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# Phase proportions, carbon equivalent, mechanical properties and their effect on material cost of railway axle steels

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*Abstract*

*Commuter trains with solid axle configuration are produced from medium carbon steel due to cost restrictions. High-speed trains have hollow axle configuration for reduced weight and are made from high strength low-alloy (HSLA) steels. The HSLA steels have higher amounts of C, Cr, Ni, Mo, V and Nb, and are more expensive than medium carbon steels. The effects of phase proportions, carbon equivalent (CE), yield strength and ultimate tensile strength (UTS) on material costs of existing railway axle steels were studied using Thermo-Calc. Medium carbon rail axle steels had higher* $Fe_3C$ *phase proportions than the HSLA steel rail axle grades. Higher affinity of Cr, Mo and V for C than Fe resulted in decreased cementite proportions. The HSLA steels had yield strengths above 370 MPa, and UTS above 750 MPa, with increased material cost above $3300 per ton. A scattered distribution was observed for the pearlite weight fraction and material costs, with most between $3200 and $3400. The yield and tensile strengths increased with increasing carbon equivalent and pearlite weight fraction. The data aided the selection and design of alloys with better mechanical and corrosion properties at reduced material cost.*

## INTRODUCTION

Railway axles are considered safe [1], but ballast impact, corrosion, fretting wear and non-metallic inclusions nucleate surface and sub-surface cracks [1 ,2, 3, 4, 5]. These cracks can grow into fatigue cracks resulting in premature failure, although rail axles were designed for finite service life of ~30 years (~$10^9$ cycles to failure) [2,4]. Some of the rail axles have also been prematurely recalled from service due to defects, since cracks exceeding critical sizes, if not detected, lead to derailment [4, 5, 6]. To ensure the structural integrity of rail axles, medium carbon and high strength low-alloy steels were specified by the European Standard [6], which are either normalised or quenched and tempered with a ferrite-pearlite microstructure [5, 6, 7, 8]. The ferrite is soft, whereas the pearlite is hard, thus providing appreciable strength and toughness, which is required for high in-service life of rail axles. The strength of the rail axle is largely determined by the ferrite-pearlite phase proportions. Higher phase proportions of pearlite to ferrite at the near surface of the axle result in high hardness and strength, but decrease towards the core, where high ferrite phase proportions are observed. Higher volume fractions of pearlite and fine interlamellar spacing also increase the flow stresses [9].

Rail axles of conventional commuter trains with speed limits of 200 km/h are produced from medium carbon steels [6]. These classes of steels are cheap with good balance of strength and ductility, but with poor corrosion resistance [10]. Axles of high-speed bullet trains are produced from high strength low-alloy steels (HSLA) with higher strength and ductility than the medium carbon grades [6]. Their superior mechanical and corrosion properties are due to the higher amounts of alloying elements. Alloying elements are either soluble or insoluble in Fe. The soluble ones alter the $\gamma$ to $\alpha$ transformation temperature, thus either lower or raise the eutectoid temperatures of the steel. Carbon is the main hardening element in steels and rail axle steels have hypoeutectoid carbon composition with alloying elements such as Cr, Ni, Mo, V, Nb, Mn, Si and Cu [1, 2, 3, 4, 11]. Alloying elements such as Mo, Cr, Nb, and V slow the growth rate of ferrite and pearlite through their stable carbides, but at increased material cost. Carbide proportions depend on the solubility of the alloying elements in austenite prior to heat treatment [10, 11, 16]. The resulting microstructure and fine carbide precipitates increase the yield and tensile strengths of the axle steels [5, 11].

