The Current Status of the Development and use of Air Cooled Steels for the Automotive Industry

Technical Paper Prod/A3

The Current Status of the Development and use of Air Cooled Steels for the Automotive Industry

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This Paper was presented prior to the formation of Corus plc following the merger of British Steel and Koninklijke Hoogovens. Corus Engineering Steels is the new name of British Steel Engineering Steels referred to throughout the text of this paper.

This paper was presented at the Second International Symposium on Microalloyed Bar and Forging Steel, Colorado School of Mines, Golden, Colorado, July 8-10 1996.

Abstract

The market for air cooled steels has matured in the last 10 years. The advantages of these steels, in terms of elimination of heat treatment, reduced distortion, improved machinability and more consistent properties have led to their use in a wide range of automotive components.

In Europe, most forgers, working in partnership with steel producers, now have the necessary equipment and expertise to enable cooling after forging to be controlled accurately and reliably.

The use of controlled rolling and cooling has also enabled the required mechanical properties to be achieved in bar stock without the need for heat treatment.

The paper reviews the grades of microalloyed and carbon manganese steels in current use and the properties of these steels. It considers how these properties can be influenced by the steelmaker through composition adjustment and controlled rolling, and by the forger by control of the forging and cooling conditions. A number of case studies are used to demonstrate these points.

Possible future developments of both microalloyed and carbon steels are also reviewed. These include the use of accelerated cooling and the use of higher carbon and nitrogen steels.

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Introduction

The elimination of heat treatment and improved machinability of air cooled carbon and microalloyed steels results in lower through costs. These steels are now well-established for the manufacture of automotive forgings and for controlled rolled bar. It is a measure of their success that they are increasingly “first choice” when selecting material for new automotive components.

Previous papers [1, 2, 3] have described the development of the VANARD range of microalloyed steels by British Steel and since then activities have focussed on developing applications of these and other air cooled steels.

British Steel Engineering Steels, working with British Steel Technology, has an extensive database which relates composition, properties and section size, as well as the forging and rolling conditions for a range of air cooled steels. This expert knowledge is used in collaboration with forgers and end users to exploit the application of these steels over an expanding range of products.

This paper reviews the main grades in current use, the properties obtained and how they can be controlled. Several case studies are presented, together with future developments.

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Air Cooled Steels produced by British Steel Engineering Steels

The most common carbon and microalloyed steels used for forgings and control rolled bars are given in Table 1.[4]

The choice of grade depends upon the mechanical properties required. Microalloyed steels generally offer higher values of 0.2% proof stress and tensile strength compared to carbon steels. Apart from a variant of 38MnSiVS5 with 0.03/0.05% Nb, there is no significant application of Nb microalloyed steels.

For improved machinability, sulphur, calcium and lead additions can be made.

Table 1 Composition and Properties of Air Cooled Steels

Grade	C	Si	Mn	S	V	Others	0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)	BHN
080A47 mod	0.45/0.50	0.10/0.35	0.70/0.90	0.06/0.08	-	-	400	735-925	14	20	217-255
38MnSiS5	0.36/0.40	0.50/0.65	1.40/1.55	0.03/0.065	-	N0.015/0.020	450	750-900	12	30	-
VANARD 925	0.37/0.42	0.15/0.40	1.20/1.40	-	0.08/0.13	-	560	850-1000	12	-	248-302
VANARD 1000	0.42/0.47	0.15/0.40	1.20/1.40	-	0.15/0.20	-	620	925-1075	10	-	269-331
38 MnSiVS5	0.35/0.40	0.50/0.80	1.20/1.50	0.05/0.08	0.08/0.13	Ti0.015/0.030	580	820-1000	12	25	-
27MnSiVS6	0.25/0.30	0.50/0.80	1.30/1.60	0.030/0.050	0.08/0.13	Ti0.015/0.030	500	800-950	14	30	-
27MnSiVS6 mod	0.30/0.35	0.50/0.70	1.40/1.60	0.03/0.065	0.07/0.12	-	570	800-950	14	45	238-280
49MnVS3	0.44/0.50	0.50	0.70/1.00	0.03/0.05	0.08/0.13	-	450	750-900	-	20	-
49MnVS3 mod	0.42/0.46	0.15/0.40	0.70/1.00	0.03/0.05	0.07/0.10		500	750-900	8	-	222-266
17M	0.17/0.22	0.20/0.35	1.20/1.40	0.03/0.065	0.05/0.15	Cr0.10/0.15	460	610	20	27JCV at 20°C	
Macalloy 3M	0.60/0.65	0.20/0.35	0.75/0.90	0.05/0.075	0.09/0.15	Cr0.80/0.90	835*	1030*	6*	25*	-

