A regression equation for the Ar_3 temperature for coarse grained as-cast steels

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Regression analysis for Ar_3, Hot ductility, Continuous Casting, Nb,Ti, TRIP steels

Abstract

A regression equation for the Ar_3 temperature for as-cast ferrite/pearlite steels has been obtained. At these coarse grain sizes, very little influence of grain size on the Ar_3 is observed. Out of all the elements examined, C, Mn and Nb had the major influence in decreasing the Ar_3. A change in cooling rate from 10 to 200K/min results in only a small decrease of around 25°C. Of particular interest is the very marked effect of Nb in reducing the Ar_3, an addition of 0.03%Nb causing a decrease in the Ar_3 of 55°C.

Introduction

Accurate prediction of the start and end temperatures, Ar_3 and Ar_1 respectively of the austenite transformation temperatures is important in both casting as well as in hot rolling.
In the case of casting, knowledge of the Ae_3 (for which satisfactory regression and thermodynamic calculations are available) and the Ar_3 (limited data available) establishes the width of the hot ductility trough in ferrite/pearlite steels and hence the temperature range which should be avoided where possible on straightening during continuous casting, Fig.1[1]. Here, the austenite grain size is very coarse (300 to 2000μm) and the strain rate very slow, (10^{-2} to 10^{-3}/s). The strain applied is also very low ~3%.

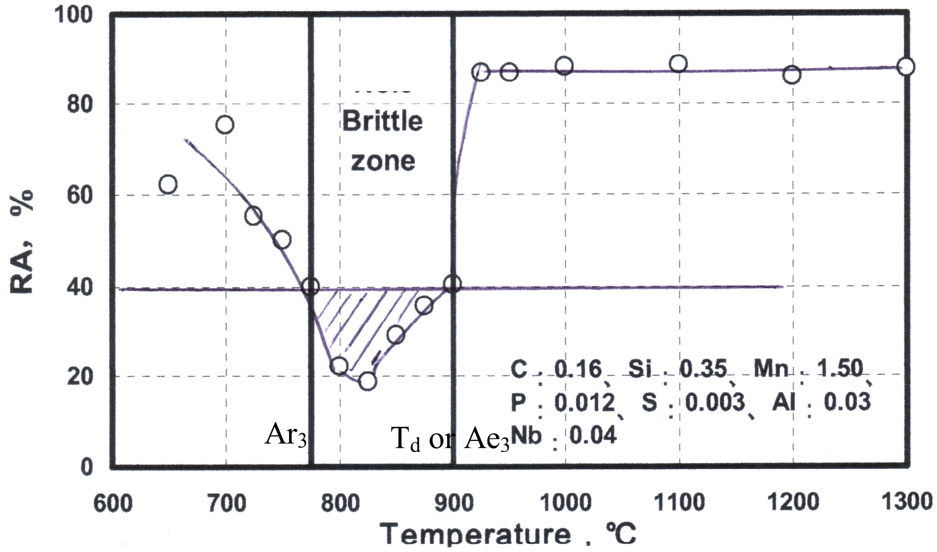

Fig.1 The hot ductility curve for a Nb containing HSLA steel showing the trough which stretches from Td to the Ar_3, this being the temperature range in which cracking can occur on bending [2].

By contrast for hot and controlled rolling, the austenite grain sizes are much finer (20-100µm prior to transformation) and the strain rate (10/s) and strains are high (5-80%). Here, knowledge of the Ar_3 is important for predicting whether dynamic recrystallisation or elongation of un-recrystallised austenite is likely to occur before transformation and the likelihood of rolling in the two phase region leading to a mixed grain size.
The Ar_3 equations that have been developed [3-9] do not include a multiplying factor for the grain size or cooling rate and the influence of niobium in decreasing the Ar_3 is often obscured by its grain refining ability. Coarser grain sizes will delay the transformation as will faster cooling rates. It should be noted that for hot rolling it is the Ar_3 measured under deformation conditions which is important (Ar_{3D}) not the un-deformed Ar_3, (Ar_{3U}). Deformation accelerates the rates of reaction and the value for the Ar_{3D} will be significantly higher than the Ar_{3U} which falls between the Ae_3 and Ar_{U3}.

The importance of the Ar_3 in casting arises because the majority of continuous cast steels will on casting, undergo the γ to α transformation. It has been found that when this transformation starts there is a thin film of ferrite present surrounding the coarse γ grains. Ferrite is the softer of the two phases and although its ductility is excellent, the presence of this softer film causes all the strain to concentrate there leading to low ductility, ductile inter-granular failure so that on unbending the strand, cracks form. It has been found that this film is generally deformation induced and can form at temperatures well in excess of the Ar_{3U} and as high as the Ae_3. Although deformation allows ferrite to easily form at the grain boundaries in these coarse grained steels because of the low strain rate, low strain and coarseness of the grain size, it is not sufficient to allow widespread ferrite formation which would lead to improved ductility and a narrowing of the trough and prevention of transverse cracking.

