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II. METAL FABRICATION EFFECTS

The effects of residual elements on the properties of engineering steels

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The effect of a variety of residual elements on the tensile and toughness properties of special carbon and low alloy engineering steels has been determined. The major objective of this work has been to identify the extent to which residual element contents can be allowed to rise without infringing the specification and in-service performance requirements of these steels.

In C–Mn and C–Mn–B steels, the main effect of the residual elements, chromium, molybdenum, nickel and copper, is to raise hardenability and tensile strength with a concurrent reduction in ductility. The effects on toughness are dependent upon the microstructural changes accompanying the increase in hardenability and can be either beneficial or detrimental. A statistical approach has been adopted in quantifying the influence of these elements on hardenability. In many cases, naturally occurring levels of chromium, molybdenum, nickel and copper can be used to advantage as the basis for providing cheaper alternatives to low alloy steels. However, it might be necessary to compensate for very high residual element levels by reducing the carbon and/or manganese levels in order to maintain the currently specified hardenability limits.

In low alloy steels, phosphorus, arsenic and tin were found to exhibit the greatest influence on toughness and this effect was most detrimental in the Cr and Ni–Cr steels. The presence of molybdenum reduced the susceptibility to embrittlement. In most of the low alloy steel grades examined, it has been concluded that there would be no foreseeable violations of property specifications, even if the residual content were allowed to rise much above the current levels. Only in certain cases, e.g. 815H17, was it concluded that the phosphorus, arsenic and tin contents must be maintained at the current levels produced by electric arc steelmaking in order to satisfy user requirements.

1. Introduction

The production of special carbon and alloy engineering steels is based on the remelting of iron units and ferro-alloys in basic electric arc furnaces. Although other forms of iron units are being used increasingly, steel scrap remains the primary feedstock for these furnaces and the main source of residual elements in these steels. During the past 10 years, scrap has become an international commodity and in periods of economic boom, good quality scrap is both scarce and expensive. At such times, steelmakers may be forced to use poorer grades of scrap with lower metallic yield and higher levels of residual elements.

Although the steel industry in the U.K. has not enjoyed full capacity demand since 1974, the problems faced by B.S.C. at that time precipitated major investigations into the more effective selection and segregation of scrap in works in the Sheffield area and this topic forms the basis of a complementary paper from B.S.C. (Hartley *et al.*, this symposium). At the same time, detailed investigations were initiated at B.S.C.'s Sheffield Laboratories into the property

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implications of higher residual contents and this work constitutes the treatment of the current paper.

Whereas elements such as nickel, chromium and molybdenum are residual elements in carbon steels, they constitute deliberate additions in alloy steels. For this reason, the following text has been subdivided to deal separately with the two types of steel, but in both cases consideration is given to copper, arsenic, tin and phosphorus which also arise as residual elements.

2. Carbon engineering steels

(a) *Hardenability*

Most specifications for engineering steels carry a Jominy hardenability requirement and since most elements promote hardenability an understanding of the effect of residual elements is crucial in meeting specifications. Whereas the critical diameter (D_1) concept of Grossman (1942) is still widely used, commercial specifications are invariably based on hardness-distance data and the authors have adopted a statistical analysis of these criteria in their treatment of the results.

Jominy hardenability data from commercial casts of steel containing 0.3–0.4 % C were supplemented by data from experimental casts which were made deliberately to extend the ranges of elements such as phosphorus (0.008–0.042 %), chromium (0.08–0.25 %), molybdenum (0.01–0.10 %), nickel (0.08–0.40 %), copper (0.10–0.60 %) and tin (0.015–0.10 %). Separate regression analyses were carried out on two steel types, i.e. C–Mn–B and C–Mn grades. The results of these analyses are shown in table 1, in terms of the constants and coefficients for different elements at various end-quench (J) distances.

As expected, chromium has a positive coefficient that generally exceeds that of manganese and other elements, with the exception of molybdenum. Nickel has a relatively small effect on hardenability but the introduction of negative coefficients in the C–Mn boron-free steel is not considered to be valid metallurgically. Copper was shown to have a small positive effect on hardenability but variations in tin were not significant. Phosphorus appears in these prediction equations with positive coefficients at higher J values and predictably, sulphur produces an adverse effect on hardenability due to the formation of MnS and a reduction in the active manganese content.

An illustration of the effect of increasing residual levels on the hardenability of a 0.35 % C, 0.75 % Mn steel is shown in figure 1. These data were generated from a single base melt but with the use of a split casting and incremental addition technique aiming to achieve the variations in residual elements given in table 2. Codes A and B constitute typical but distinct maximum levels of residual ranges in commercial practice, whereas code C represents exaggerated levels that might occur if scrap selection were not practised. The major effect on hardenability is apparent from this figure and whereas code C residuals represent a currently unrealistic residual content, it can be seen that the use of such levels could lead to a violation of the hardenability limit for 080H36 steel.

Table 2. Residual element contents (percentages by mass)

residual code	Cr	Mo	Ni	Cu	Sn
A	0.15	0.05	0.20	0.20	0.035
B	0.20	0.08	0.30	0.30	0.050
C	0.25	0.10	0.40	0.50	0.100

Table 1. Statistical analysis of the effect of compositional variables on hardenability

(Multiplying factors, R_c; Jominy distance, $\frac{1}{16}$ in. (1.6 mm).)

