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Laboratory simulation of the strip rolling of plain carbon and niobium-microalloyed steels

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SYNOPSIS

Multiple-pass hot-strip-rolling schedules of carbon steels and niobium-microalloyed ferrite–pearlite steels were simulated on a Gleeble 1500 thermomechanical test apparatus. The effects of finishing temperature, coiling temperature, and chemical composition on the as-deformed ferrite grain size and hardness of the steels were determined.

Low finishing temperatures and low coiling temperatures both contributed to ferrite grain refinement. Good agreement was found for the microstructure and hardness of the steels between the as-rolled condition and the results obtained from rolling simulations. The progress of recrystallization and precipitation was followed from examinations of the flow-stress curves during the hot-rolling simulations. The flow-stress behaviour during the finishing passes was consistent with the resulting changes in final ferrite grain size. It was found that the no-recrystallization temperature, T_{NR}, is raised by increased additions of niobium.

SAMEVATTING

Veelvuldigesteek warmbandwalsskedules van koolstofstale en Nb-mikrolegeerde ferrities/perlitiese stale is met behulp van 'n Gleeble 1500 termomeganiesetoets-apparaat gesimuleer. Die effek van walsvoltooiingstemperatuur, haspeltemperatuur en chemiese samestelling op die ferrietkorrelgrootte en hardheid van die stale, is bepaal.

Lae walsvoltooiingstemperature en haspeltemperature bevorder ferrietkorrelverfyning. Goeie ooreenstemming is verkry vir die mikrostruktuur en hardheid van die stale tussen die soos-gewalste toestand en die walssimulasietoestand. Die verloop van herkristallisasie en presipitasie is waarneembaar uit die maksimumvloeispanning-gedrag tydens die walsvoltooiingstappe. Die maksimumvloeispanning-gedrag is versoenbaar met veranderinge in die finale ferrietkorrelgrootte. Daar is gevind dat die geenherkristallisasie-temperatuur, T_{NR}, verhoog met toenemende Nb-byvoegings.

INTRODUCTION

Traditionally, the optimization of mill-processing parameters, in order to achieve desired mechanical properties in strip steels by means of microstructural control, was done on a trial-and-error basis. The refinement of grain size is the only mechanism by which the strength and ductility of a steel can be improved simultaneously[1–3]. With the introduction of sophisticated laboratory equipment such as the Gleeble 1500 thermomechanical test apparatus, it is now possible to simulate a wide range of thermomechanical treatments in the laboratory. The accurate simulation of temperature, strain, and strain rate in the laboratory reduces the cost and time required for the optimization of strip-rolling schedules in order to give the desired mechanical properties.

The objectives of the work described here were to determine whether the microstructure and strength data obtained from strip-rolling simulations on the Gleeble apparatus compared favourably with the results obtained from actual as-rolled strip steel, and to determine the effects of finishing temperature, coiling temperature, and chemical composition on the final microstructure and hardness of carbon and niobium-microalloyed steels. The relationship between flow-stress behaviour and final microstructure was also examined.

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EXPERIMENTAL PROCEDURE

The chemical composition of the five steels studied are given in Table I. The strip samples, mill-schedule data, and tensile-test results of the steels were supplied by Iscor's Vanderbijlpark Hot Strip Mill. A typical hot strip-rolling schedule at Vanderbijlpark Works is given in Table II. The average finishing temperature currently aimed at is 875 to 910°C, and the coiling temperature is varied between 750 and 600°C. No rolling simulations were performed on steel E owing to a lack of material, although the mill-schedule data and tensile-test results for this steel were used in the regression analysis.

Rectangular specimens, shown in Figure 1, were machined (10 x 10 x 18 mm^3) from as-rolled material. All the specimens were austenitized at the aimed mill reheating temperature of 1250°C for 15 minutes, followed by cooling to the first roughing-pass temperature at a rate of 3,5°C·s^{-1}. Since the specimens were of a much smaller volume than industrial billets, a holding time of 15 minutes at 1250°C

Table I

Chemical composition of steels in percentages by mass

Steel	C	Mn	Si	P	S	Al	Nb
A	0,052	0,22	0,005	0,017	0,090	0,037	–
B	0,150	0,65	0,013	0,016	0,012	0,038	–
C	0,054	0,33	0,154	0,006	0,019	0,048	0,016
D	0,070	0,84	0,226	0,013	0,023	0,039	0,027
E	0,100	1,50	0,340	0,014	0,011	0,026	0,030

Ni, Cr, and Mo are present in trace quantities

Table II

Typical rolling schedule at Vanderbijlpark Hot Strip Mill (North Works)

Pass	Temp. °C	ε mm/mm	q s^{-1}	t s
R1	1220	0,40	10	9
R2	1206	0,30	10	9
R3	1187	0,35	10	9
R4	1177	0,40	12	9
R5	1150	0,25	12	9
R6	1135	0,30	12	9
R7	1120	0,35	15	43
F1	970	0,50	10	7
F2	955	0,30	15	5
F3	943	0,25	25	2,5
F4	930	0,20	35	1,2
F5	925	0,18	40	1,1
F6	913	0,10	45	0,7

R = Roughing F = Finishing

was thought to be sufficient for the simulation of billet soaking. The specimens were then subjected to three simulated roughing passes and six simulated finishing passes, detailed in Table III.