For the continuous casting operation ductility only improves then the straightening operation is carried out at about 20°C below the Ar_{3U} when substantial amounts of ferrite (~40%) are present prior to deformation. The strain is then distributed more evenly between the austenite and ferrite phases. For continuous casting as a result of the low strain rate and coarse grain size, it is the Ar_{3U}, not the Ar_{3D}, which dictates the width of the trough at its low temperature end.

In order to determine the width of the region that is likely to give poor ductility during continuous casting, see Fig.1, two temperatures are required. It should be noted that although testing conditions are kept close to the commercial continuous casting operation there are major differences between deformation in the tensile test and the unbending operation. Although deformation induced ferrite can often form in large amounts above the Ar_3 in a tensile test where the strains are high, thus improving ductility, this is not so during the un-bending operation when the strains are low around 2-3% and so ductility remains poor throughout the temperature range from the Ae_3 to Ar_3. Increasing the temperature to above the Ae_3 removes the ferrite, but γ itself at these higher temperatures, where grain boundary sliding can readily occur, does not have good ductility and precipitation in the γ can extend the width of the trough to much higher temperatures than the Ae_3. Nevertheless, the temperature at which dynamic recrystallisation in a tensile test T_d occurs can be taken as that temperature at which the ductility recovers sufficiently for transverse cracking not to occur during continuous casting [1]. For plain C-Mn steels this can be taken as the Ae_3 temperature. However, when precipitates are present, they delay dynamic recrystallisation to a higher temperature than the Ae_3, the Td, a temperature when the precipitates are either sufficiently coarse or few in number to be effective in influencing the ductility. The temperature T_d can either be established from the tensile curves which show an inflexion after the peak stress,

when dynamic recrystallisation takes place or from micro-structural examination when fine grains are first observed.
The present paper focuses on the Ar_{3U} temperature for as cast steels.

Experimental

Considerable dilatometry work has been carried out in the past by Corus R & D and formerly British Steel to determine the Ar_3 temperature of plain C-Mn and HSLA steels for the hot ductility work carried out at the City University, London. This paper employs all this data and incorporates it into a regression equation. The Ar_3 temperature as well as being dependent on the γ grain size is also dependent on the prior cooling rate. An increase in either of these leading to a lower Ar_3, the former by decreasing the number of grain boundary nucleation sites for ferrite whereas the latter reduces the time available for transformation.

In general, to simulate the continuous casting operation a solution treatment has been chosen which is sufficiently high to take all the microalloying additions and aluminium into solution and produce a very coarse γ grain size similar to that encountered during continuous casting. This involves heating to a high temperature and for most of the dilatometry work a solution temperature of 1300-1350°C has been used. Austenite grain sizes are then in the range 100µm to 1mm. The cooling rate is chosen to closely simulate that undergone during the continuous casting operation, although it is a simplification of the continuous cast cooling conditions; an average cooling rate to the test temperature of 60K/min being commonly chosen to simulate cooling close to the surface of 220mm thick slab and a faster cooling rate of 100-200K/min for thin slab casting (50-100mm thick slab). The steels examined, in which the prior γ grain size was measured at the solution temperature covered the following compositional ranges:0.04 to 0.75%C, 0.30-1.6%Mn, 0.02-0.49%Si, 0-0.31%Nb, 0.014-0.085%Al, 0.004-0.008%N. A total of 25 steels were examined. The range of cooling rate investigated was 10 to 100K/min and the austenite grain size varied from 70 to 950µm. The full compositions, cooling rate and grain size for these steels are given in Table I together with the measured Ar_{3U}.
It is the N in solution, N_f, that determines the Ar_3 not the combined N. For these steels it is assumed that because of the low Al and N levels and the sluggish precipitation of AlN that there will be no difference between the total N content and the N in solution. However, one of the steels, steel 12 had a small Ti addition and this will have combined with the N and the N_f in this case has been taken as zero. Also previous work [10] has indicated that although AlN precipitation is sluggish and there is little evidence for it forming in low N low Al containing steels when the [Al][N] product is in excess of 2.5×10^{-4} precipitation does occur. Hence, for steels having $[Al][N] > 2.5 \times 10^{-4}$ it has been assumed that all the N will be precipitated as AlN.

Table I
Composition wt.per.cent., austenite grain size, cooling rate and Ar$_3$ for steels in which the grain size was determined.