	C–Mn–B								C–Mn							
element J	1	4	6	8	10	12	16	28	1	2	3	4	6	8	10	12
constant	34.6	28.8	−5.4	−37.0	−47.1	−50.7	−25.1	−44.7	36.8	28.7	−6.8	−31.5	−19.1	−14.6	−16.2	−14.9
C	51.2	53.4	70.7	47.7	52.6	73.6	69.0	22.2	42.1	49.9	59.6	64.1	57.3	58.6	57.8	52.7
Si					16.3	21.8	13.1				32.9	45.5			16.9	13.8
Mn	1.3	3.1	17.4	40.9	42.8	37.3	17.6	35.7	2.5	4.6	16.8	24.5	18.6	13.0	9.8	9.1
P				104.2	82.9								91.9	51.6	74.1	59.3
S	−13.5			−94.1	−105.6	−94.6		93.9								
Cr		3.5	35.5	53.5	49.7	43.6	24.8	35.5		7.8	47.7	53.1	33.2	20.1	21.1	19.5
Mo				91.6	109.7	114.4	62.7	90.9	8.6				65.5	79.6	55.6	45.3
Ni		4.6	15.0					9.6				15.8	−18.3	−22.1	−10.6	−7.8
Cu			15.6	25.9	18.9	20.6							13.3	12.2		
Sn									−26.1							
Ti							−70.4									
B	214.5					−721.6										
mean	53.6	51.5	47.0	37.8	32.4	29.0	22.0	23.5	55.3	53.5	46.6	38.8	30.7	27.5	25.6	24.2
explained %	80.9	84.8	73.8	88.5	92.2	91.4	73.5	82.8	73.9	68.9	5813	82.6	88.0	83.6	81.5	83.2
2σ	1.9	1.8	6.2	7.2	6.0	5.7	3.9	5.1	1.9	2.9	9.6	8.5	5.9	5.5	5.0	4.3

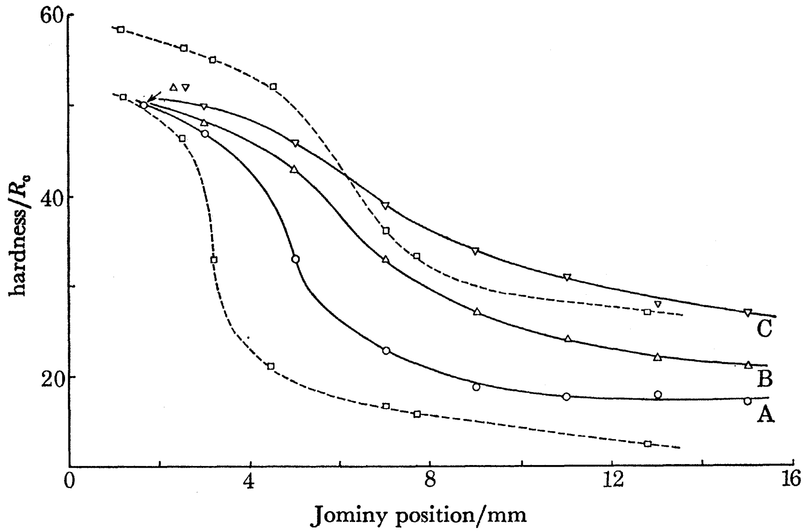

FIGURE 1. Effect of residual elements on the hardenability of 080H36 steels: ○, code A; △, code B; ▽, code C; --□--, specified BS 970, hardenability band 080H36.

(b) *Tensile and impact properties*

A great deal of experimental work has been carried out on a variety of carbon steel grades but only a selection of data can be presented in this paper.

(i) *Normalized condition*

Property determinations were carried out on a base steel containing 0.30 % C, 0.75 % Mn with the three levels of residual elements designated A, B and C in the previous section. The tensile and impact properties of these steels were determined in 15.8, 28.6 and 63.5 mm diameter bars after normalizing from 850 °C, and the results are shown in table 3. As expected from the hardenability data for these steels, an increase in residual content produces an increase in tensile strength in the smallest bar size but the hardenability effects are insufficient to produce any significant effect on tensile strength in the 63.5 mm bar. The only effect on elongation is in the 15.8 mm bar size, where a slight decrease in ductility accompanies the increase in residual content and tensile strength.

TABLE 3. MECHANICAL PROPERTIES OF NORMALIZED 0.30 % C–Mn STEEL

bar size mm	residual code	tensile strength MPa	lower yield stress MPa	elongation (%)	reduction of area (%)	Charpy	
						J at 20 °C	f.a.t.t./°C
15.8	A	625	425	27.8	47.0	96	−22
	B	631	434	27.8	46.0	102	−22
	C	730	436	—	38.0	35	22
28.6	A	616	405	29.3	58.0	185	−8
	B	621	415	29.7	58.0	82	+2
	C	670	446	25.5	51.0	66	+3
63.5	A	605	391	21.9	62.0	66	+2
	B	620	409	28.2	58.0	66	−2
	C	645	434	28.5	55.0	65	+10

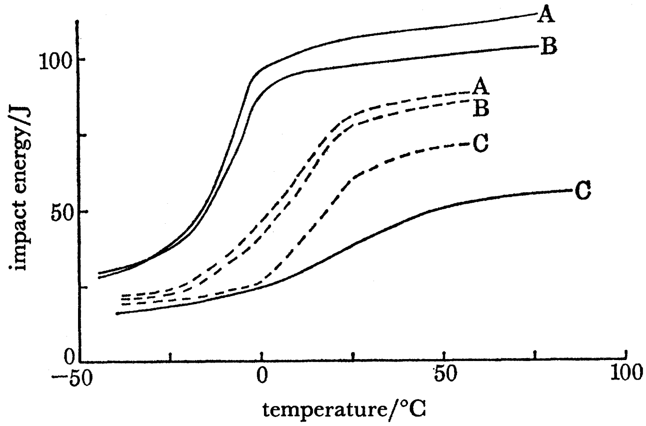

FIGURE 2. Effect of residual elements on the impact properties of normalized 0.30 % carbon steel: ——, 15.8 mm bar; – – –, 28.6 mm bar.