The high reheating and deformation temperatures necessitated the use of tungsten carbide deformation dies. To reduce oxidation on the surfaces of the specimens, the deformation was carried out under vacuum at 10^{-3} torr. A strain rate (q) of 2 s^{-1} was applied during all nine passes. The temperature of the specimen, flow stress, time (t), and strain (ε) were recorded continuously. A delay period of 42 seconds between the last roughing pass and the first finishing pass was included to simulate the time taken for the transfer of material between the roughing and the finishing trains. Three finishing sequences were simulated: (1) high temperature, ending at 940°C, (2) medium temperature, ending at 900°C, and (3) low temperature, ending at 835°C. Water-spray cooling of the strip after the last finishing pass was simulated by the blowing of argon gas onto the specimens to provide a cooling rate of 15°C·s^{-1} down to the coiling temperature, which was varied between 750 and 550°C. The specimens were then cooled to 50°C below the coiling temperature in 30 minutes to simulate the slow cooling of the coil surface. Polished specimens were etched in 2 per cent nital to reveal the final microstructures, and were studied by light optical microscopy. The ferrite grain size was determined by the linear-intercept method. The Vickers hardness of the as-rolled material was determined and divided into the ultimate tensile strength in order to obtain a multiplication factor to convert the hardness values obtained from the simulation tests to values of ultimate tensile strength. The multiplication factor for all the steels was calculated to be approximately 3,4.

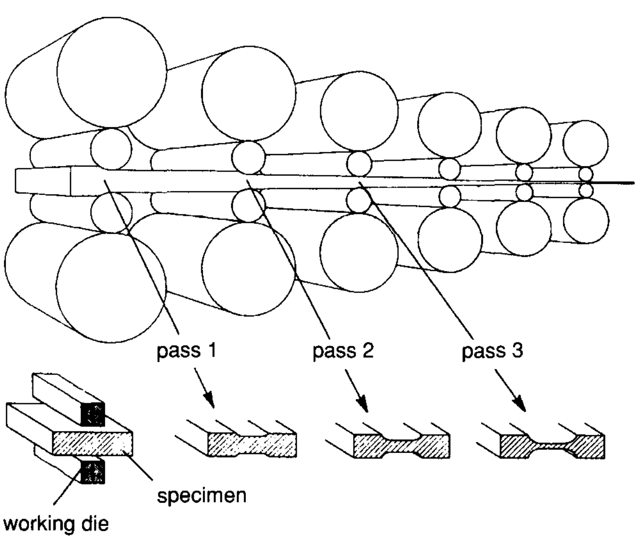


Figure 1—Schematic diagram showing the dimensions of the Gleeble specimens and the relationship between Gleeble deformation and hot-strip rolling[4]

Table III

Deformation parameters used during strip-rolling simulations on a Gleeble 1500 apparatus

Roughing pass	Temp. °C	ε mm/mm	q s^{-1}	t s
R1	1200	0,2	2	9
R2	1170	0,2	2	9
R3	1130	0,2	2	43

Finishing pass	(1) High temp. °C	(2) Med. temp. °C	(3) Low temp. °C	ε mm/mm	q s^{-1}	t s
F1	1000	1000	910	0,31	2	2
F2	990	980	895	0,35	2	2
F3	980	960	880	0,37	2	2
F4	970	940	865	0,25	2	2
F5	955	920	850	0,25	2	2
F6	940	900	835	0,12	2	2

RESULTS AND DISCUSSION

Microstructure

As-rolled versus Simulated

The as-rolled and simulated microstructures for steels A and C are given in Figure 2.

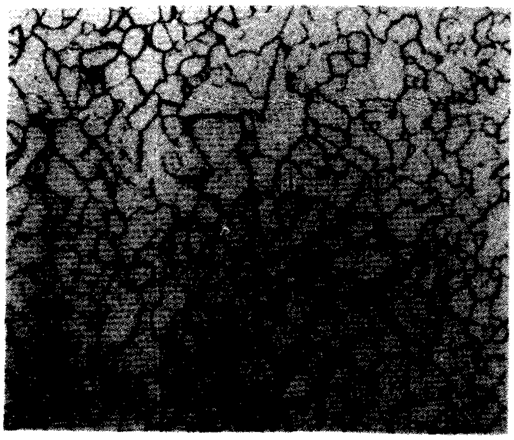
Steel A was finished at 900°C and coiled at 675°C. The ferrite grain sizes of the as-rolled and simulated materials, found after actual rolling and simulated rolling, were 13 μm and 15 μm respectively.