•After 3% stretching

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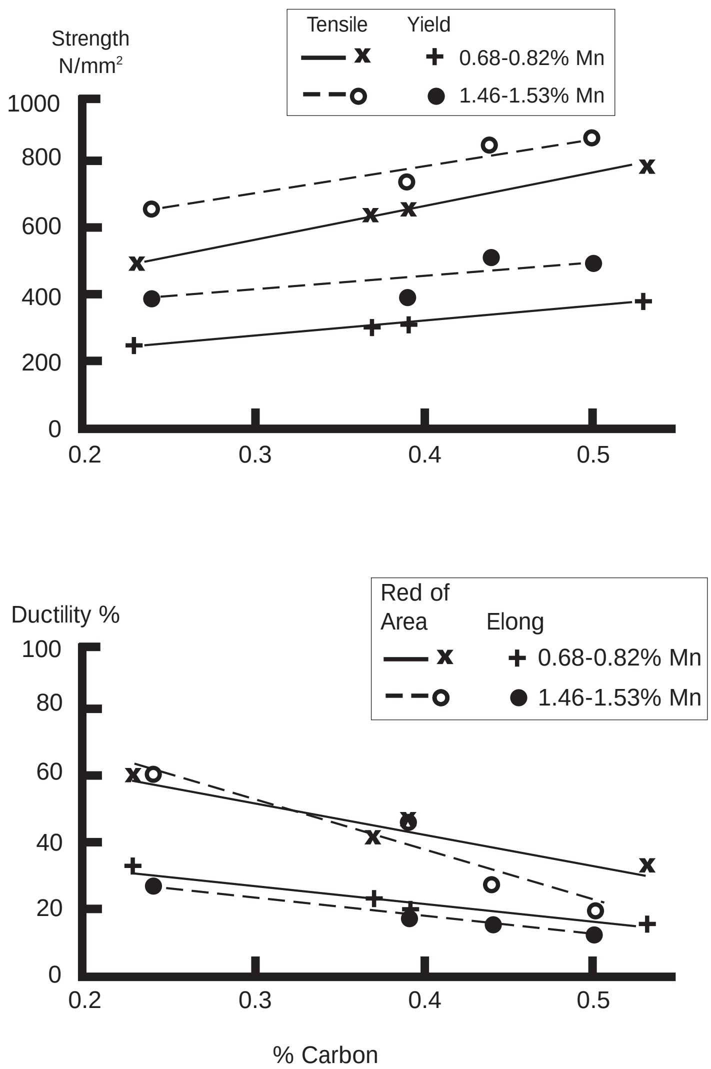
Influence of Composition upon Mechanical Properties

In air cooled carbon and microalloyed steels with ferrite-pearlite structures there is an increase in strength level with increasing carbon and manganese content. This is illustrated in Fig. 1 for carbon steels air cooled from 1150°C as a 50mm section. The increase in strength and associated reduction in ductility and toughness is associated with an increase in the proportion of pearlite with higher carbon and manganese levels.

Figure 1 Effect of Composition on Mechanical Properties of Air Cooled Carbon Steels (50mm Section-1150°C AC)



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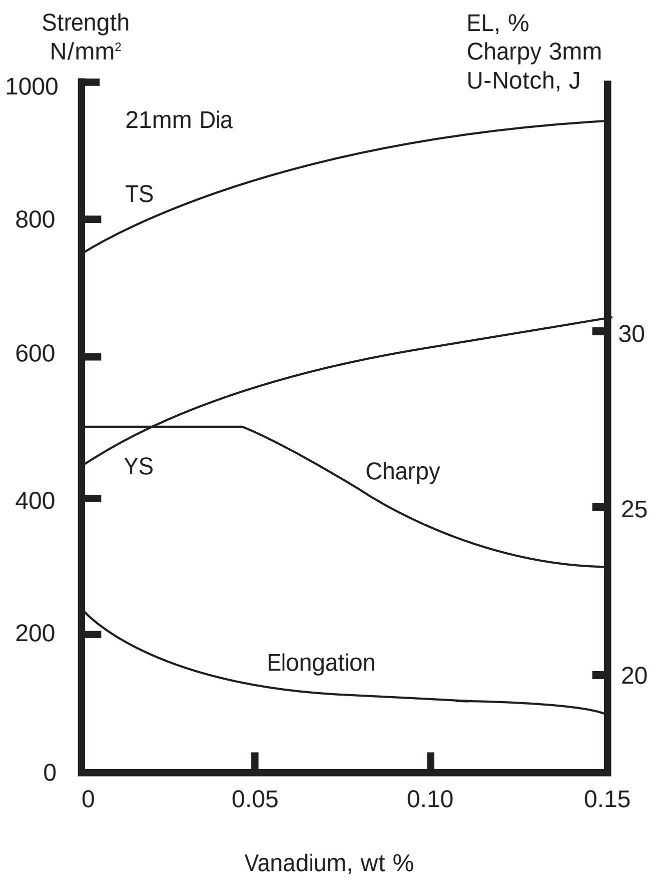
As shown in Fig. 2, the addition of vanadium results in an increase in yield and tensile strength levels, with an associated reduction in ductility and toughness. [(5) (6)] This is associated with interphase precipitation of vanadium carbo-nitride in the ferrite and also within the ferrite lamellae of the pearlite. In steels treated with niobium, the niobium acts in a similar way and results in the precipitation of niobium carbo-nitride.