The impact transition curves for these steels are shown in figure 2. Again, these results are compatible with the tensile data and the effect of residual content is only markedly discernible in the 15.8 mm bar. In this case, the upper shelf energy is reduced and the 50 % fracture appearance transition temperature (f.a.t.t.) is increased in the code C material.

(ii) *Quenched and tempered condition*

Tensile and impact transition data were determined on C–Mn and C–Mn–B steels, by using the split melt technique to achieve the variations in residual content cited earlier (codes A, B and C).

Bars of 15.8, 28.6 and 63.5 mm diameter were again investigated and were oil quenched or water quenched from 860 °C. The properties were determined after tempering at 550 and 660 °C and the results are shown in tables 4 and 5.

The tensile strength – elongation relations for these steels are summarized in figures 3 and 4 for the tempered 550 °C condition. From these graphs, it is obvious that an increase in residual

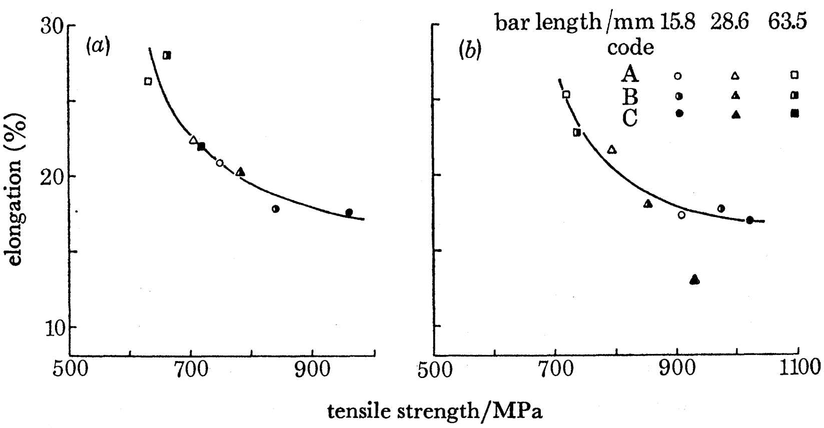

FIGURE 3. Tensile strength – elongation relations, 860 °C oil quench, tempered at 550 °C (*a*) 0.3 % C–Mn; (*b*) 0.36 % C–Mn–B.

TABLE 4. MECHANICAL PROPERTIES OF 0.36 % C–Mn–B STEEL

bar size mm	quench	tempering temperature °C	residual code	tensile strength MPa	lower yield stress MPa	elongation (%)	reduction of area (%)	Charpy J at 20 °C	Charpy f.a.t.t./°C
15.8	oil	550	A	908	831	17.3	58.0	90	−32
			B	975	905	17.7	58.0	60	−25
			C	1023	955	17.0	50.0	47	−5
		660	A	744	681	22.0	60.0	125	−65
			B	786	698	21.6	64.0	109	−50
			C	815	739	21.3	62.0	92	−38
	water	550	A	934	868	12.9	50.0	66	−40
			B	954	868	11.0	30.0	60	−40
			C	1018	905	8.3	20.0	50	−15
		660	A	749	657	24.0	64.0	136	−70
			B	766	657	22.5	63.0	107	−57
			C	795	719	19.3	58.0	89	−63
28.6	oil	550	A	794	536	21.6	64.0	24	+72
			B	854	796†	18.1	56.0	34	+45
			C	931	779†	—	58.0	29	+50
		660	A	712	464	25.0	68.0	34	+55
			B	751	589	22.0	64.0	95	+10
			C	794	655	22.0	66.0	92	+5
	water	550	A	906	849	17.0	57.0	64	−10
			B	952	870	14.5	51.0	66	−9
			C	985	941	16.5	57.0	45	+8
		660	A	745	639	23.3	66.0	130	−48
			B	764	660	27.6	64.0	113	−54
			C	790	687	21.9	62.0	90	−35
63.5	oil	550	A	719	459	25.3	60.0	38	+48
			B	735	475	22.8	59.0	35	+45
			C	791	589	—	—	32	+62
		660	A	647	398	28.6	60.0	46	+39
			B	676	420	25.0	58.0	43	+25
			C	714	538	23.0	61.0	48	+35
	water	550	A	740	471	21.6	62.0	37	+46
			B	789	533	20.4	62.0	35	+44
			C	853	662†	17.5	45.0	32	+43
		660	A	694	444	26.2	62.0	44	+44
			B	719	517†	23.9	66.0	56	+44
			C	776	681†	21.1	61.0	101	+5

† 0.2 % proof stress.

content leads to an increase in tensile strength but in fact the section size effect is probably more dominant. This increase in tensile strength is accompanied by a reduction in ductility but the main point to note is that residual content *per se* does not appear to be a significant factor in this relation. The yield: tensile strength ratio increases with residual content.

The wealth of impact transition data that was determined in this investigation cannot be discussed in detail and therefore only the more significant trends will be highlighted. In general, an increase in residual content leads to a decrease in ductile shelf energy and an increase in impact transition temperature. This is illustrated in figure 5 for the 15.8 mm bar in the C–Mn steel, oil quenched from 860 °C and tempered at 550 °C. However, in evaluating such effects, it is important to bear in mind that this embrittling effect of residual elements is also associated