Steel C was finished at 900°C and coiled at 700°C. The ferrite grain sizes after actual rolling and simulated rolling were 7,6 μm and 8,1 μm respectively. Although similar, the grain sizes of the as-rolled material were slightly smaller than those of the simulated material owing to the larger total strain imparted during rolling than during laboratory simulation.

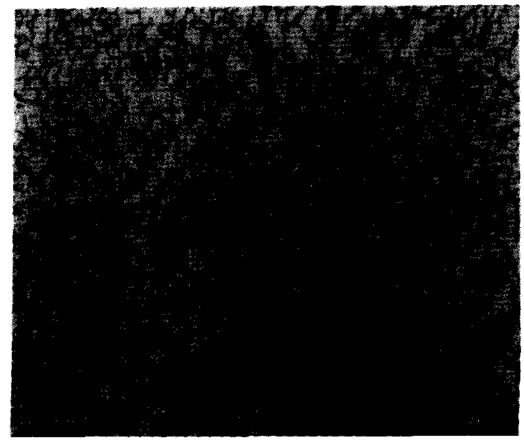
The as-rolled microstructures of steels B and D were generally similar to those found after rolling simulations.

Finishing Temperature and Coiling Temperature

Figure 3 shows a plot of measured grain size against coiling temperature for steels A, B, C, and D. All the steels, except steel A, showed a significant decrease in grain size with decreasing coiling temperature. The lack of grain refinement with decreasing coiling temperature in steel A is probably due to the fact that transformation was complete at high temperatures (higher than 750°C). There was only a small reduction in grain size when the finishing temperature was lowered from 940 to 900°C, although significant grain refinement occurred when the finishing temperature was lowered from 900 to 835°C.

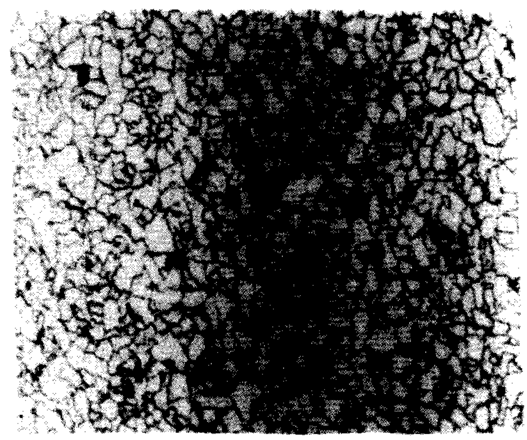


Steel A as-rolled
d_{α} = 13 μm



Steel C as-rolled
d_{α} = 7,6 μm

Steel A Gleeble simulation
d_{α} = 15 μm



Steel C Gleeble simulation
d_{α} = 8,1 μm

Figure 2—Comparison between the as-rolled and simulated microstructures of steels A and C (steel A was finished at 900°C and coiled at 675°C, steel C was finished at 835°C and coiled at 700°C)

Figure 4 shows the change in final microstructure of steels B and D as a function of decreasing finishing temperature, the coiling temperature being held constant at 700°C. Steel B had a coarse ferrite grain size of 15 μm after finishing at 940°C (high finishing sequence). Finishing at 835°C (low finishing sequence) resulted in significant refinement of the ferrite grain size to 10,2 μm. The grains were equiaxed in both cases, implying that full recrystallization had occurred throughout the simulated rolling schedule. The microstructure in steel D changed from a coarse polygonal ferrite–pearlite (grain size = 13 μm) at a finishing temperature of 940°C to a fine ferrite–pearlite structure at 835°C (grain size = 5,8 μm). The ferrite grains were directional and varied in size, suggesting that a certain amount of deformation had taken place below the no-recrystallization region. More pearlite was present in steel B owing to its higher carbon content.

When steel B was finished at 900°C and coiled at 600°C, an acicular ferrite–bainite structure resulted (Figure 5). Bainite was not observed in any of the other steels after coiling at 600°C. The fact that bainite is present only in steel B after coiling at 600°C is due to its higher carbon content (0,15 per cent), which increases its hardenability.

Strength and Hardness

Multiple linear-regression analysis was conducted on the results of 81 tensile tests taken from the as-rolled material of the five steels. The following regression equations and correlation coefficients were found:

$$R_e = 1008 - 0{,}536[FT] - 0{,}411[CT] + 302[\%C] + 6858[\%Nb] \qquad R^2 = 0{,}90 \qquad [1]$$

$$R_m = 636 - 0{,}115[FT] - 0{,}332[CT] + 889[\%C] + 6718[\%Nb] \qquad R^2 = 0{,}94, \qquad [2]$$

where FT is the finishing temperature in °C, CT is the coiling temperature in °C, and $\%C$ and $\%Nb$ are the carbon and niobium contents in percentages by mass. The standard errors of the yield strength and ultimate tensile strength were 29 and 23 MPa respectively. The limits of the parameter values that can be used in equations [1] and [2] are given in Table IV.