Figure 2 Effect of Vanadium on Strength, Ductility and Toughness of Air Cooled 0.45% C, 0.9% Mn Steel



Silicon, chromium and nitrogen contribute to the strength of air cooled carbon and microalloyed forging steels. However, the total level of residual and alloying elements needs to be restricted to prevent the formation of bainite.

In some steels, in order to improve ductility and toughness, additions of titanium are made to control the austenite grain size on reheating. [(5 - 8)] A fine dispersion of titanium nitride particles is formed which do not dissolve or coarsen significantly at the soaking temperature.

Influence of Processing Conditions

Variations in hot working and cooling conditions can have significant effects on the mechanical properties of forgings and as-rolled bars. The factors which are important are the reheating temperature and time, the finish forging or rolling temperature, the cooling rate immediately after forging and during transformation, and the binning or stacking temperature.

In general, there is an increase in tensile strength with increasing reheating temperature in carbon and microalloyed steels. This is associated with a coarser austenite grain size on reheating, which influences the final prior austenite grain size, and results in a greater proportion of pearlite, and also with increased solution and reprecipitation of vanadium and niobium carbo-nitrides in microalloyed steels.

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The effect of forging temperature on the mechanical properties of microalloyed steels is shown in Figs. 3 and 4.[9] As the forging temperature is reduced there is an improvement in ductility and toughness associated with a refinement in the austenite and ferrite grain sizes. There is also some reduction in strength level as a result of a reduction in the proportion of pearlite.

Increasing the cooling rate by fan cooling results in an increase in the strength level (provided that bainite is not formed), with little or no reduction in toughness as shown in Figs. 3 and 4. This results from a refinement in the ferrite grain size, a refinement in the pearlite interlamellar spacing and finer carbo-nitride precipitates. An increase in the cooling rate immediately after hot working also restricts growth of the austenite grains. Changes in cooling rate also affect the properties of carbon steels, but to a lesser extent than for microalloyed steels.

The binning or stacking temperature can influence the properties and should be below 600°C to ensure that transformation has occurred during air cooling.

Silicon Killed Steels

The improved machinability of ferrite/pearlite air cooled steels compared with quenched and tempered steels is well known,[10] but many of these steels are still specified with an aluminium addition, similar to that used in heat treated steels for grain size control. As the AlN which controls grain growth is totally in solution at rolling and forging temperatures and precipitates only slowly on subsequent cooling, it has no effect upon the grain size of air cooled steels. Therefore, there is no justification for the inclusion of aluminium for grain size control.

Figure 3 Variation in Tensile Properties with Forging Temperature (Soaking Temperature 1250°C)