Carbon equivalent (CE) is an empirical equation which relates the combined effects of different alloying elements on hardenability of carbon steels. Carbon equivalent was designed mainly for deducing the effects of alloying elements on welding of steels [10], but since it determines the hardenability (ability to form martensite) of steels, it was used to estimate the strength of the axle steels and its effect on material cost. The proportions of strengthening phases such as martensite and carbides are dependent on the carbon equivalent and the cooling rate of the steel after heat treatment [5, 9, 10]. The phases present and grain sizes of medium carbon steels are determined by the composition, and any changes in composition can alter their mechanical and corrosion properties. Factors which affect the hardenability of steels are austenite grain size, elements which interact with carbon, or reduce the austenite-ferrite transformation temperatures, or segregate to the austenite grain boundary, and inclusions at the grain boundaries [10].

The compositions of rail axle steels from Europe, North America, Australia, Indian, Japan, China and South Africa are given in Table 1. Recent innovations to reduce weight, improve corrosion and wear resistance, and reduce production costs have led to the use of higher alloyed steels [2, 3]. For instance, corrosion resistant alloys MS3 and MS6 were developed in India with improved corrosion resistance than the conventional

Indian grades at a reduced cost [5]. In this work, the Thermo-Calc thermodynamic programme and information from literature were used to ascertain relationships between the yield strength, UTS, carbon equivalence (CE) and pearlite proportions and their impact on the material costs of railway axle steels, using commercial alloys. These results were then used as basis for the selection of composition ranges for the design of new rail axle steel alloys with estimated material cost cheaper than standard rail axle steel grades [5] with improved mechanical and corrosion properties, which are essential for better fatigue life of rail axles.

## EXPERIMENTAL PROCEDURE

### Thermo-Calc calculations of phase proportions of rail axle steels

Composition ranges of commercial railway axle steel grades from India [5], Europe [6], North America [7], China [12, 13], Japan [14] South Africa [15], and Australia [16] (Table 1) were used as input for the Thermo-Calc calculations with the TCFe5 database and the calculations were done for equilibrium conditions. The phase proportions were plotted from 200-1500°C and the mass and volume percent of the phases were calculated at 400°C using Equations 1 and 2.

$$M_A = M_P / M_T \qquad (1)$$

$$V_A = V_P / V_T \qquad (2)$$

where: $M_P$ = mass percent of a particular phase A, $M_A$ = mass of phase A, $M_T$ = total mass at 400°C, $V_P$ = volume percent of A, $V_A$ = volume of A and $V_T$ = total volume at 400°C.

### Calculation of the pearlite weight fraction of the rail axle steels

The medium carbon and high strength low alloy (HSLA) rail axle steels were of the hypo-eutectoid carbon composition, and the pearlite weight fraction was calculated using the lever rule (Equation 3). For hypoeuctectoid steels, pro-eutectoid ferrite forms at temperatures above the eutectoid temperature (727°C) and the residual austenite fully transforms to pearlite. The pearlite weight fraction was assumed to be the same as that of the austenite from which it was formed:

$$W_P = C_s - 0.022 / 0.76 - 0.022 \qquad (3)$$

Table 1. Chemical compositions of typical rail axle steels.

