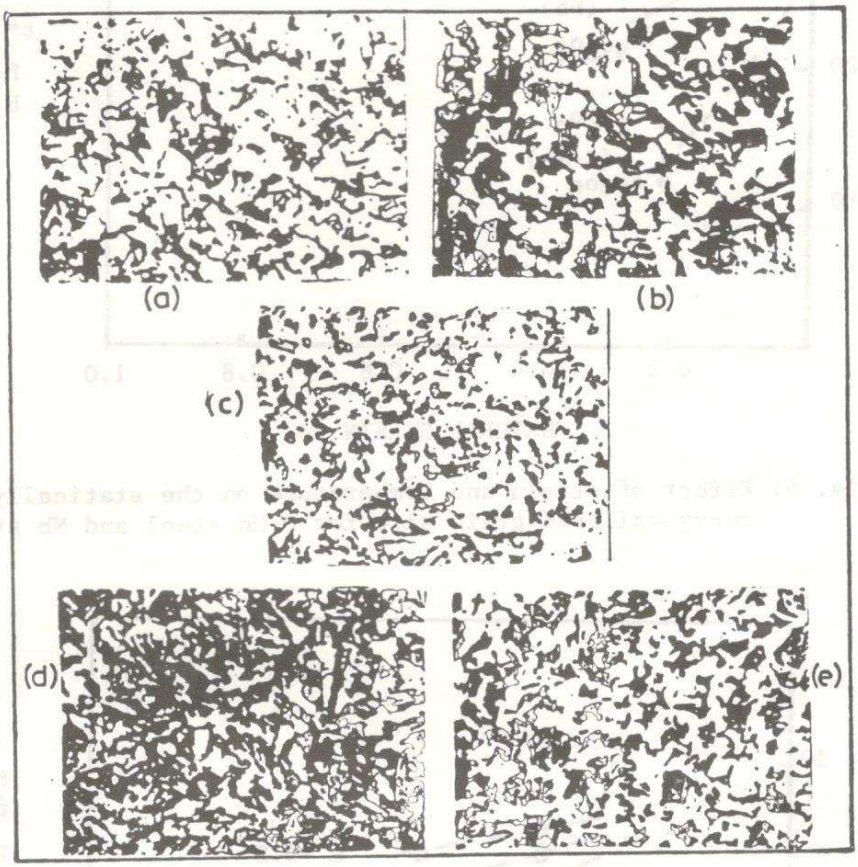


Fig. 3: Static recrystallisation in C-Mn steel previously deformed to $\varepsilon = 0.3$, $T = 950°C$, $\dot{\varepsilon} = 12s^{-1}$, Holding times (s): (a) 0.5 (b) 1.0 (c) 3.0 (d) 10.0 (e) 30.0s.