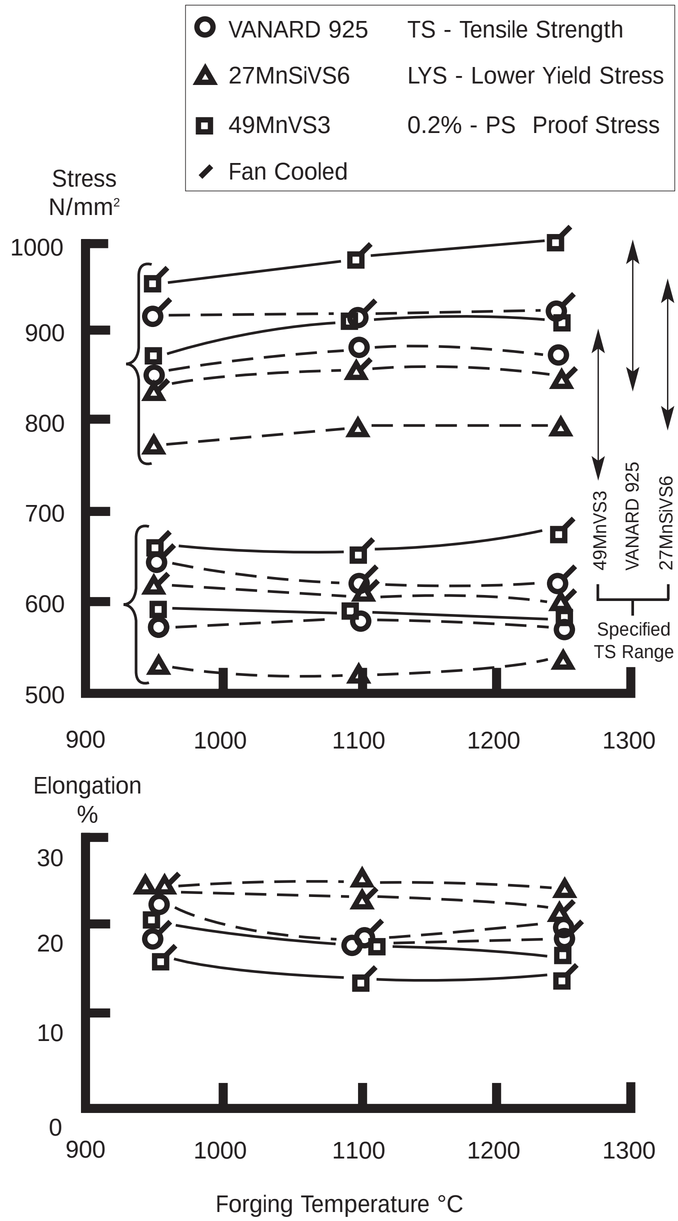

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Figure 4 Variation in Toughness with Forging Temperature (Soaking Temperature 1250°C)

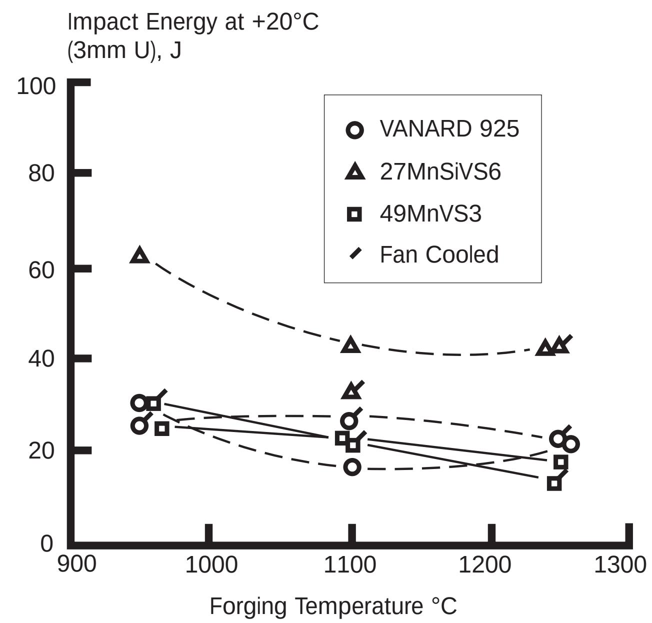

Figure 5 Comparative Machinability of 080A47 Grade with and without an Aluminium Addition

A disadvantage of adding aluminium, however, is the formation of abrasive Al_2O_3 inclusions which can be detrimental to machinability.

A comparison of machinability, using high speed steel tools on similar heats of 080A47 grade in the air cooled condition is given in Fig. 5. It can be seen that the absence of aluminium gives an improvement in turning tool life [11]. Similar benefits were found with carbide tooling.

Air cooled connecting rod forgings were produced at British Steel Forgings using similar heats of 080A47 grade with and without an aluminium addition. The compositions and properties of the forgings are found in Table 2.