| **Rail axle steel** | **Chemical composition (wt%)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **C** | **Si** | **P** | **S** | **Mn** | **Mo** | **Ni** | **Cr** | **V** |
| | European grade | | | | | | | | |
| EA1N [6] | 0.4 | 0.24-0.5 | 0.02 | 0.02 | 1.2 | 0.08 | 0.3 | 0.3 | 0.06 |
| EA4T [6] | 0.22-0.29 | 0.29-0.4 | 0.02 | 0.02 | 0.5-0.8 | 0.15-0.3 | 0.3 | 0.9-1.2 | 0.06 |
| 34CrNiMo6 [6] | 0.3-0.38 | 0.4 | 0.025 | 0.035 | 0.5-0.8 | 0.6-0.8 | 1.3-1.7 | 1.3-1.7 | - |
| 30NiCrMoV12 [6] | 0.28-0.34 | 0.4 | 0.025 | 0.02 | 0.5-0.8 | 0.4-0.6 | 2.7-3.2 | 0.6-0.9 | 0.08-0.13 |
| | Australian grades | | | | | | | | |
| AS1440 [16] | 0.38-0.43 | 0.15-0.3 | 0.035 | 0.04 | 0.6-0.9 | 0.2-0.3 | 1.65-2.0 | 0.7-0.9 | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| AS4340 [16] | 0.38-0.43 | 0.20-0.30 | 0.05 | 0.04 | 0.6-1.0 | 0.2-0.3 | 1.65-2.0 | 0.7-0.9 | - |
| | South African grades | | | | | | | | |
| Grade A [14] | 0.45-0.59 | 0.15* | 0.045 | 0.05* | 0.6-0.9 | 0.15* | 0.4* | 0.3* | - |
| Grade B [14] | 0.3-0.45 | 0.15-0.50 | 0.05 | 0.6-1.0 | 0.6-0.9 | 0.15* | 0.4* | 0.3* | - |
| | Association of American Railroad (AAR) grade | | | | | | | | |
| Carbon steel [7] | 0.45-0.59 | 0.15 | 0.045 | 0.6-0.9 | - | - | - | - | - |
| | Chinese grades | | | | | | | | |
| LZ50 [13] | 0.47 | 0.26 | 0.014 | 0.007 | 0.78 | - | 0.028 | 0.02 | - |
| 35CrMo [12] | 0.35 | 0.27 | 0.016 | 0.015 | 0.55 | 0.2 | 0.06 | 0.9 | - |
| | Indian grades | | | | | | | | |
| Conventional [5] | 0.37-0.38 | 0.15-0.46 | 0.04-0.05 | 0.04-0.05 | 1.12-1.20 | 0.05-0.06 | 0.05-0.06 | 0.3-0.4 | 0.05-0.06 |
| MS3 [5] | 0.29-0.3 | 0.63-0.7 | 0.02-0.03 | 0.02-0.03 | 1.54-1.6 | - | - | - | 0.1-0.3 |
| MS6 [5] | 0.19-0.2 | 0.34-0.35 | 0.02-0.03 | 0.01-0.02 | 1.34-1.4 | - | - | - | 0.11-0.2 |
| | Japanese Industrial standard | | | | | | | | |
| JIS SFA [14] | 0.3-0.48 | 0.15-0.4 | 0.05* | 0.05* | 0.4-0.9 | - | - | - | - |

(*maximum allowable limit, the SFA grade is the Japanese medium carbon steel grade for rail axles).

## Carbon equivalent calculation of rail axle steels

Carbon equivalent ($C_{eq}$), which determines the hardenability index of steels, for the commercial railway axle steels were estimated from Equation 4 [10]. The alloying elements are quoted in weight percent.

$$C_{eq}=\%C+\%{}^{Mn}/_{6}+\%{}^{Ni}/_{15}+\%{}^{Cr}/_{5}+\%{}^{Cu}/_{13}+\%{}^{Mo}/_{4} \quad (4)$$

## Material cost calculations

The material costs of the axle steels were estimated from the prices of the elements and scrap metals (Table 2), on 22nd July 2015. This cost was based solely on the elemental compositions, and any other manufacturing costs were ignored.

**Table 2.** Costs of elements in the steels per kg from Insimbi Refractory and Alloys Supplies Ltd, Johannesburg, South Africa (retrieved on 22nd July 2015).

| **Elements** | **C** | **Si** | **Mn** | **Al** | **Ni** | **Cr** |
|---|---|---|---|---|---|---|
| **Cost ($)** | 0.38 | 2.20 | 4.40 | 2.97 | 14.58 | 14.23 |
| **Elements** | **Ti** | **V** | **Nb** | **Mo** | **Cu** | **Fe** |
| **Cost ($)** | 5.56 | 34.02 | 20.78 | 20.7 | 8.93 | 3.20 |