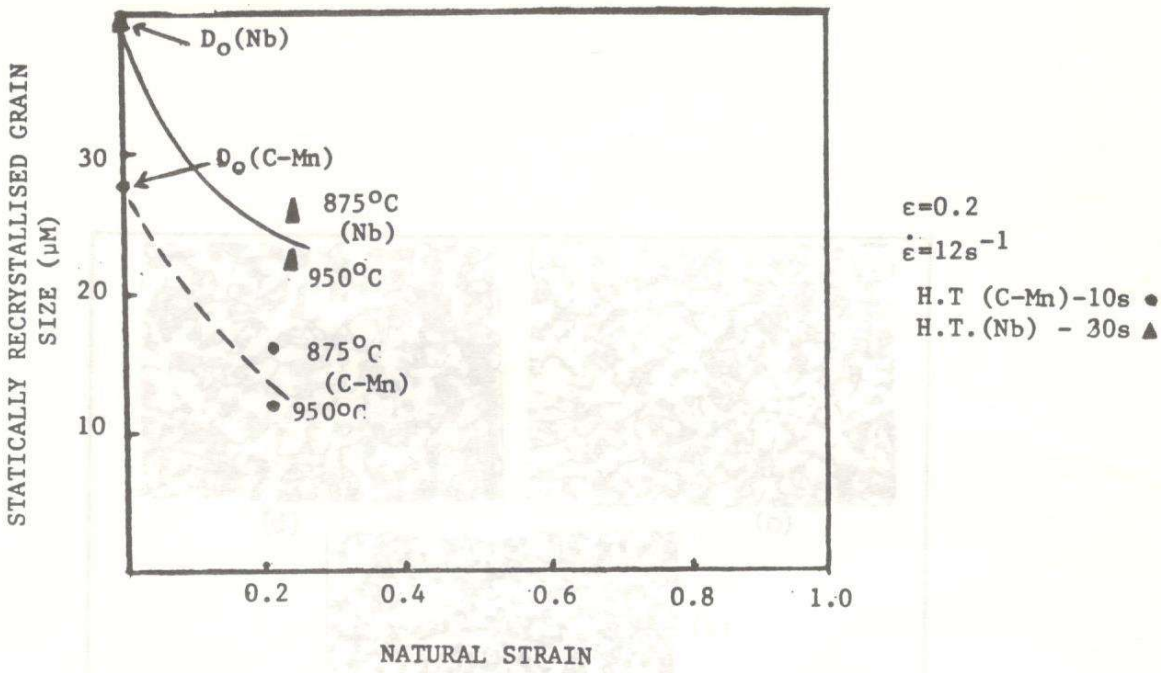


Fig. 4: Effect of strain and temperature on the statically recrystallised grain size for C-Mn steel and Nb steel.

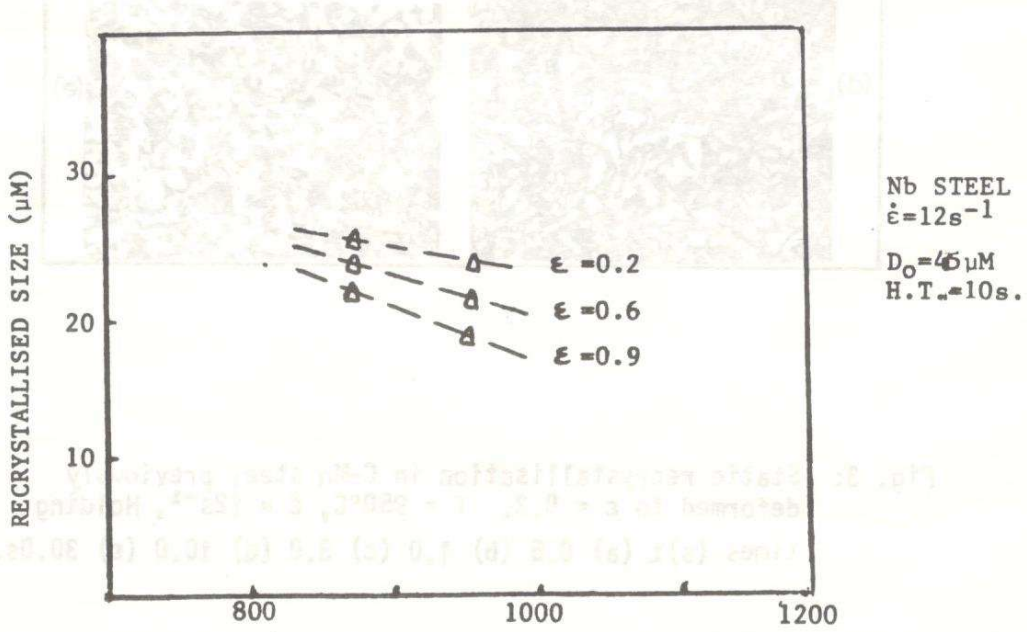


Fig.5: Effect of Temperature on recrystallised grain size for strains (0.2) static, 0.6 (metadynamic) and 0.9 (dynamic) for Nb steel.