Table 2

Heat No.	C	Si	Mn	S	Al	0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)	ASTM Grain Size
BA703	0.47	0.23	0.74	0.06	0.02	445	780	17	30	2/4½
Q4118	0.47	0.21	0.77	0.08	-	420	780	16	31	2/4½

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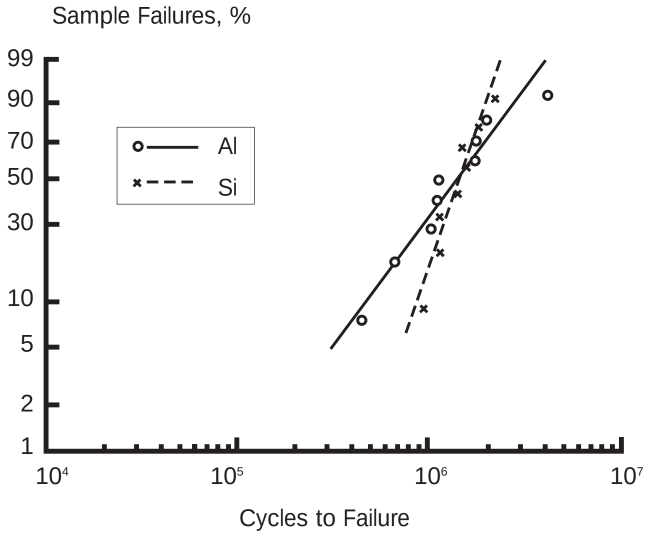
Connecting rod forgings were machined and mounted in a test rig to which loads of -48KN and +25KN were applied to simulate the push-pull fatigue conditions in a car engine. A Weibull analysis of the test data, given in Fig. 6, shows that as expected, there was no great difference between the two heats, with a slightly better performance from the silicon killed heat.

Figure 6 Weibull Analysis for Aluminium and Silicon Killed 080A47 Con-rods



British Steel Engineering Steels avoids the use of aluminium additions in air cooled steels, unless required by customer specification. Such aluminium-free steels are commonly referred to as “silicon-killed”.

Case Studies

Crankshafts in Commercial Vehicle Diesel Engines

Microalloyed steel alternatives to conventional hardened and tempered alloy steels have been available for some time. These offer cost savings from the elimination of heat treatment and straightening and improved machinability, in addition to savings in alloy content. A further development by British Steel Engineering Steels and British Steel Forgings has been the use of controlled air cooled SAE 1548 steel with induction hardening. Fillet induction hardening enables hardnesses of more than 45 HRc to be obtained to a depth of up to 2mm and this hardening gives similar bending fatigue performance from this and other steels regardless of the properties in the body of the forging.

Resonant dwell fatigue testing has shown that fatigue strengths in the range 850/920 N/mm^2 can be achieved from air cooled carbon and microalloyed crankshafts, comparable to that of heat treated steels. Typical compositions of these steels and properties achieved in the body of crankshafts are found in Table 3.

Table 3

Grade	C	Si	Mn	S	V	Others	0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)
SAE 4140 H&T	0.43	0.25	0.86	0.020	-	1.0Cr, 0.2Mo	680	875	20	55
SAE 1046 mod H&T	0.45	0.22	0.98	0.032	-	-	620	875	21	57
38MnSiVS5 A/C	0.38	0.57	1.37	0.062	0.11	-	598	896	19	39
SAE 1548 mod A/C	0.47	0.23	1.17	0.020	-	-	460	803	17	34
38MnSiS5	0.37	0.59	1.43	0.038	-	0.016N	476	820	19	49

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Table 4

	C	Si	Mn	S	V	0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)
080A47	0.47	0.16	0.77	0.079	-	459	802	16	35
SAE 1045	0.45	0.21	0.74	0.032	-	430	781	17	37
C70S6	0.72	0.22	0.49	0.062	0.04	530	910	12	20
VANARD 925	0.38	0.24	1.25	0.070	0.094	627	907	22	50

Car and Commercial Vehicle Connecting Rods

The use of air cooled carbon steels in car connecting rods is well established and British Steel Engineering Steels, in conjunction with British Steel Forgings, have successfully developed a number of applications. These offer the normal reduced through costs over conventional hardened and tempered steels by elimination of heat treatment and alloy costs and by giving improved machinability. Extensive machining is carried out on connecting rods and improvements in machining performance are particularly beneficial to cost reduction.

For larger connecting rods, such as those used in commercial vehicle engines, higher strength levels are required and microalloyed steels such as VANARD 925 are employed.