Both equations [1] and [2] show that lowering the finishing and coiling temperatures and increasing the carbon and niobium contents result in increased strength.

To determine the compatibility between the hardness values of production and simulated materials, multiple linear-regression analysis was conducted on the Vickers-

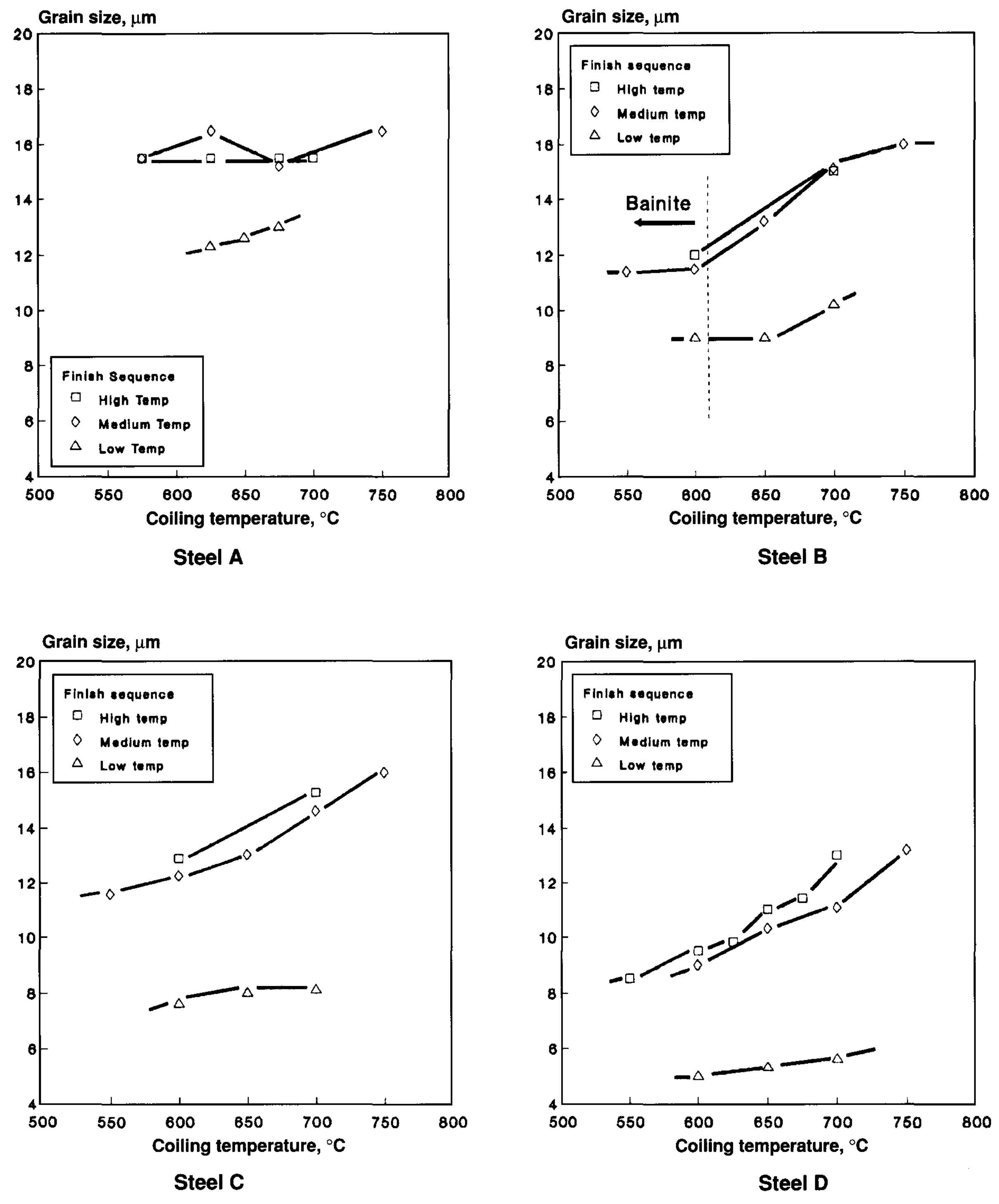


Figure 3—Gleeble rolling simulations: measured ferrite grain size against coiling temperature

hardness data obtained from 45 Gleeble simulation tests and on 81 equivalent strip-hardness values obtained from tensile tests on the five steels. The regression equation and correlation coefficient are given by equation [3]. The standard error of hardness was 6,7 HV. The high degree of correlation between the measured and the predicted hardness values is reflected by Figure 6.