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TABLE 5. MECHANICAL PROPERTIES OF 0.30 % C–Mn STEEL

bar size mm	quench	tempering temperature °C	residual code	tensile strength MPa	lower yield stress MPa	elongation (%)	reduction of area (%)	Charpy J at 20 °C	Charpy f.a.t.t./°C
15.8	oil	550	A	748	576	20.9	57.0	134	−62
			B	839	694	17.8	56.0	130	−52
			C	962	867	17.7	54.0	95	−30
		660	A	661	498	25.3	69.0	210	−80
			B	710	577	24.5	68.0	197	−73
			C	781	681	23.8	63.0	162	−82
	water	550	A	872	781	16.8	56.0	122	−56
			B	915	839	17.7	60.0	103	−53
			C	996	931	16.8	52.0	82	−38
		660	A	732	635	23.0	66.0	153	−73
			B	744	639	20.3	60.0	130	−86
			C	789	697	23.7	67.0	119	−85
28.6	oil	550	A	703	506	22.5	62.0	126	−45
			B	783	600	20.2	58.0	82	−35
			C	838	688	—	54.0	107	−10
		660	A	639	458	28.9	63.0	144	−34
			B	670	496	26.4	68.0	141	−51
			C	713	570	23.1	62.0	167	−73
	water	550	A	776	604	21.0	60.0	94	−42
			B	836	686	21.0	60.0	110	−53
			C	906	780	19.2	55.0	66	−50
		660	A	694	534	25.0	67.0	138	−62
			B	710	560	24.3	67.0	165	−52
			C	769	646	22.9	65.0	135	−59
63.5	oil	550	A	630	422	26.3	59.0	86	−13
			B	663	446	28.0	60.0	116	−7
			C	717	544	28.0	56.0	88	−12
		660	A	586	396	29.4	63.0	153	−8
			B	608	412	30.2	52.0	135	−16
			C	653	511	27.6	61.0	145	−30
	water	550	A	663	449	26.0	60.0	105	−2
			B	701	486	26.6	57.0	105	−18
			C	734	559	23.8	55.0	117	−33
		660	A	608	409	32.9	64.0	158	−46
			B	629	424	30.0	64.0	185	−50
			C	662	508	28.8	66.0	142	−55

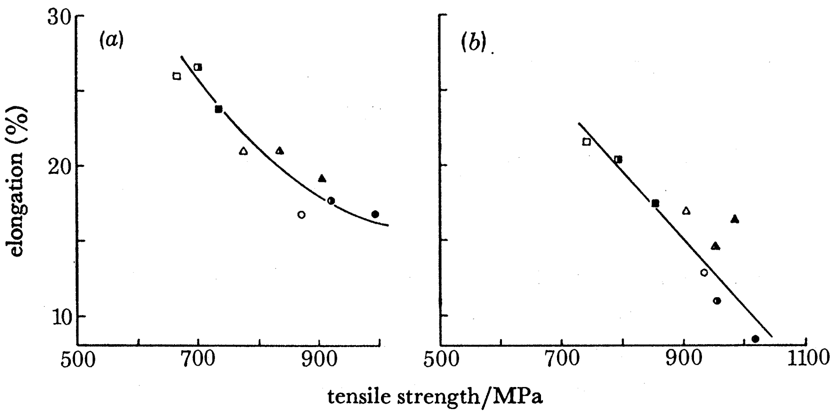

FIGURE 4. Tensile strength – elongation relations, 860 °C water quench, tempered at 550 °C. (*a*) 0.3 % C–Mn; (*b*) 0.36 % C–Mn–B. Symbols as for figure 3.

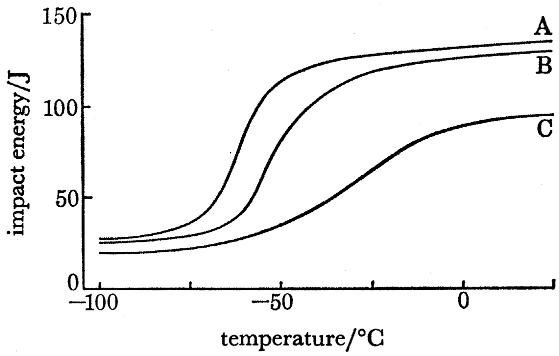

FIGURE 5. Effect of residual elements on the impact properties of 0.30 % C steel (oil quench, tempered at 550 °C; 15.8 mm bar).

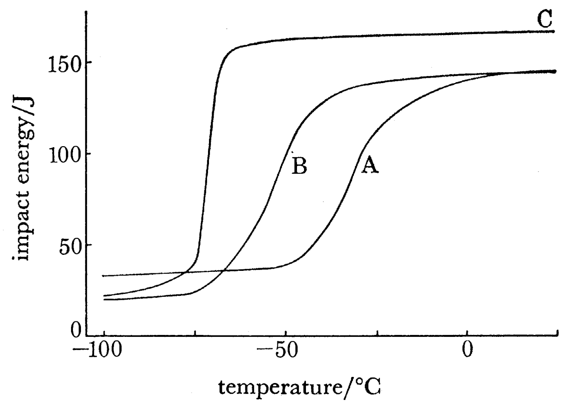

FIGURE 6. Effect of residual elements on the impact properties of 0.30 % C steel (oil quench, tempered at 660 °C; 28.6 mm bar).

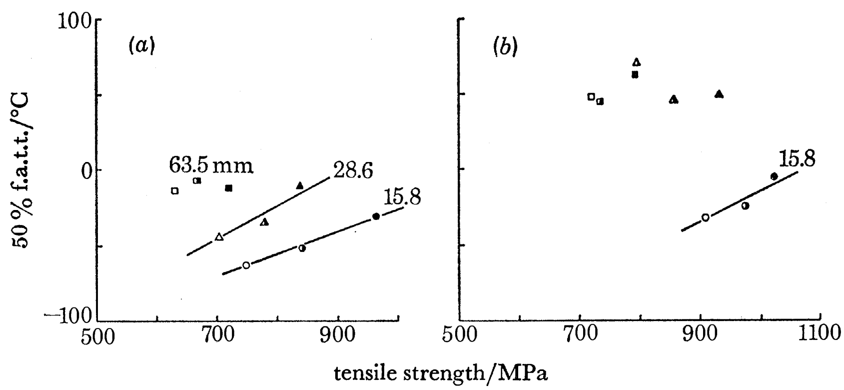

FIGURE 7. Tensile strength – toughness relations, 860 °C oil quench, tempered at 550 °C. (*a*) 0.3 % C–Mn; (*b*) 0.36 % C–Mn–B. Symbols as for figure 3.

with a significant increase in hardenability and tensile strength. Nevertheless, in certain instances the toughness improves as the residual content increases as shown in figure 6.