A recent development in the manufacture of connecting rods is the use of fracture splitting. This process, whereby the big end cap is removed from the body of the connecting rod by notching and fracturing, offers major investment and processing cost savings in the downstream manufacturing operations. Alternative materials to forged steel, such as sintered powder forgings and cast iron, with inherently brittle structures, are more readily fracture split than steel forgings. The use of a 0.70%C steel, C70S6, similar to that originally developed by Ford [12] enables satisfactory properties and fracture characteristics to be obtained, see Fig. 7. There are some reservations concerning the machinability of this steel and British Steel is exploring the possibility of using alternative air cooled carbon and microalloy grades which will enable satisfactory fracture splitting with excellent machinability.

Typical properties achieved in controlled air cooled connecting rods are found in Table 4.

Figure 7 Fracture Split Connecting Rod in C70S6 Air Cooled Grade

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Figure 8 Four Wheel Drive Vehicle Hub Flange

Four Wheel Drive Vehicle Hub

The hub shown in Fig. 8 has been made using the air cooled microalloyed steel 38MnSiVS5 in place of hardened and tempered 605M36 grade alloy steel. The actual composition used is detailed in Table 5.

Table 5

	C	Si	Mn	S	Mo	V
38MnSiVS5	0.37	0.56	1.39	0.061	0.03	0.09
605M36 Spec	0.32/0.40	0.10/0.35	1.30/1.70	0.05max	0.22/0.32	

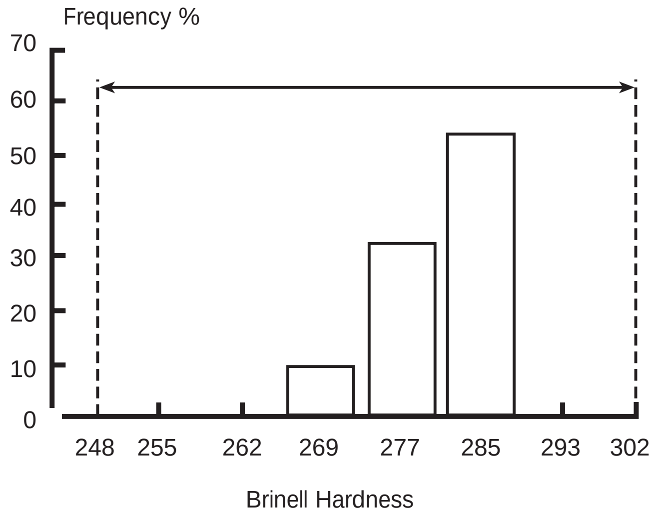
The mechanical properties required were easily met and are detailed in Table 6.

Table 6

	Measured	Specified
0.2% PS (N/mm^2)	614	560 min
TS (N/mm^2)	911	850/1000
El (%)	16	12 min
RoA (%)	40	-

After forging, each component was individually cooled to less than 600°C at a controlled rate before stowing in a bin, by using a dedicated conveyor system with cooling fans. This precise control enabled highly reproducible surface hardness results to be achieved as shown in Fig. 9. The mean Brinell hardness was 280.7 and the standard deviation 5.4, well within the specified range. In addition to an overall cost saving of £0.52 (approx. $0.80) per component, improved machinability has been reported.

Figure 9 Brinell Hardness Distribution in Air Cooled Hub Flanges



As Rolled Bars

British Steel Engineering Steels employs controlled rolling to achieve enhanced properties in straight bars of carbon and microalloyed steels in the size range 22mm to 47mm dia. This enables components to be machined directly from bar without the expense of heat treatment and of course with the benefit of improved machinability from the ferrite/pearlite structure. This results in lower final component costs.

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A specialised non-automotive product using as-rolled microalloyed steel bar is worthy of inclusion here. A range of bar sizes from 19 to 95mm dia is produced in 17M grade for a civil engineering tie bar application where the use of heat treatment would be uneconomic. A low carbon microalloyed steel is used to ensure that the low temperature impact requirement, critical in this application, is met.

Typical compositions and mechanical properties of controlled rolled bar are detailed in Table 7.

Table 7

Grade	C	Si	Mn	S	V	Other	Bar Size (mm)
080A47	0.48	0.25	0.89	0.071	0.04	-	22
VANARD 1000	0.46	0.29	1.33	0.037	0.16	-	40
17M	0.18	0.22	1.30	-	0.10	Cr0.14	19
17M	0.19	0.23	1.44	-	0.13	Cr0.11	85

Grade	0.2% PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)	CV2 (J) @ -20°C
080A47	630	864	16.7	36.2	
VANARD 1000	687	974	18.0	42.0	
17M	467	661	28.0		38, 52, 55
17M	507	678	21.0		35, 37, 37

For controlled rolling of the medium carbon steels the final reheat zone temperature is reduced by 75°C and the mill rolls at reduced speed, achieving finish rolling temperatures of down to 920°C, depending upon size. This has the effect of refining the product grain size, enabling normalised properties to be achieved in the as-rolled bar. The required properties in 17M grade can be achieved with normal rolling practice.