Steel	C	Si	Mn	S	P	N	Al	Nb	Ti	GS	CR	Ar$_{3U}$
1	0.04	0.2	1.5	0.013	0.002	0.004	0	0	-	290	60	772
2	0.1	0.2	1.5	0.013	0.002	0.004	0	0	-	320	60	744
3	0.19	0.2	1.5	0.013	0.002	0.004	0	0	-	355	60	697
4	0.09	0.32	1.48	0.016	0.013	0.001	0	0	-	300	200	720
5	0.65	0.28	1.4	0.003	0.002	0.005	0	0	-	280	60	598
6	0.19	0.2	1.5	0.013	0.002	0.004	0	0	-	290	60	720
7	0.19	0.2	1.5	0.013	0.002	0.004	0	0	-	180	60	725
8	0.19	0.2	1.5	0.013	0.002	0.004	0	0	-	70	60	740
9	0.082	0.013	0.39	0.008	0.007	0.004	0.026	0	-	450	60	783
10	0.079	0.019	0.4	0.008	0.006	0.005	0.085	0	-	460	60	803
11	0.078	0.35	1.39	0.009	0.01	0.0078	0.016	0	-	420	60	735
12	0.083	0.058	0.38	0.008	0.008	0.004	0.01	0	0.037	120	60	820
13	0.092	0.31	0.58	0.02	0.013	0.004	0	0	-	275	10	795
14	0.092	0.31	0.58	0.02	0.013	0.004	0	0	-	275	60	785
15	0.4	0.35	1.58	0.006	0.01	0.008	0	0	-	110	10	660
16	0.4	0.35	1.58	0.006	0.01	0.008	0	0	-	110	60	650
17	0.4	0.35	1.58	0.006	0.01	0.008	0	0	-	110	100	640
18	0.75	0.22	0.91	0.02	0.016	0.006	0.014	0	-	500	10	685
19	0.75	0.22	0.91	0.02	0.016	0.006	0.014	0	-	500	60	655
20	0.75	0.22	0.91	0.02	0.016	0.006	0.014	0	-	500	100	640
21	0.082	0.5	0.61	0.005	0.027	0.0042	0.03	0	-	290	60	800
22	0.15	0.09	1.41	0.007	0.007	0.0073	0.021	0	-	620	60	700
23	0.089	0.49	0.6	0.005	0.023	0.0043	0.029	0.031	-	450	60	737
24	0.14	0.1	1.4	0.006	0.026	0.0052	0.022	0.031	-	530	60	670
25	0.1	0.3	0.32	0.009	0.016	0.0045	0.023	0	-	286	60	798
26	0.1	0.3	0.33	0.004	0.015	0.0045	0.023	0	-	262	60	810
27	0.1	0.29	1.34	0.019	0.016	0.0045	0.02	0	-	367	60	726
28	0.1	0.29	1.47	0.004	0.015	0.0038	0.022	0	-	350	100	726
29	0.1	0.28	0.31	0.032	0.010	0.0049	0.032	0	-	950	100	835
30	0.11	0.32	0.32	0.003	0.010	0.0036	0.037	0	-	650	100	800
31	0.15	0.09	1.41	0.007	0.007	0.0073	0.021	0	-	620	200	710
32	0.15	0.09	1.41	0.007	0.007	0.0073	0.021	0	-	620	25	695
33	0.14	0.10	1.40	0.006	0.026	0.0052	0.022	0.031	-	530	200	640
34	0.14	0.10	1.40	0.006	0.026	0.0052	0.022	0.031	-	530	25	670

Results

1) Grain size

Soaking in the 1000-1350°C region resulted in austenite grain sizes between 70µm and 950µm. For the range of cooling rates used, 25-200K/min, the Ar$_{3U}$ varied between 640°C and 835°C.

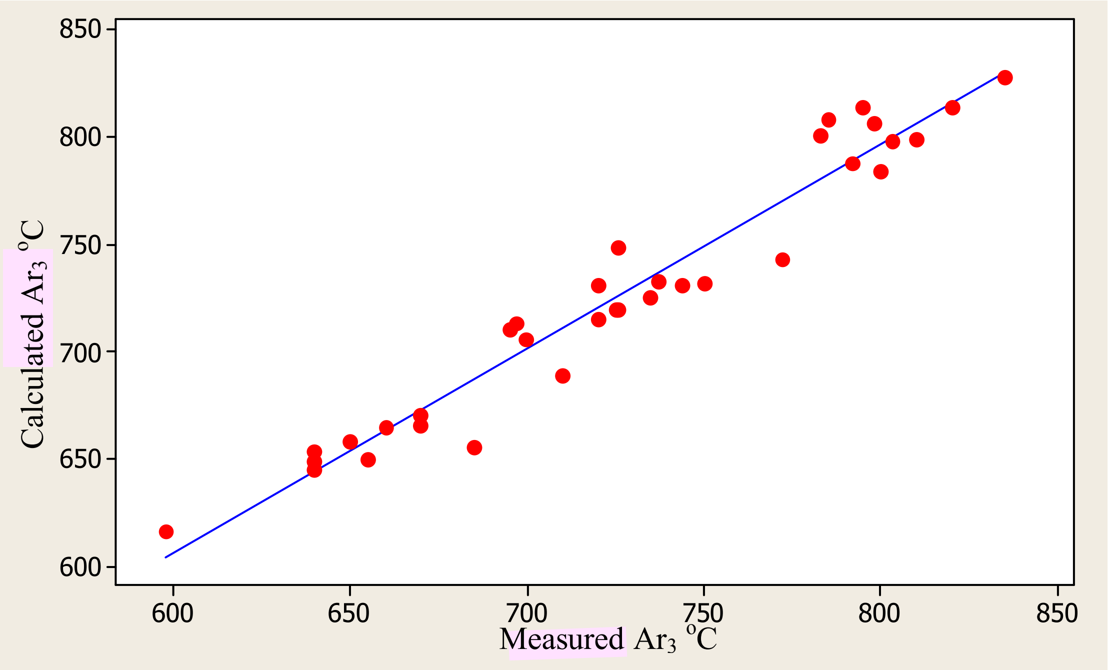

Fig.2. Calculated Ar_3 from equation 1 against the experimentally determined Ar_3
SE =15.9 $R^2 = 0.949$, R^2 (adj.) = 0.935