Tensile strength – toughness relations for both the boron-free and boron-bearing steels are shown in figures 7 and 8, referring to the oil-quenched condition. From these graphs, it is obvious that a great deal of difficulty has been experienced in highlighting the predominant

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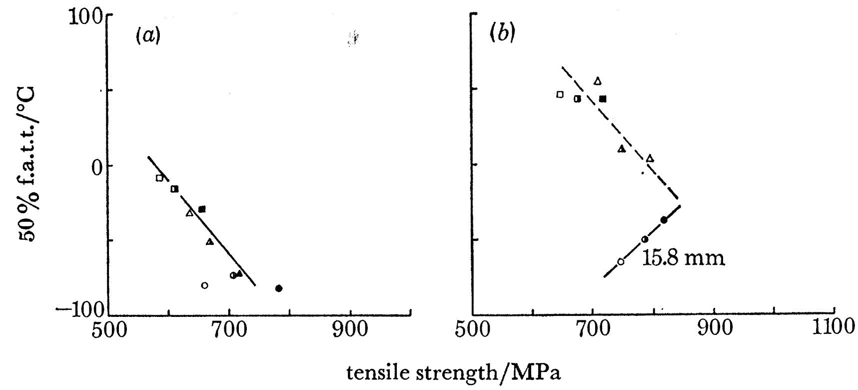

FIGURE 8. Tensile strength – toughness relations, 860 °C, oil quench, tempered at 660 °C. (*a*) 0.3 % C–Mn; (*b*) 0.36 % C–Mn–B. Symbols as for figure 3.

trends in what represents a very complex metallurgical situation. For example, it is possible to demonstrate the classical relation between increasing strength – decreasing toughness for the smaller bar sizes in figure 7*a*. On the other hand, a relation involving increasing strength – increasing toughness can be identified for larger bar sizes, as illustrated in figure 8.

In order to appreciate the reason for this apparently conflicting behaviour, it is necessary to understand the underlying microstructural relation that accompany these changes in residual

TABLE 6. MICROSTRUCTURES OF HEAT-TREATED C–Mn–B STEELS

quench	tempering temperature °C	residual code	bar size 15.8 mm	bar size 28.6 mm	bar size 63.5 mm
oil	550	A	1	2, 3	5, 3
		B	1	4	5, 3
		C	1	4	2, 3
	660	A	1, 6	2, 6	5, 3
		B	1, 6	4, 6	5, 3
		C	1, 6	4, 6	2, 6
water	550	A	1	4	5, 3
		B	1	4	5, 3
		C	1	4	4
	660	A	1, 6	4, 6	5, 6
		B	1, 6	1, 6	2, 6
		C	1, 6	4, 6	4, 6

Key: 1, tempered martensite; 2, ferrite–pearlite, some bainite; 3, spheroidized carbide; 4, tempered bainite; 5, ferrite–pearlite; 6, severe spheroidization of carbide.

content and section size. A summary of the microstructures developed in these steels is given in tables 6 and 7 for the C–Mn–B and C–Mn steels respectively. From these tables, it is apparent that an increase in residual content promotes the formation of lower temperature transformation products, i.e. martensite as opposed to bainite, whereas an increase in bar diameter produces the reverse effect. From the work carried out by Gladman *et al.* (1975) the effect of increased strength on toughness is dependent upon the metallurgical strengthening mechanisms employed. They have shown that an increase in dislocation or dispersion strengthening leads to an increase in the impact transition temperature of about 0.3 °C f.a.t.t. per 1 MPa increase in

Table 7. Microstructures of heat treated C–Mn steels

quench	tempering temperature °C	residual code	bar size 15.8 mm	bar size 28.6 mm	bar size 63.5 mm
oil	550	A	1	7, 3	5
		B	1	8	5
		C	1	4	2
	660	A	1	2	5, 3
		B	1, 6	4, 6	5, 3
		C	1, 6	4, 6	2, 3
water	550	A	1	4	5
		B	1	4	5
		C	1	4	5
	660	A	1, 6	4, 6	5, 3
		B	1, 6	4, 6	5, 3
		C	1, 6	4, 6	5, 3

Key: 1, tempered martensite; 2, ferrite–pearlite, some bainite; 3, spheroidized carbide; 4, tempered bainite; 5, ferrite–pearlite; 6, severe spheroidization of carbide; 7, mixed pearlite and bainite; 8, tempered bainite, some pearlite.

yield strength. On the other hand, the refinement of the ferrite grain size or bainite/martensite lath packet leads to an increase in both strength and toughness, with a decrease in the impact transition temperature of about −0.7 °C f.a.t.t. per 1 MPa increase in yield strength.

The two dominant trends that have been identified are shown again schematically in figure 9*a*. Alongside this diagram, the effects of the underlying metallurgical mechanisms are illustrated in figure 9*b*. However, it is obvious that all the data do not fit these classical trends and for example in figure 8*a*, the smaller bar sizes exhibit a wide range of tensile strength at virtually the same level of toughness. It is postulated that such relations result from an interaction between the classical grain refinement and dislocation/dispersion strengthening mechanisms.