## RESULTS

Thermo-Calc phase proportion plots of a typical medium carbon rail axle standard grade (Association of American Railroad (AAR)) with lower and upper composition limits as a function of temperature are given in Figures 1 and 2.The six phases calculated for both lower and upper composition limits of AAR were FCC_A1, MnS, Liquid, BCC_A2#1, $Fe_3C$ and $M_3P$. For medium carbon rail axle steels, high phase proportions of $Fe_3C$ occur due to no or low amounts of Cr, Mo, V and Nb, because they are strong carbide formers, reducing any residual carbon in the steel. The phase proportion plots of lower and upper composition limits of a typical European HSLA rail axle steel grade 35NiCrMoV12 are given in Figures 3 and 4. Twelve phases were calculated, which were Liquid, MnS, FCC_A1#1, BCC_A2, FCC_A1#2, KSI_Carbide, $M_{23}C_6$, $Fe_3C$, $M_3P$, FCC_A1#3, FCC_A1#4 and $M_7C_3$. Due to the small differences in the lower and upper limit compositions of the rail axles, the same phases were calculated for these, as expected. Low phase proportions of $Fe_3C$ and carbides such as KSI_Carbide, $M_{23}C_6$ and $M_7C_3$ (where M represents the carbide forming elements: Cr, Mo, Nb or V) were found, which were not calculated in the medium carbon steels.

Based on the phase proportions of $Fe_3C$ and α-Fe, the rail axle steels were classified as medium carbon or low alloy rail axle steels. The medium carbon rail axle steels had higher $Fe_3C$ phase proportions than the low alloy steel grades. The phase proportions of the rail axle steels are given in Table 3. The medium carbon rail axle steel grades included EA1N, AAR, MS3 lower composition, LZ50, AS1444/4344 and South African Grades A and B. The low alloy rail axle steels grades were conventional European grade, 35CrMo, MS3 (upper composition limit), MS6, 35CrNiMoV12, 30NiCrMoV6 and EA4T compositions.

The effect of pearlite weight fraction on the mechanical properties of ferrite-pearlite steels is important, because the pearlite volume fraction decreased from the rail axle surface to the core with decreasing hardness [11]. The pearlite weight fraction was calculated to determine how small changes in carbon content affect the pearlite volume fraction, since it is largely dependent on carbon content. The pearlite weight fraction and its effect on the material cost based on the composition of the rail axle steels show a scattered distribution (Figure 5). Most of the rail axles of conventional commuter trains are made from medium carbon steels, hence their material cost ranged between $3,100.00 and $3,400.00. Rail axle steels produced from low alloy steels were alloyed with Ni, Cr, Mo, Nb and V, resulting in the higher material cost than the medium carbon steels (Table 2).

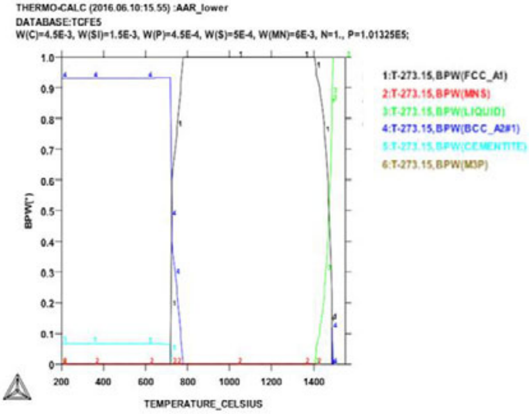

Figure 1. Phase proportions of North American AAR rail axle steel (lower limit composition).

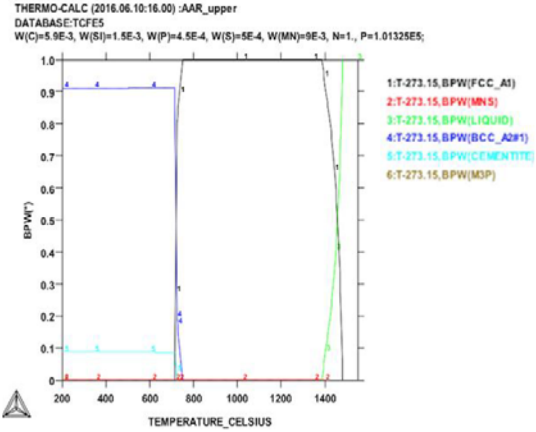

Figure 2. Phase proportions of North American AAR rail axle steel (upper limit composition).