The regression equation obtained for these steels is as follows:

Ar_3 °C = 833.6 -190.6%C -67.4%Mn + 1522%S -2296N_f-1532%Nb-+7.91%$d^{-1/2}$- 0.117CR
--------------------(1

where d is the austenite grain diameter in $mm^{-1/2}$ and CR is the cooling rate in K/min
The R^2 value is high at 94.9 and the standard error, SE, is 15.9. The statistical significance of the coefficients in this equation is given in Table II and the calculated Ar_3 plotted against the experimentally determined Ar_3 is plotted in Fig.2.
The coefficients in this regression for C,Mn, S and Nb were significant. Si and P together with grain size and N_f were not significant in the analysis..
Grain size only had a small influence on the Ar_3 in the coarse grain size range under examination, 100µm to 1 mm. The best co-relation with grain size was given by $d^{-1/2}$ rather than d or d^2.

Table II
Statistical data for the Ar_3 equation for steels in which a grain size determination was made.

Variable	Coefficient	Standard Error Coefficient	t	p
Constant	833.6	15.1	55.2	0.000
C	-190.6	15.1	-12.7	0.000
Mn	-67.4	6.8	-9.9	0.000
S	1522	456	3.34	0.003
N_f	-2296	1698	-1.35	0.188
Nb	-1532	302	-5.07	0.000
$d^{-1/2}$	7.91	5	1.58	0.126
CR	-0.117	0.062	-1.88	0.072

Having established that austenite grain size in excess of ~100um has only a small influence on the Ar_3 it is then possible to include many of results in which grain size had not been determined.

Much of the more recent work[1] on hot ductility has been carried out on TRIP assisted steels in which P or Al has been substituted for the traditional Si addition, the latter giving a poor surface condition on galvanising. Generally, the C level for these steels is in a narrow range of 0.1 to 0.2%C but the Mn level is often much higher than in conventional HSLA steels. Al levels ranged from 0.02 to 1-2% and P, 0 to 0.1% the higher values being orders of magnitude greater than found in traditional constructional steels. The full compositions, cooling rates and measured Ar_{3U} temperatures are given in Table III. The steels were soaked in the temperature range 1300-1350°C.

Table III
Additional TRIP type steels included in the regression analysis

Steel	C	Si	Mn	S	P	N	N_f	Al	Nb	Ti	CR	Ar_3
35	0.21	0.61	1.41	.004	.01	0.0042	0.0000	0.98	0	-	60	756
36	0.13	0.60	1.40	.005	.076	0.0040	0.0000	0.022	0	.012	60	735
37	0.12	0.61	1.02	0.004	0.072	0.0030	0.0000	0.022	0	.014	60	760
38	0.20	0.39	1.5	0.001	0.077	0.0012	0.0012	0.03	0	-	60	722
39	0.21	0.39	1.49	0.001	0.078	0.0018	0.0000	0.21	0	-	60	702
40	0.22	0.40	1.53	0.001	0.081	0.0024	0.0000	0.43	0	-	60	679
41	0.20	0.25	1.49	0.001	0.11	0.0034	0.0000	0.41	0	-	60	688
42	0.215	0.41	1.51	0.001	0.077	0.0022	0.0000	0.87	0	-	60	719
43	0.163	1.05	2.41	0.004	0.012	0.0054	0.0000	0.063	0.025	-	60	581
44	0.156	0.22	2.42	0.003	0.012	0.012	0.0000	0.052	0.025	-	60	579
45	0.160	0.22	2.39	0.0034	0.012	0.014	0.0000	0.052	0.025	-	60	569
46	0.183	0.006	2.52	0.0056	0.016	0.007	0.0000	1.55	0.026	-	60	571
47	0.184	0.006	2.48	0.0056	0.016	0.006	0.0000	1.54	0.026	-	60	584
48	0.175	0.53	2.48	0.005	0.015	0.007	0.0000	1.04	0.024	-	60	573
49	0.175	0.53	2.48	0.005	0.015	0.006	0.0000	1.04	0.024	-	30	562
50	0.161	0.22	2.35	0.004	0.014	0.008	0.0000	0.06	0.025	-	60	536
51	0.161	0.22	2.35	0.004	0.014	0.008	0.0000	0.06	0.025	-	30	561
52	0.172	0.22	2.42	0.005	0.013	0.014	0.0000	0.055	0.024	-	60	544
53	0.172	0.22	2.42	0.005	0.013	0.014	0.0000	0.055	0.024	-	30	591

Cooling rate for these steels was 60K/min except for two instances where the cooling rate was slightly lower at 30K/min.

A regression analysis was carried out just on these steels (total 19 data points) and the equation obtained was as follows:

Ar_{3U} (°C) = 870 – 586%C – 630%P + 18.1%Al – 8151%Nb----------------------------(2)

SE = 16.6, $R^2 = 0.967$, R^2 (adj) = 0.957.

The statistical significance of the coefficients in this equation is given in Table IV.