As Rolled and Cold Worked Bar

A recent development in the use of microalloyed steels has been their application to bright drawn bar. Drawing gives a significant increase in the 0.2% proof stress value, overcoming one of the weaknesses of microalloyed air cooled steels, which have inherently low 0.2%PS/TS ratios of 0.6-0.7, compared to about 0.8 in the hardened and tempered steels which they replace.

Coiled bar 17 to 22mm dia is produced in 27MnSiVS5 mod grade using an adjusted analysis range to ensure that the required properties can be achieved throughout the coil. A typical composition and range of properties in the as-rolled condition are detailed in Table 8:

Table 8
(Overall results from 5 coils at 11 positions through the coil, 18mm dia)

C	Si	Mn	V	Ti		0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)
0.31	0.61	1.45	0.11	0.03	Ave	512	845	19.4	48.4
					Range	403/639	772/909	14/24	30/55

The widest variation in properties is seen from end to centre of the coil as expected, with the end positions showing the highest strength values and the middle positions the lowest. The customer requirement is for a TS of 750/900 N/mm^2 and for a ferrite/pearlite structure without martensitic areas. The coils are drawn to wire with a reduction of around 15% to develop the final properties of 960/1020N/mm^2.

The final product is a steering component produced by cold forming, [(13)] with a significant overall cost reduction compared to a heat treated alloy steel.

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A second example is the use of a 38MnSiVS5 grade rolled to 25mm dia coiled bar. Cold drawing after rolling is used to achieve a minimum 0.2% PS requirement, overcoming the low 0.2%PS/TS ratio which is typical of air cooled steels. The details are found in Table 9.

Table 9

(Coil ends and middles, 11 tests after cold drawing to 23.4mm dia)

C	Si	Mn	V	0.2%PS (N/mm^2)	TS (N/mm^2)	El (%)	RoA (%)
0.37	0.54	1.4	0.09	Ave 624	891	18	42
				Range 596/643	884/896	17/18	40/48

(Front and rear of 3 coils, as-rolled)

				Ave 878	991	7.8	-
				Range 840/907	957/1014	7.5/8.0	

The cold drawn bars are used for car gearbox shafts, requiring a minimum 0.2% PS of 750 N/mm^2.

The third example is an alloy microalloyed steel which is control rolled to straight bar in the size range 25 to 52mm dia. The finish rolling temperature of between 920 and 960°C depends on size and three ranges of analysis are used depending on the bar size. The details are found in Table 10.

Table 10

C	Si	Mn	Cr	V	0.1% PS (N/mm^2)	UTS (N/mm^2)	El (%)
0.60/0.65	0.20/0.35	0.75/0.90	0.80/0.90	0.09/0.15	835 min	1060 min	6 min

The bars are another specialist non-automotive application, that of pre-stressing concrete beams used in civil engineering. The above properties are obtained in the bars after plastically stretching by approximately 3%.

Future Developments

Accelerated Cooling

There is a market potential for lower through cost steels with a better combination of strength and toughness than can be achieved in ferrite-pearlite structures formed on air cooling. Potentially, a better combination of properties can be achieved in bainitic (or acicular ferrite) structures, provided that high carbon martensite can be avoided. To avoid the need for costly alloying additions, accelerated cooling using water sprays has been investigated as a means of forming suitable microstructures. This technology is already established in the production of plates and has been applied to forgings. [(10)] Trials were undertaken with 50mm square bars which were instrumented with embedded thermocouples in order to control the temperature range for accelerated cooling. After reheating at 1200°C and water spray cooling from 900°C to temperatures in the range 300-600°C, tensile strength levels in the range 850-1080 N/mm^2 were achieved in 0 2%C, 1.4%Mn steels with and without an addition of vanadium. 3mm U-notch impact energies in the range 20-45J were also achieved.

Further development of the steels and process route are required to optimise the level of properties that can be achieved.