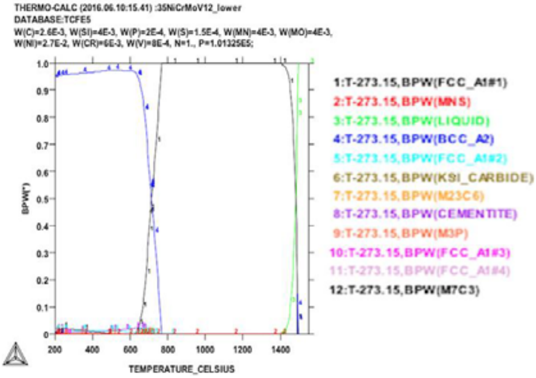

Figure 3. Phase proportions of European HSLA steel grade 35NiCrMoV12 (lower limit composition).

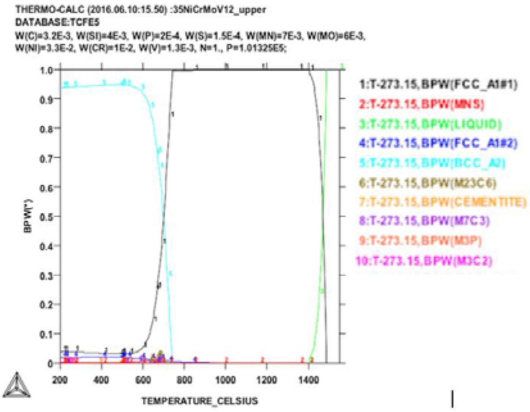

Figure 4. Phase proportions of European HSLA steel grade 35NiCrMoV12 (upper limit composition).

Table 3. Phase proportions of rail axle steels (L = Lower and U = Upper).

| **Axle steel** | | **Mass of phases (%)** | | | **Volume of phases (%)** | | |
|---|---|---|---|---|---|---|---|
| | | **α -Fe** | **$Fe_3C$** | **others** | **α** | **Fe3C** | **others** |
| European grades | | | | | | | |
| Conventional standard grades | L | 96.56 | 2.11 | 1.33 | 95.70 | 2.16 | 2.14 |
| | U | 96.08 | 0.33 | 3.59 | 96.09 | 0.33 | 2.50 |
| EA1N | | 94.41 | 5.25 | 0.34 | 94.22 | 5.38 | 0.41 |
| EA4T | L | 98.05 | 0.00 | 1.95 | 97.81 | 0.00 | 2.19 |
| | U | 97.31 | 0.00 | 2.69 | 97.03 | 0.00 | 2.97 |
| 35CrNiMoV12 | L | 96.69 | 0.90 | 2.41 | 96.50 | 0.92 | 2.58 |
| | U | 94.54 | 0.00 | 5.46 | 94.27 | 0.00 | 5.73 |
| 30NiCrMoV6 | L | 96.98 | 1.32 | | 97.02 | 0.98 | |
| | U | 97.57 | 1.09 | | 97.13 | 1.21 | |
| North America grade | | | | | | | |
| AAR grade | L | 93.15 | 6.72 | 0.14 | 92.98 | 6.85 | 0.17 |
| | U | 91.06 | 8.81 | 0.14 | 90.85 | 8.98 | 0.17 |
| Indian grades | | | | | | | |
| MS3 | L | 96.09 | 2.98 | 0.93 | 95.92 | 3.05 | 0.28 |
| | U | 96.55 | 1.35 | 2.10 | 96.29 | 1.38 | 2.33 |
| MS6 | L | 97.87 | 0.16 | 0.17 | 97.72 | 0.17 | 2.11 |
| | U | 97.87 | 0.00 | 0.30 | 97.69 | 0.00 | 2.31 |
| Chinese and Australian grades | | | | | | | |
| LZ50 | L | 92.96 | 7.01 | 0.03 | 92.81 | 7.15 | 0.04 |
| 35CrMo | U | 96.29 | 1.98 | 1.73 | 96.03 | 2.11 | 1.86 |
| AS1444/4344 | | 95.00 | 3.31 | 1.69 | 94.68 | 3.40 | 1.92 |
| South African (Transnet grades) | | | | | | | |
| Grade A | L | 93.92 | 5.92 | 0.49 | 93.12 | 6.05 | 1.00 |
| | U | 91.14 | 8.10 | 0.76 | 90.93 | 8.28 | 0.79 |
| Grade B | L | 95.57 | 3.39 | 0.84 | 95.43 | 3.68 | 0.89 |
| | U | 93.24 | 5.95 | 0.81 | 93.43 | 6.09 | 0.54 |