Si was not found to have any influence on the Ar_3 but both P and Al were.

Table IV
Statistical significance of the coefficients in equation 2 for the TRIP assisted steels

Variable	Coefficient	Standard Error	t	p
Constant	870	36	24.0	0.000
C	-586	177	-3.3	0.005
P	-630	225	-2.8	0.014
Al	18	8.5	2.1	0.051
Nb	-8151	628	-13	0.000

It can be seen from the plot of the calculated versus observed Ar_3, Fig.3, that the data separates into two distinct regions one for Nb free steels having 1.4%Mn and the other for the high 2.5% Mn, Nb containing TRIP steels, steels 35-42 and steels 45-53, respectively in Table III.

Surprisingly, increasing the Mn level from 1.4 to 2.5% did not appear to have any significant influence on the Ar_3 for these steels. This may be related to the presence of Nb in the higher Mn steels but not in the 1.4%Mn steel. Nb again depressed the Ar_3 to very low temperatures. More surprisingly, P appeared to lower the Ar_3 in contrast to its expected behaviour in raising the Ae_3. The multiplying factors for Nb and C in equation 2 are much higher than those in equation 1.

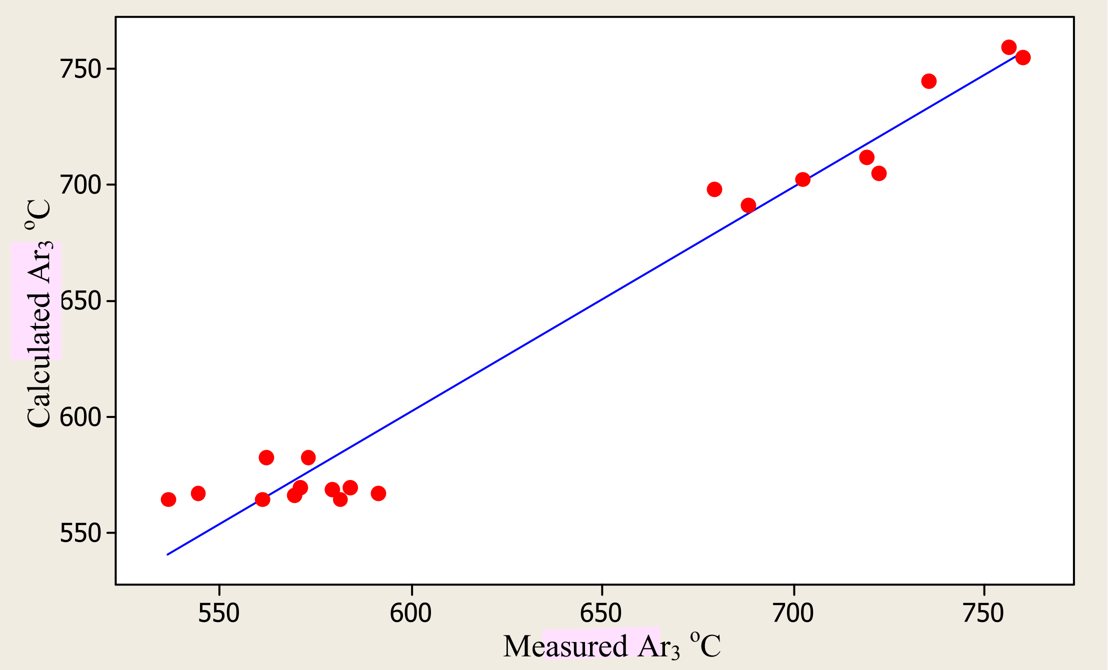

Fig.3. Ar_3 temperature calculated from equation 2 for the TRIP steels plotted against the observed values.

The substantial difference between the coefficients in equations 1 and 2 illustrates the danger of using regression equations which cover only a small data base and have only a limited compositional range.

In addition to the data given in Table II, an equal amount of dilatometry for the Ar$_{3U}$ has also been accumulated for more conventional steels in which no austenite grain size measurements had been carried out. These steels all had a carbon content of ~0.1C% with two steels (74 and 75, Table V) at 0.14%C and all except one steel, 66 had a Mn level of ~1.4%. There was however, a wide variability in the cooling rates from 25-200K/min. This involved a further 21 data points (11 new steels). The, Ar$_3$ temperatures, composition and cooling rates for these steels are given in Table V