Table IV

Range of variables valid for equations [1] to [3]

Value	Finishing temp.,°C	Coiling temp., °C	C wt %	Nb wt %
Min.	835	600	0,05	0
Max.	900	700	0,15	0,03

$$HV = 201 - 0{,}05[FT] - 0{,}094[CT] + 258[\%C] + 2119[\%Nb] \qquad R^2 = 0{,}95 \qquad [3]$$

Although equations [1] to [3] will be affected by varying reheat temperatures and cooling rates, they can be used as a guide in the design of hot strip-rolling schedules for the five steels to achieve the required strengths. For example, the required niobium content and coiling temperature, for a constant carbon content of 0,1 per cent and a constant finishing

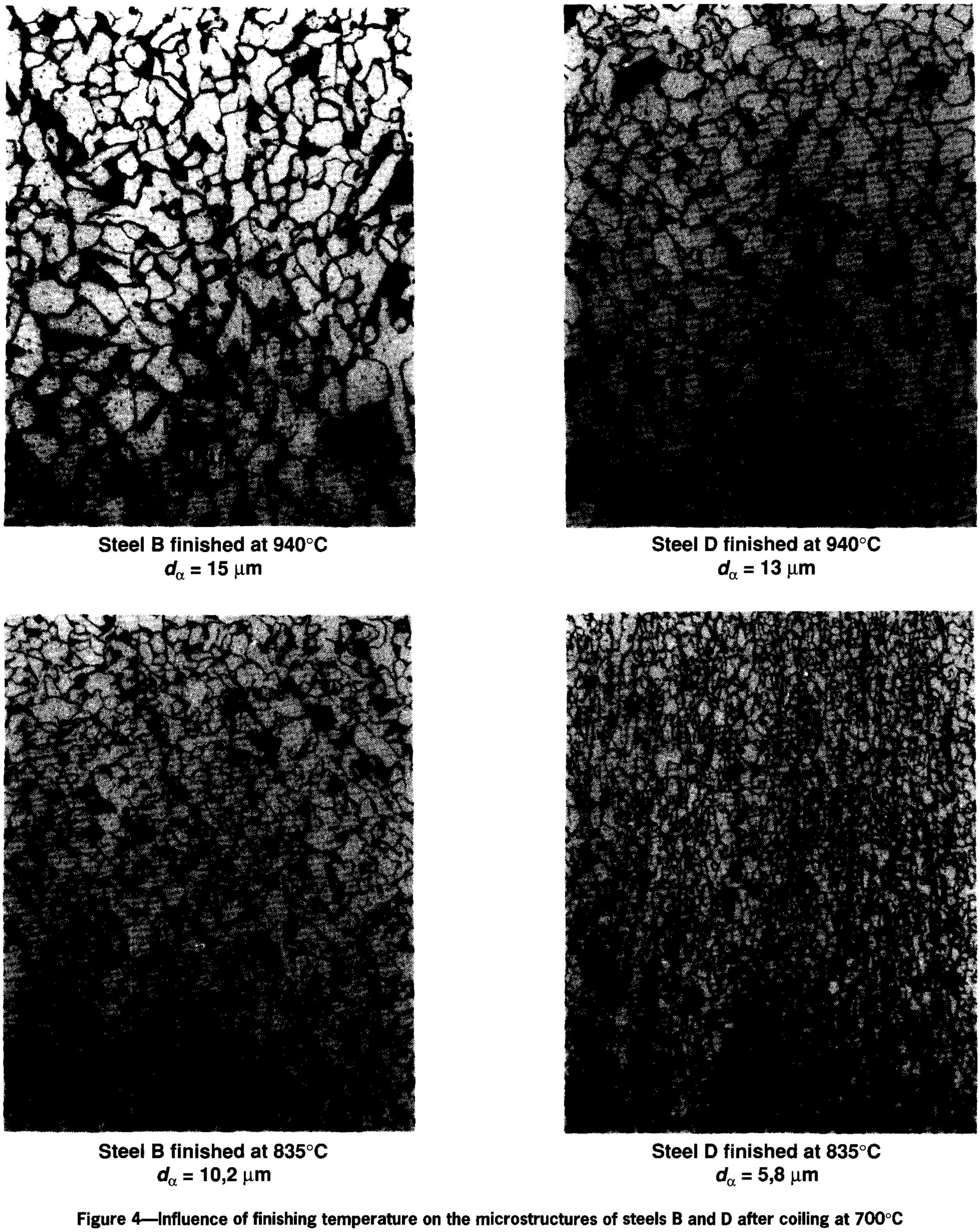


Figure 4—Influence of finishing temperature on the microstructures of steels B and D after coiling at 700°C

temperature of 880°C, to give a specified yield strength and ultimate tensile strength can be found from Figure 7.