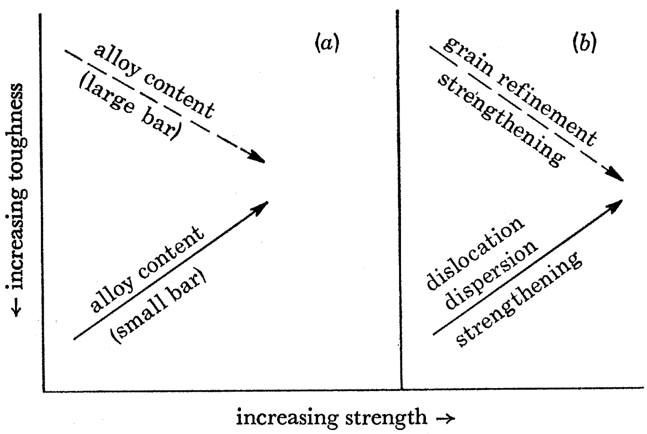

Figure 9. (*a*) Property trends. (*b*) Metallurgical mechanisms.

From a practical standpoint, the only conclusion that can be drawn from this work is that residual elements such as chromium, molybdenum, nickel and copper behave as normal alloying additions. Although an increase in these elements may produce a deterioration in ductility and toughness, these effects are related solely to changes in microstructure and cannot be attributed to deleterious characteristics of the elements *per se*.

3. Alloy engineering steels

In this sector, investigations have been carried out on a range of popular automotive grades (table 8). Although 080M40 (En 8) is essentially a carbon grade, it has been grouped in this paper with the alloy steel types in view of its usage in the automotive industry.

Table 8

steel type	specification	typical application
C–Mn	080M40 (En 8)	crankshafts
Mn–Mo	605M36 (En 16)	axle beams
1 % Cr	530M40 (En 18)	crankshafts
1 % Cr–Mo	709M40 (En 19)	crankshafts
$\frac{1}{2}$ % Ni–Cr–Mo	SAE 8620	carburized gears
$1\frac{1}{2}$ % Ni–Cr–Mo	815M17 (En 353)	carburized gears
$1\frac{1}{2}$ % Ni	817M40 (En 24)	large shafts

The effects of phosphorus, copper and tin were investigated using experimental casts with the following variations: tin, 0.02–0.20 %; copper, 0.15–0.60 %; phosphorus, 0.02–0.04 %. Separate melts were also made in SAE 8620, 605M36 and 530M40 to investigate the effects of arsenic (0.025–0.20 %), antimony (0.004–0.04 %) and cobalt (0.05–0.50 %).

(*a*) *Hardenability*

Jominy hardenability tests were carried out on the complete range of experimental steels, but in the present paper the remarks will be confined to the effects observed at the $J = 10$ mm position, i.e. the cooling rate experienced by a 25 mm bar during oil quenching. Only copper and tin were shown to have any significant effects and these were confined to the lower alloyed, carburizing grades. In SAE 8620, an increase in hardness of $5R_c$ is produced at the $J = 10$ mm position with the simultaneous increase of 0.15–0.60 % Cu and 0.02–0.15 % Sn. In 815M17, these increments of copper and tin produced an even smaller increase in hardness, i.e. $2R_c$. Cobalt had a small but detrimental effect on hardenability.

(*b*) *Tensile properties*

A statistical analysis of the tensile strength and elongation data eliminated many of the residual element variables and the function was reduced to

$$12\text{P} + 7\text{Sn} + \text{Cu}.$$

A summary of the tensile properties, plotted against the above factor, is shown in figures 10 and 11. It is apparent that residual elements have the greatest effect in steels of low alloy content such as SAE 8620 and virtually no effect on highly alloyed compositions such as 817M40. However, this effect is influenced by the small sections employed in this investigation. The ductility values are compatible, SAE 8620 showing the greatest deterioration, but a small adverse effect is also noted in 817M40. Since a hardenability effect is not operative at small section sizes in this composition, the deterioration in ductility is assumed to be related to an embrittling mechanism. This hypothesis is in accord with the work of Viswanathan & Sherlock (1972) who have suggested that the influence of residual elements on tensile properties is confined to those steels that are severely embrittled.

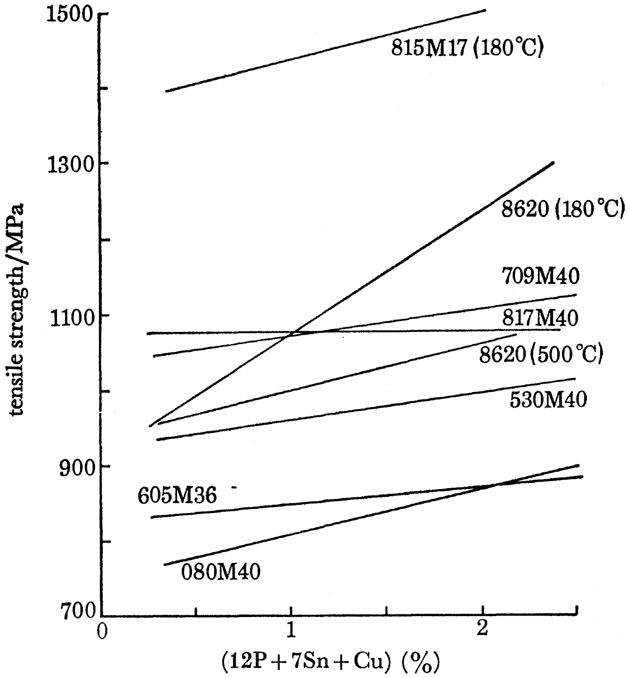

FIGURE 10. Effect of residual elements on tensile strength.

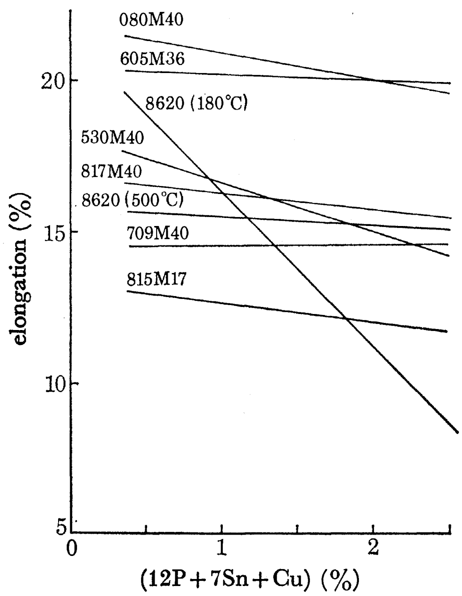

FIGURE 11. Effect of residual elements on ductility.