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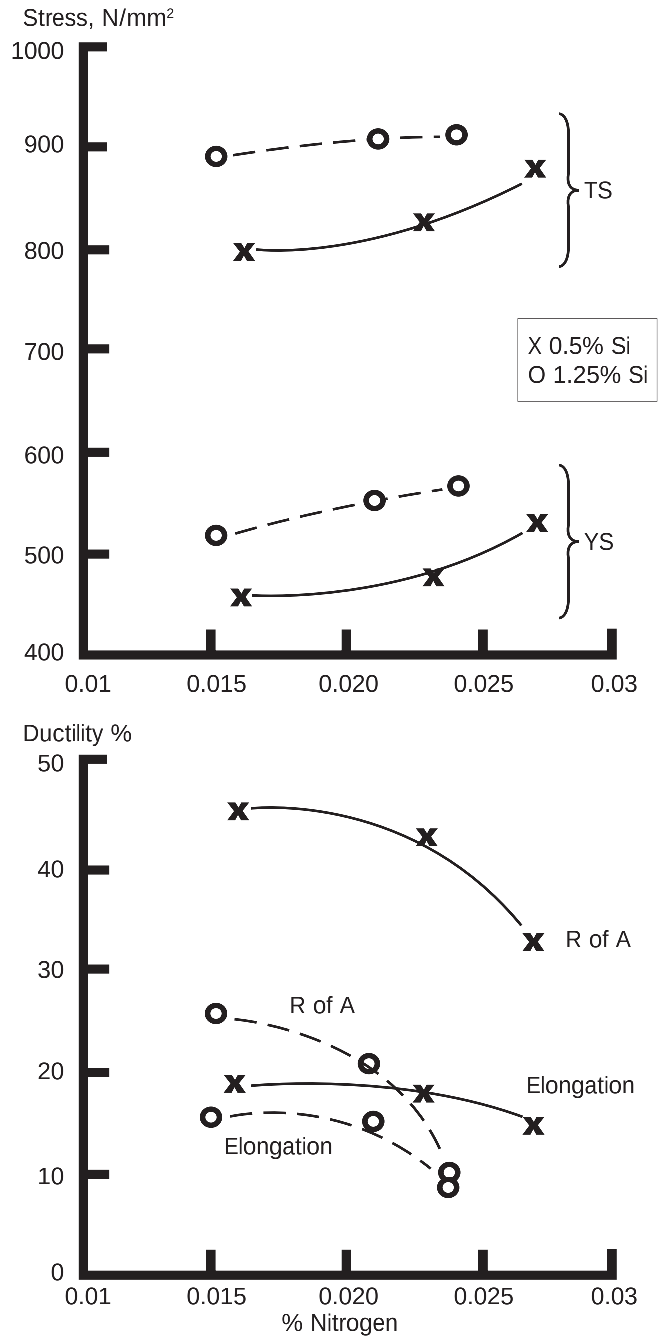
High Nitrogen Carbon Steels

Increased nitrogen levels can be used to increase the strength level of carbon steels through solid solution strengthening, without the need for other alloying additions. These high nitrogen steels are produced without an aluminium addition to avoid aluminium nitride formation. The effect of increasing nitrogen and silicon level in a 0.4%C, 1.5% Mn steel is shown in Fig. 10. Increasing nitrogen in the range 0.016-0.027% and silicon in the range 0.5-2.0% led to an increase in yield and tensile strength level, but gave rise to a reduction in ductility.

Acceptable properties are obtained in 38MnSiS5 grade with 0.4%C, 0.5%Si, 1.5%Mn and 0.2%N after air cooling from 1150-1200°C. It may be possible to extend the range of strength levels by using slightly higher carbon and silicon levels.

Figure 10 Variation in Tensile Properties with Nitrogen and Silicon Levels



The future in metal

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Conclusions

1 The grades of microalloyed steel in regular use have been concentrated into several common types which are used in increasing quantities.

2 A notable feature for automotive applications is a similar growth in air cooled carbon manganese steels with no microalloying constituent. These steels offer further reductions in cost whilst giving acceptable properties and are of equal importance to microalloyed steels.

3 There is a case for the elimination of aluminium additions to air cooled steels in order to offer potential improvements in machinability.

4 The successful application of air cooled steels for forgings requires:

(a) Close control of the forging and cooling conditions with suitable cooling facilities being available.

(b) Co-operation between the steelmaker, forger and end user.

5 Future developments will focus on enhanced properties by using accelerated cooling and/or higher nitrogen steels for forgings and the use of controlled rolling and cold working for bar.

Acknowledgements

Thanks are expressed to Dr. I.G. Davies, Technical Director, British Steel Engineering Steels and Dr. K.N. Melton, Research Director, Swinden Technology Centre, British Steel plc, for permission to publish this paper.

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