Flow Stress

The maximum flow stress recorded during the simulated multiple-pass rolling of steels A, B, C, and D is plotted as a function of absolute inverse temperature in Figure 8. The flow stresses during the roughing passes ranged from 80 to 120 MPa for all the steels, and increased slightly when the temperature was lowered from 1200 to 1130°C. The relatively slight increase in flow stress during all the roughing passes implied that full or nearly full recrystallization had occurred during the delay period after deformation.

The flow stresses during finishing were always much higher than those found during roughing owing to the sharp temperature drop between the end of roughing and the start of finishing (1000 to 910°C). The flow curves for steels A and B show a gradual flattening out after the second finishing pass for both the medium-temperature finishing sequence ending at 900°C and the low-temperature

Figure 5—Steel B finished at 940°C and coiled at 600°C, showing acicular ferrite and bainite (steel B finished at 940°C is also shown in Figure 4)

finishing sequence ending at 835°C, implying that a certain degree of recrystallization had occurred during finishing. The flow stresses of steel C followed the same pattern as steel B during the medium-temperature finishing sequence, although the low-temperature finishing sequence resulted in rapid strain hardening with progressive passes, i.e. no recrystallization had occurred in this stage of processing. For steel D, recrystallization took place during the high-temperature finishing sequence ending at 940°C, although no recrystallization occurred during both the medium- and the low-temperature finishing sequences. This result is

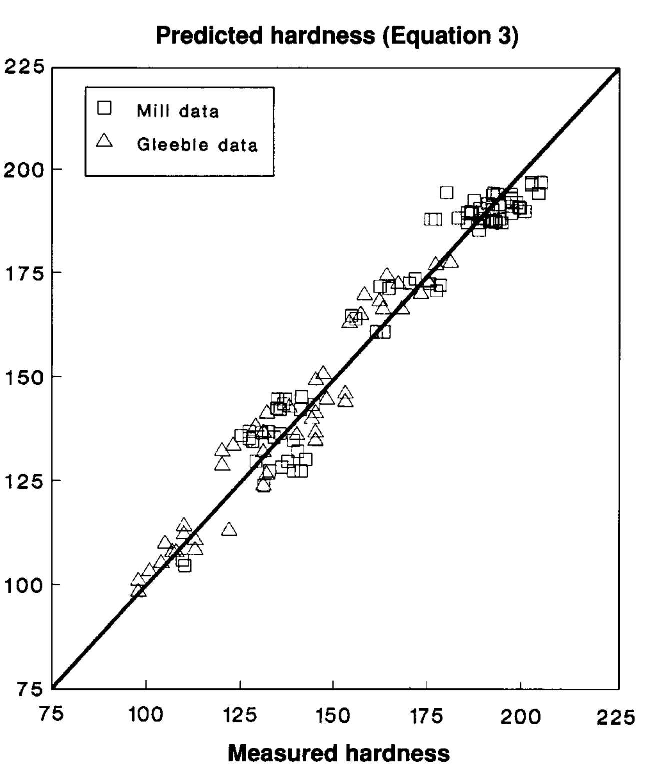


Figure 6—Measured versus predicted values of Vickers hardness

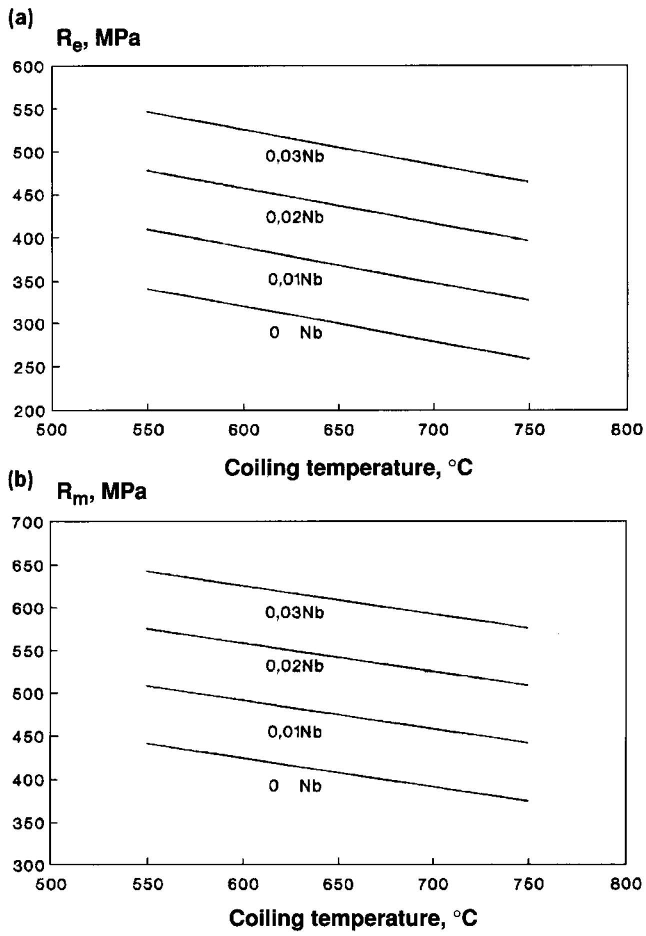


Figure 7—(a) Yield strength and (b) ultimate tensile strength as a function of niobium content and coiling temperature (finishing temperature = 880°C and carbon content = 0,1 per cent)