Table V

Steels used to examine the influence of cooling rate on the Ar$_3$

	C	Si	Mn	S	P	N	Nf	Al	Nb	Ti	CR	Ar$_3$
54	0.10	0.31	1.40	.010	.017	.0070	.0030	0.052	0.000	0.011	200	740
55	0.10	0.31	1.40	.010	.017	.0070	.0030	0.052	0.000	0.011	100	745
56	0.10	0.31	1.40	.010	.017	.0070	.0030	0.052	0.000	0.011	25	765
57	0.09	0.35	1.44	.011	.017	.0040	.0000	0.016	0.042	0.014	200	690
58	0.09	0.35	1.44	.011	.017	.0040	.0000	0.016	0.042	0.014	100	685
59	0.09	0.35	1.44	.011	.017	.0040	.0000	0.016	0.042	0.014	25	685
60	0.09	0.32	1.50	.012	.018	.0067	.0067	0.009	0.000	0.000	100	720
61	0.09	0.32	1.50	.012	.018	.0067	.0067	0.009	0.000	0.000	25	710
62	0.09	0.29	1.33	.014	.017	.0064	.0064	0.006	0.000	0.000	100	745
63	0.09	0.29	1.33	.014	.017	.0064	.0064	0.006	0.000	0.000	25	750
64	0.09	0.29	1.31	.013	.017	.0076	.0000	0.045	0.000	0.021	100	750
65	0.09	0.29	1.31	.013	.017	.0076	.0000	0.045	0.000	0.021	25	770
66	0.10	0.33	0.31	.009	.019	.0040	.0040	0.025	0.000	0.000	60	838
67	0.10	0.30	1.36	.020	.020	.0040	.0040	0.030	0.000	0.000	60	731
68	0.10	0.30	1.36	.020	.020	.0040	.0040	0.030	0.000	0.000	25	721
69	0.10	0.30	1.47	.004	.018	.0040	.0040	0.025	0.000	0.000	200	701
70	0.10	0.30	1.47	.004	.018	.0040	.0040	0.025	0.000	0.000	60	701
71	0.10	0.30	1.40	.003	.016	.0050	.0050	0.024	0.000	0.000	200	689
72	0.11	0.30	1.36	.003	.016	.0040	.0040	0.024	0.030	0.000	200	642
73	0.11	0.30	1.36	.003	.016	.0050	.0050	0.024	0.030	0.000	60	665
74	0.15	0.29	1.45	.008	.003	.0060	.0060	0.017	0.000	0.000	60	720
75	0.16	1.22	1.41	.005	.009	.0032	.0032	0.023	0.000	0.000	60	732

Finally, all the data, 75 data points were put through a regression analysis and the following equation obtained:

$Ar_3(^{o}C) = 862 - 182\%C - 76.1\%Mn + 1121\%S - 1804\%Nb - 0.084\%CR + 1168Ti - 2852N$.--
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The statistical significance of the coefficients is given in Table VI and the plot of the observed Ar$_3$ against that calculated from equation 3, is given in Fig.4.

Table VI
Statistics for equation 3 for all the steels examined

Variable	Coefficient	Standard Error Coefficient	t	p
Constant	862	9.5	91	0.000
C	-182	15.3	-12	0.000
Mn	-76	5.1	-15	0.000
S	1121	388	2.9	0.005
Nb	-1804	189	-9.6	0.000
CR	-0.084	0.045	-1.87	0.066
Ti	1168	348	3.35	0.001
N	-2852	1006	-2.83	0.006

SE = 18.6, R^2=0. 942, R^2 (adj)= 0.936

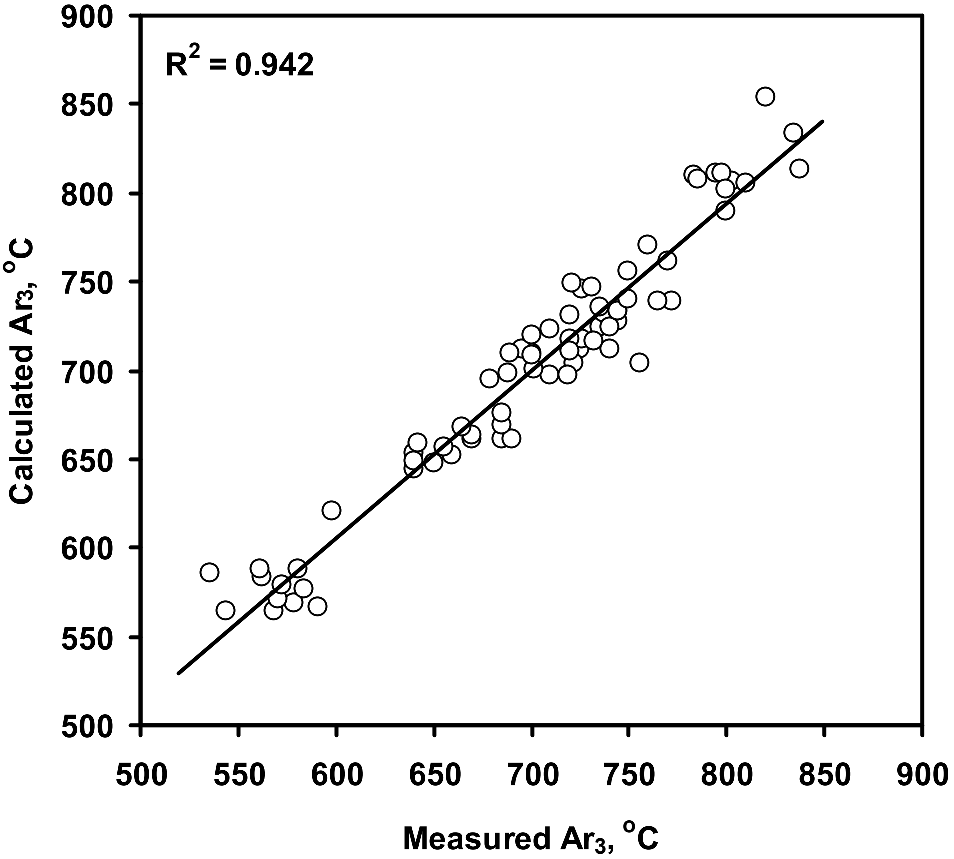

Fig.4. Ar_3 calculated from equation 3 for all the steels examined against the measured Ar_3