(c) *Impact properties*

Regression work indicated that residual elements respected two basic classes of steels with regard to their effect on impact properties. In C–Mn and Mn–Mo steels, phosphorus and tin were shown to be significant and the f.a.t.t. was increased according to the following function:

$$7P + 3Sn.$$

This effect is illustrated graphically in figure 12.

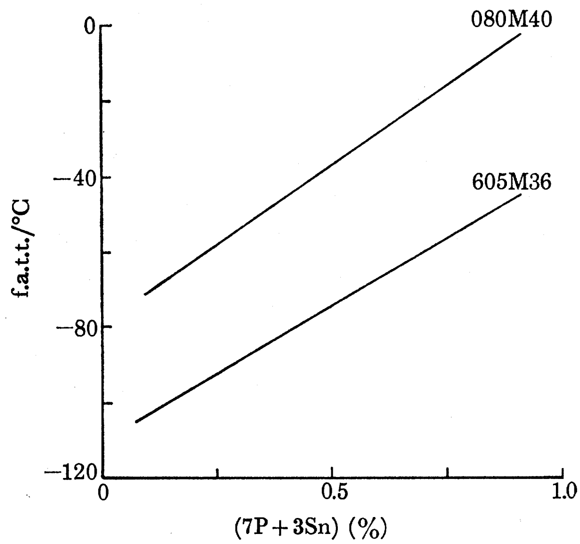

FIGURE 12. Effect of residual elements on toughness.

The second class of steels, embodying plain Cr and Ni–Cr types, was shown to be adversely affected by arsenic and the following function was generated for an increase in f.a.t.t.:

$$11.5P + 4.5As + 4Sn.$$

Graphical presentations for this second class of steels are given in figure 13. These steels are all susceptible to temper embrittlement in the quenched and tempered condition and the effect is most marked in SAE 8620 after tempering at 500 °C (e.g. roller chain parts). Whereas minor hardenability effects might be responsible for the slight deterioration in toughness in the tempered

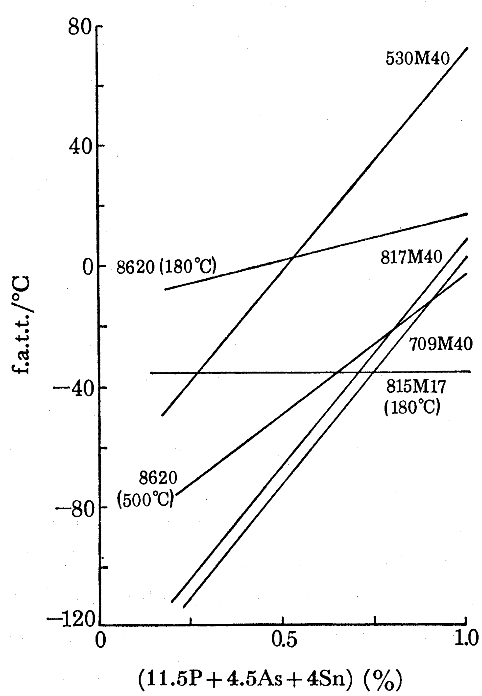

FIGURE 13. Effect of residual elements on toughness.

180 °C condition (e.g. carburized gears), the major effect after tempering at 500 °C can be attributed to classical temper embrittlement.

The Cr and Ni–Cr direct hardening grades were tempered in the range 600–650 °C and show a similar dependence on residual content. However, it will be noted that the toughness of 530M40 (1 % Cr) is inferior to that of either the Cr–Mo or Ni–Cr–Mo steels and this is in agreement with the established beneficial effect of molybdenum in reducing the susceptibility to temper embrittlement (Narayan & Murphy 1973). Auger electron spectroscopy studies have suggested that molybdenum retards embrittlement by inhibiting the segregation of impurities to the carbide–matrix interface and other boundaries associated with the fracture path.

Antimony, in the presence of arsenic, also appeared to produce an embrittling effect, but the effect was not statistically significant and was only apparent at antimony contents much higher than that currently obtained in commercial steels.

4. Commercial implications

It has been the intention of this paper to identify the effect of increasing residual element contents on the properties of popular carbon and alloy engineering steels and to determine the maximum levels of these elements that can be tolerated without violating property specifications.

With C–Mn and C–Mn–B steels, additions of chromium, molybdenum, nickel and copper increase hardenability with the expected effects on microstructure and tensile properties, In these cases, the residual elements behave simply as alloying elements and afford a cheap method of achieving higher strength levels without resort to the deliberate addition of expensive alloying elements. This conclusion is confirmed by customer practice, and in certain carbon or lower-alloyed grades, such as 605M36, the specification of a minimum residual element content (typically chromium) is essential to meet either hardenability and/or tensile strength requirements in specific ruling sections. Indeed, there is a continuing trend to use leaner and cheaper C–Mn and C–Mn–B steels as alternatives for alloy steels and residual elements undoubtedly make a vital contribution to this replacement.

However, if residual elements are allowed to rise in an uncontrolled fashion, it is possible that the hardenability limits for carbon steels can be exceeded, as shown in figure 1. The high molybdenum and copper contents are mainly responsible for the high hardenability of the residual code C cast and it must be emphasized that such levels have not been encountered in commercial practice.