consistent with the photomicrograph of steel D finished at 835°C (Figure 4), which shows a dramatic refinement in grain size for the low-temperature finishing sequence. These findings show that an increase in the concentration of the niobium microalloy increases the temperature to which recrystallization is prevented, i.e the T_{NR}. The flow-stress behaviour in Figure 8 shows that the T_{NR} of steel B lies below 835°C. For steel C, the T_{NR} lies between 900 and 835°C and, for steel D, the T_{NR} is above 900°C. The results are in agreement with the data published by Cuddy[5], who found the T_{NR} for 0,027 Nb steel (similar to steel D) to be 940°C and that for 0,016 Nb steel (similar to steel C) to be 875°C. Extrapolation of Cuddy's data shows the T_{NR} of 0 Nb steel (steel B) to be below 800°C.

For a given set of finishing rolling conditions, there is a critical temperature, i.e. T_{NR}, above which precipitation does not occur, and full or partial recrystallization occurs if sufficient deformation is applied. This results in rounded flow curves[6]. The recrystallized austenite is transformed to relatively coarse ferrite. Deformation in the temperature range between the T_{NR} and the A_{r3} results in rapid work-hardening, i.e. a rapid increase in flow stress, due to precipitation, which retards or prevents recrystallization. This produces elongated or pancaked austenite, and forms a larger volume fraction of potential ferrite nucleation sites than partially or fully recrystallized austenite; this is beneficial for strength and ductility. The T_{NR} also provides an indication as to where significant increases in rolling force might occur.