It can be seen that incorporating the Ar_3 data from the TRIP steels, with their very different compositions to the plain C-Mn and HSLA steels, fits very well indicating that these compositional differences are being accounted for by one equation and that they are all from the same population. Titanium additions can be seen to increase the Ar_{3U}. Although the grain refining ability of Ti can not be ruled out to account for this increase it is unlikely from these low Ti additions and from the relative insensitivity that this work has shown of grain size to the Ar_{3U} at these coarse grain sizes.

Discussion

Composition

A list of the available equations found in the literature is given in Table VII [3-9] although it is not always clear whether they have been obtained with or without deformation. The currently determined Ar_3 equations are also included in this table.

Table VII.
Summary of Ar_3 Equations

Ref	$Ar_{3,0}$	C	Si	Mn	P	S	N	Nb	Ni	Cr	Mo	Cu	Al	$d^{-0.5}$	CR	Type
	°C	%	%	%	%	%	%	%	%	%	%	%		µm	°C/min	
3.Shiga	910	-273		-74	-	-	-	-	-56	-16	-9	-5		-	-	Rolling
4.Ouchi	910	-310		-80	-	-	-	-	-55	-15	-80	-20		-	0.35(t-8)	Rolling
5.Tamura	868	-396	25	-68					-36	-25		-21				Rolling
6.Blas.	903	-328		-102				116							0.0151	Rolling
7.Choquet.	902	-527	60	-62												unknown
8.Pickering*	910	-230	45	-21					-15		32					unknown
9.Steel-forming	879	-516	38	-66	274											Unknown
9.Steel-forming	901	-325	33	-92	287								40			unknown
Present one Mintz	870	-184		-80		1090	-2884	-1534					43		0.135	No deformation
Present	862	-182		-76.1		1121	-2852	-1804						Ti=+1168	-0.084	No deformation

* Equation also includes coefficients for W, 13 and V, 104.

It can be seen from the previous equations for the Ar_3, Table VII, that the constants are generally fairly close ranging from 880 to 910°C. However, the multiplying factors for C range from 100-527, for Mn from 21-144 and for Si, 33-60. Such wide variations are worrying. The present work has examined both a very wide range of C and Mn contents resulting in high t values for the coefficients for these elements.

Ouchi et al [4] have obtained the Ar_{3D} after controlled rolling for a series of steels including Nb and V containing steels, TableVII. Their coefficient for C was significantly higher than that given by the present regression equation but that for Mn was similar. Surprisingly, the Ar_{3D} was found not to be influenced by Nb or V but this may be related to the finer grain size in their steels compared to the as-cast state.

Previous work on the influence of Nb on the Ar_3 has given it as having no influence [4] or a very small positive influence [6], Table VII. However, a recent paper by Yuan et al [11] has shown that for coarse grained steels (~250µm), Nb additions up to 0.025%Nb lead to a considerable decrease in the Ar_{3U}, Fig. 5. This is in accord with the present work. In Fig.5, at the highest Nb level they examined, 0.04%, there is an increase in the Ar_3. This is due to the grain refining action of Nb, (69µm) at this level causing the Ar_{3U} to increase.

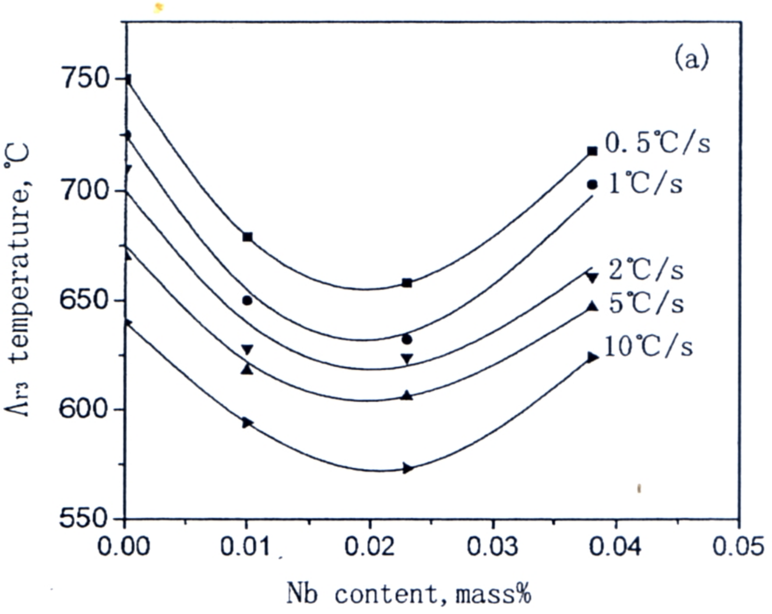

Fig.5 Relationship between Ar_3 and Nb content for non-deformed steels. After Yuan *et al.*[11]

Yuan et al.[11] obtained two regression equations, one for the Ar_{3U} and the other for the Ar_{3D} for C-Mn-Al steels having the base composition: 0.11%C, 0.2%Si and 1.2%Mn and Nb in the range 0-0.04%.