Where high residual element contents raise the hardenability of a steel to above the specified limits, the possibility exists of compositional adjustments, i.e. reducing the carbon and/or manganese contents to compensate for the higher residual content. Several methods are available for calculating hardenability from chemical composition but discrepancies are apparent in the multiplying factors for specific elements quoted by different authors. However, for 080H36, it is estimated that the manganese content must be reduced to 0.57 % and 0.44 % in a code C base in order to simulate the hardenability that is achieved at codes B and A levels respectively.

The toughness of carbon steel is affected by residual elements but the change is dependent upon the particular metallurgical strengthening mechanisms involved.

Phosphorus and tin also increase the strength and f.a.t.t. of carbon steels and the adverse effect on toughness can be attributed to the temper embrittling characteristics of these elements.

Table 9. Acceptable residual element levels to satisfy toughness specifications

(Percentages are by mass.)

steel type	room temp. Izod ft lbf†	equiv. Charpy J	equiv. f.a.t.t. °C	spec. max. phosphorus (%)	av. phosphorus (%)	av. tin (%)	av. arsenic (%)	av. copper (%)	max. calculated phosphorus (%)	max. calculated tin (%)	max. calculated arsenic (%)
080M40	15	15	+65	0.050	0.022	0.025	0.028	0.23	0.220	0.410	
	25	26	+39						0.180	0.340	—
605M36	25	26	+34	0.040	0.018	0.026	0.028	0.26	0.180	0.310	
	40	45	0						0.130	0.220	—
530M40	40	45	0	0.040	0.022	0.025	0.028	0.23	0.054	0.066	0.065
709M40	20	21	+34	0.040	0.018	0.026	0.028	0.23	0.078	0.136	00.125
	40	45	−25						0.035	0.014	00.017
817M40	25	26	+20	0.040	0.030	0.023	0.028	0.21	0.070	0.108	0.103
	40	45	−25						0.037	0.014	0.020
SAE8620 (805M20)	15	15	+62	0.040	0.022	0.025	0.028	0.23	0.099	0.195	0.180
815M17	20	21	+33	0.040	0.022	0.025	0.028	0.23	0.078	0.135	0.125

† 1 ft lbf = 1.356 N m.

In the direct hardening alloy steels, phosphorus, tin and copper were shown to increase the tensile strength slightly, the effect being most marked in the leaner steels. Phosphorus, arsenic and tin also produced a detrimental effect on impact properties but arsenic was shown to be significant only in the Cr and Cr–Ni steels.

In the low alloy, case-carburized steels, residual elements had a major effect in increasing tensile strength and reducing ductility after tempering at 180 °C, although the f.a.t.t. was not markedly altered. After a 500°C temper, the f.a.t.t. was increased significantly by residuals but the tensile properties were less markedly increased.

It is therefore apparent that the major effect of residual elements in alloy steels is manifest in the impact properties. An analysis has therefore been made to determine the extent to which the residual elements can be allowed to rise without detriment to room temperature impact requirements. For heat treatable steels, this is usually specified in terms of a minimum Izod value. For each steel grade under consideration, these have been converted to an equivalent Charpy value and hence to a f.a.t.t. value from a knowledge of the ductile/brittle impact transition curve. At the maximum level of phosphorus permitted in various specifications (i.e. 0.04/0.05 %), the levels of tin and arsenic that could be tolerated without violating the toughness requirements have been calculated. Similarly, the maximum tolerable level of phosphorus has been calculated, assuming the current commercial levels of arsenic and tin.

The results are given in table 9. For Mn and Mn–Mo steels, the permitted phosphorus and tin levels are at least an order of magnitude greater than the current average values. Even with the exaggerated levels of these elements investigated in this research, the f.a.t.t. remained below zero. It is therefore concluded that there are no foreseeable problems, provided classical temper embrittlement temperatures of 500 °C are avoided.

With the Cr and Cr–Ni steels (709M40 and 817M40) the specific elements that affect toughness are phosphorus, tin and arsenic, and the analysis indicates that with the current average tin and arsenic levels, the phosphorus content would have to be below the specified maximum to maintain the sub-zero f.a.t.t. requirement. However, at the current average contents of these elements, the f.a.t.t. is quite satisfactory. While the calculated maximum permitted values of tin and arsenic are below the current average values, it should be remembered that these estimates were based on the maximum specified phosphorus level and therefore the maximum calculated phosphorus level defines the allowable content in the presence of the other elements at their current levels. No increase in their level can be tolerated without a compensatory reduction in the phosphorus level.

For the other alloy steels, there is again no real problem when the f.a.t.t. requirements are above room temperature.

With regard to tensile strength and elongation, similar calculations show that the levels of phosphorus, tin and arsenic can be allowed to rise very significantly before the specification requirements are violated.

The use of these regression equations therefore provides a valuable guideline in conjunction with future trends in residual movement to assess the ability to meet specific requirements and the extent to which residuals can be relaxed. However, it should also be remembered that many factors, including the intrinsic toughness of the alloy, its hardenability and susceptibility to temper embrittlement, all contribute to the impact properties realized in practice.

5. Conclusions

From the point of view of property requirements, most special carbon and alloy steels can tolerate higher levels of residuals than are currently encountered.

In special carbon steels, residual elements can be used to advantage as a cheap and effective means of raising the hardenability and strength of the steel. The effect of residual elements on the toughness of these steels is complex but understood; it depends upon the particular strengthening mechanism induced by the residual elements. However, the basic point to emerge from this work is that residual elements such as chromium, nickel, molybdenum and copper behave as normal alloying in C–Mn steels. Where toughness is reduced, this is a consequence of classical microstructural effects and not due to an intrinsic embrittling effect *per se* of these elements.

In low alloy steels, phosphorus, tin and arsenic have the most marked effect on the toughness in chromium and nickel bearing steels. However, only in certain steels, e.g. 709M40 and 817M40, need these elements be restricted to their current levels to satisfy impact property requirements.

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