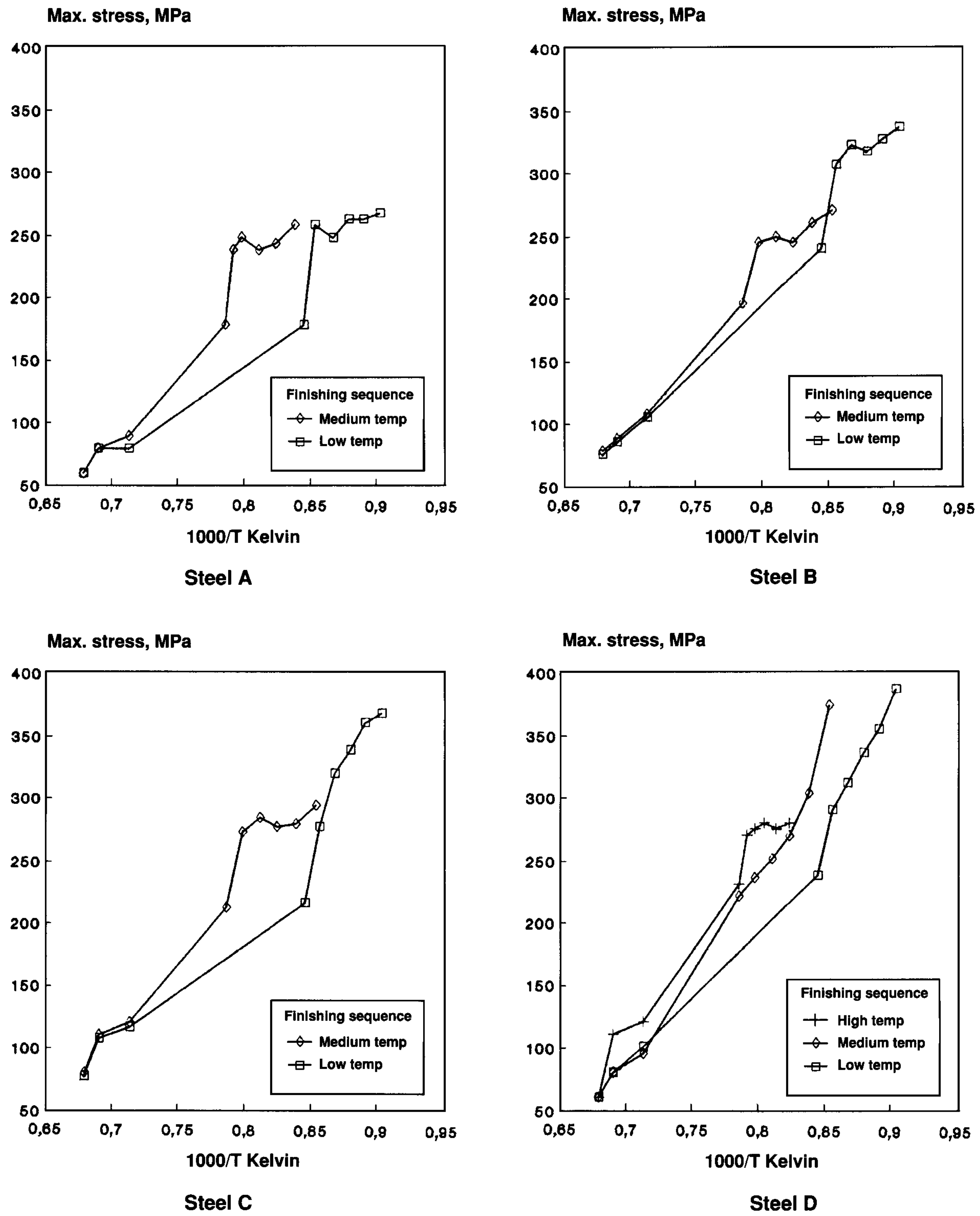


Figure 8—Maximum flow stress versus inverse absolute temperature for steels A, B, C, and D

CONCLUSIONS

(1) The Gleeble apparatus is adequate for simulating strip-rolling conditions, and for generating similar as-deformed microstructures and hardness values to those found in practice.

(2) Improvements in ferrite grain refinement and strength can be achieved in plain carbon and niobium-microalloyed strip steels if the finishing temperature is lowered from 900 to 835°C. Lower coiling temperatures also improve the grain size and strength, although caution should be taken to avoid the formation of bainite.

(3) It is possible to follow the progress of recrystallization and precipitation behaviour in hot-rolled steels from an examination of the flow curves for multiple-pass rolling simulations on a Gleeble apparatus.

(4) An increase in the niobium content of microalloyed steels shifts the no-recrystallization temperature to higher values.

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Ozone Depletion

PHASING OUT OF CHLOROFLUOROCARBONS

In terms of the Montreal Protocol, the production of all halons must cease within 270 days. Halons, which are used in certain fire-fighting equipment, are among the worst ozone-depleting substances.

There are approximately 34 months left before the production of all chlorofluorocarbons (CFCs) must cease. CFCs are used mainly as refrigerants in refrigerators, deep-freezers, and air-conditioners. Their use as blowing agents for foam plastics is fortunately being phased out rapidly.

As a signatory to the Montreal Protocol and its London amendments, the RSA, like the developed countries, is bound to the internationally accepted phasing-out timetable. Since 1st January, 1993, the developed countries may no longer import CFCs, while developing countries have been granted a 10-year period of grace.

The Department of National Health and Population Development makes a serious appeal to industry to get their houses in order and to make arrangements to utilize alternative products. It is a task that can be undertaken only by each industry itself. The Department of National Health and Population Development will give advice and make available non-confidential information.

In the months ahead, the public should be careful not to buy products containing substances that must be phased out. In many instances it will be impossible to service these products after 1995. All CFCs required for service purposes will have to come from recycled products, which will be difficult to come by and will become more expensive as time goes by.

More and more alternative products are becoming available on the market. The public should rather use these products, even if they are currently slightly more expensive.

SCIENTIFIC EVALUATION OF THE OZONE DEPLETION

The Parties to the Montreal Protocol decided in Copenhagen in November 1992 to update the report on the scientific evaluation of ozone depletion during 1994. For this purpose, the Scientific Evaluation Panel of the United Nations Environmental Programme (UNEP) was enlarged.

The Africa-group nominated Dr P.J. Aucamp of the Department of National Health and Population Development as co-chairman of the Panel. This was accepted by the parties concerned.

The Panel must report on the following aspects:

- Source gases: concentrations, emissions, and trends
- Ozone and temperature trends
- Heterogeneous processes: laboratory, field, and modelling studies
- Stratospheric processes: observations and interpretations
- Tropospheric processes: observations and interpretations
- Ozone destruction and chlorine load potential
- Future chlorine–bromine loading and ozone destruction
- Predicted aircraft effects on the stratospheric ozone
- Predicted rocket and shuttle effects on the stratospheric ozone
- Changes in ultraviolet radiation
- Evaluation of methyl bromide
- Evaluation of the influence of subsonic aircraft
- The impact of recycled controlled products on the ozone layer.

Experts are invited to contact Dr Aucamp at the following address should they wish to provide inputs regarding any of these subjects.

Scientific Evaluation Panel, UNEP, c/o Department of National Health and Population Development,
Private Bag X828, Pretoria 0002.
Fax: 012-215392; Tel: 012-3243631 x2163.