The relationship between the pearlite weight fraction and the strength of the rail axle steels is given in Figure 6. There was no discernible trend, as a scattered distribution was observed. For yield strengths below 450 MPa, which were mostly medium carbon steels, pearlite did not have much effect as the yield strength was fairly similar with increasing pearlite proportion. For the HSLA rail axle steels, the yield strengths were significantly increased, but with no discernible relationship with the pearlite weight fraction (Figure 6), and values twice those of medium carbon steels.

The relationship between the carbon equivalent and the pearlite weight fraction is given in Figure 7. The pearlite weight fraction increased with increasing carbon equivalent, although within a wide band. The carbon equivalents of medium carbon rail axle steels were between 0.4 and 0.65, whereas from high strength low alloy rail axle steels had higher carbon equivalents (mostly above ~0.7) due to the higher proportions of the alloying elements.

Many of the rail axle steels are produced from medium carbon steels because they are cheaper, due to the lower amounts of the alloying elements. Increasing the amounts of the alloying elements in the rail steels increased the yield and tensile strengths, as shown in Figure 8. The yield strengths of the medium carbon steels were clustered between 300 MPa and 400MPa, which is the minimum required for most rail axle steels. For the axles produced from HSLA, the yield strength decreased with increasing cost.

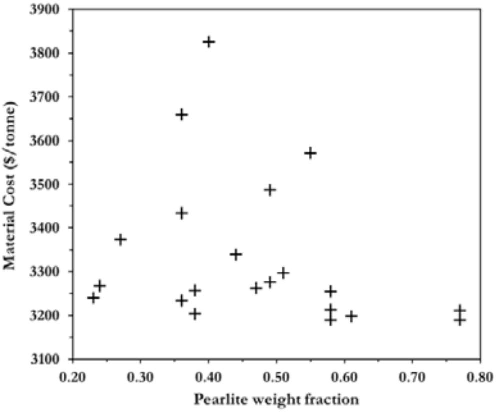

Figure 5. Effect of pearlite weight fraction on the material cost of conventional rail axle steel grades.

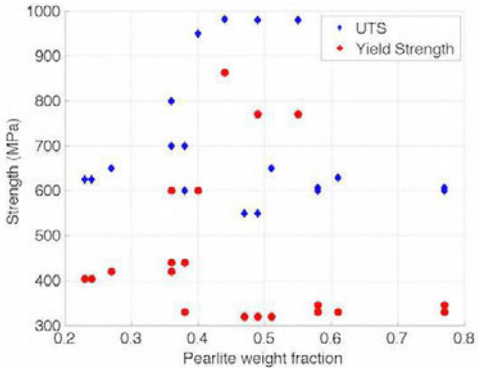

Figure 6. Effect of pearlite weight fraction on the strength of conventional rail axle steel grades.