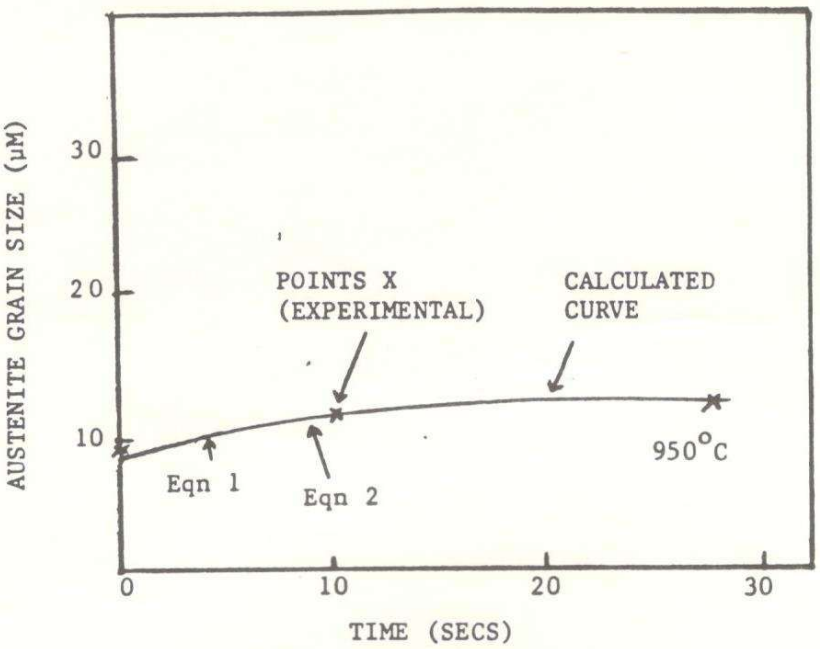


Fig. 6: Comparison of experimental and calculated grain growth characteristics following static recrystallisation of C-Mn austenite, $\varepsilon=0.2$, $\dot{\varepsilon}=12s^{-1}$, Temps. 950°C. (Calculated according to Equations (1) and (2)).

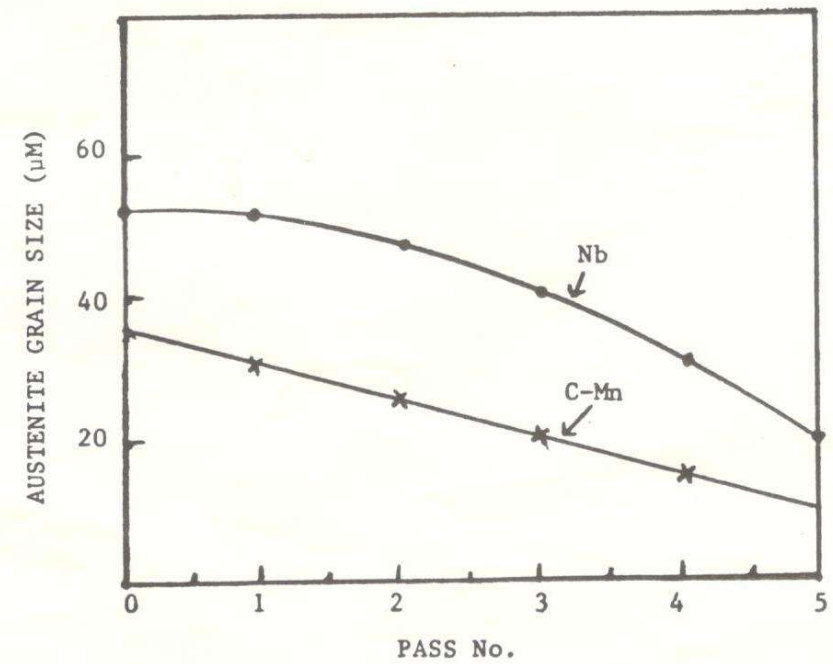


Fig. 7: Microstructural evolution in C-Mn and Nb austenites after undergoing the same 5-stage compression test.