$Ar_{3U}(^{o}C) = 370\exp(-\sqrt{d}/6.7) - 215CR^{0.1} - 5649[Nb] + 78194[Nb]^2 + 1019$………………...(4)

where cooling rate CR is in $^{o}C/min$ and d is the austenite grain size in microns.
However, a problem with the equation 4 is that for steels of composition 0.11%C, 0.2%Si and 1.2%Mn the Ae_3 would be ~ 850°C whereas the equation would give this as 1019°C.
For the Ar_{3D}, their equation was:
$Ar_{3D}\ (^{o}C) = 370\exp(-\sqrt{d}/6.7) - 198CR^{0.1} - 6646[Nb] - 2327[Nb]^2 + 66\{1/t_{0.05} + \Delta\varepsilon\} + 830$.---
---(5)

where $t_{0.05}$ is the precipitation start time and $\Delta\varepsilon$ is the residual strain in the austenite.

From equations 4 and 5, for a Nb content of 0.03%, the Ar_3 temperature would, respectively fall 99°C without deformation and 200°C with deformation. From the presently derived equation 3, the decrease in Ar_{3U} would be much less ~ 55°C.

The importance of S in increasing the Ar_3 in equation 3 probably arises because of the increased volume fraction of MnS inclusions which have been shown to encourage ferrite formation [12].

Cooling rate

Most previous examinations to determine Ar_3 were carried out at a constant cooling rate. Three previous investigations[4,5,11] have tried to include the cooling rate in their analysis. Yuan *et al* [11] have shown that for a coarse grained steel, 200-300µm, the change in cooling rate from 60 to 200K/min causes the Ar_{3U} to decrease by about 25°C, Fig. 5. This is in reasonable agreement with the present work.

In Ouchi *et als'* work [4], again the influence of cooling rate was relatively small for the range of cooling rates examined. The plate range they investigated was from 8-30mm and increasing the cooling rate from 17K/min (30mm thick plate) to 60K/min (8mm thick plate) resulted in only a 8°C decrease in the Ar_{3D}.

Blas et al[5] have found an even smaller influence of cooling rate on the Ar_3 for the range 60 to 2100K/min, this range only leading to a 35°C change in the Ar_3.

Grain size

Although coarsening of the γ grain size would be expected to lower the Ar_3, for these coarse grain sizes in the range 100-1000µm the change is small, ~20°C and the affect of grain size on transformation can be ignored for the as-cast state where the grain size is in the region of 0.5 to 2 mm. Yuan et al's equation 4 indicated, as would be expected, that coarsening of the grain size will decrease the Ar_3 and a grain size change of 100µm to 1mm would result in a 80°C fall in the Ar_3. This change is again much larger than indicated in the present work. However, their results are only based on a small number of laboratory tests.

Conclusions

1. The following regression equation for the un-deformed Ar_3 temperature of coarse grained steels has been determined.

$Ar_{3U}{}^{o}C = 862 - 182\%C - 76.1\%Mn + 1121\%S - 1804\%Nb - 0.084CR + 1168\%Ti - 2852\%N$

The compositional range covered by the equation is:
0.04-0.75 %C, 0.31-2.52 %Mn, 0.01-1.22 %Si, 0.001-0.032 %S, 0.002-0.11 %P, 0.0012-0.014 %N, 0-1.55%Al, 0-0.042 %Nb. The grain size range examined was 100-1000µm and cooling rate from the solution temperature 10-200K/min.

2. Of these elements, C,Mn and Nb had the biggest influence in decreasing the Ar_{3U}. Nb had a very marked influence, a 0.03% addition causing a decrease of 55°C. This accounts for Nb widening the trough at the lower temperature side making it more difficult to avoid the bending temperature range in which transverse cracking occurs.
3. Grain size was found to have only a small influence on the Ar_{3U}, a change in grain size from 100µm to 1000µm resulting in a decrease of ~20°C.
4. Cooling rate was also only found to have a small influence for the cooling rate range examined. An increase in cooling rate from 10 to 200K/min leading to a decrease of 25°C.

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Fig.1. The hot ductility curve for a Nb containing HSLA steel showing the trough which stretches from the Td to the Ar_3, this being the temperature range in which cracking can occur on bending [2].

Fig.2. Calculated Ar_3 from equation 1 against the experimentally determined Ar_3. SE =15.9, $R^2 = 0.949$, R^2 adj. = 0.935

Fig.3. Ar_3 temperature calculated from equation 2 for the TRIP steels plotted against the observed values. SE = 16.6, $R^2 = 0.967$, R^2 adj. = 0.957

Fig.4. Ar_3 calculated from equation 3 for all the steels examined against the measured Ar_3. SE = 19.6, R^2 =0. 936, R^2 adj. = 0.928.

Fig.5. Relationship between Ar_{3U} and Nb content for non-deformed steels. After Yuan et al. [11].