Figure 9 shows the effect of carbon equivalent on the strength of rail axle steels, with a scattered distribution. Heavily alloyed steel, e.g. 34CrNiMoV12 had higher strength than AAR carbon steel, which shows a similar trend for carbon equivalent, which measures hardenability.

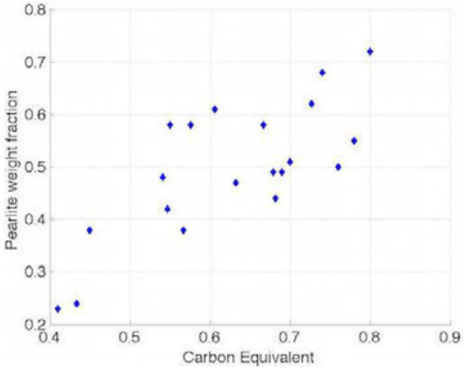

Figure 7. Carbon equivalent and pearlite weight fraction of conventional rail axle steels.

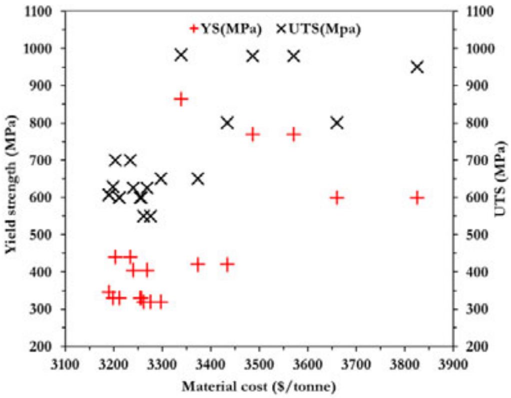

Figure 8. Relationship between material costs on the strength of conventional rail axle steel.

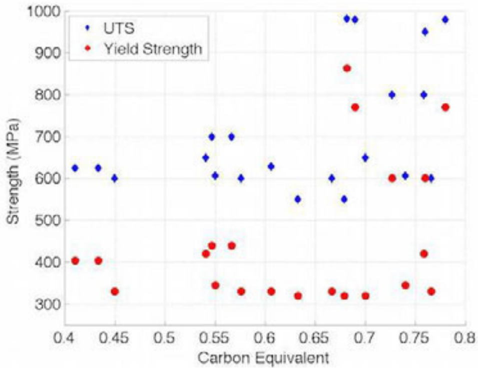

Figure 9. Effect of carbon equivalent on the strength of conventional rail axle steels.

## DISCUSSION

The two main rail axle steels are medium carbon and high strength low alloy steels. According to the EN 13261 standards [6], axles produced from medium carbon steels are considered conventional grades. The HSLA axle steel grades was necessitated by the need for high speed trains, which require weight reduction and is achieved by their hollow axle design [17]. The HSLA steel grades are commercially used and widely accepted and also known as conventional grades for high speed trains [6, 17]. From Table 3, the medium carbon steels have high cementite phase proportion and fewer phases than high strength low alloy steels. Due to the higher amounts of alloying elements (Cr, Ni, Mo, V and Nb) in the high strength low alloy steels, more carbide phases were calculated, showing the effects of the strong carbide forming elements. Generally, the pearlite weight fraction of the axle steels showed a scattered distribution.

However, the pearlite weight fraction of medium carbon steels had a smaller effect on material cost compared to the high strength low alloy steels (Figure 5). Higher amounts of Ni, Nb, Cr, V and Mo contributed to the high material cost, as these elements were very expensive (Table 2). Rail axles for conventional commuter trains, where speed is less important, have solid axle design configurations and are designed for strength at lower costs. With carefully controlled heat treatments of the carbon steels, the desired ferrite-pearlite microstructure is obtainable, but with poor corrosion resistance and less favourable ductile-to-brittle transition temperatures.

Newly developed Indian rail axle steels, MS3 and MS6, had better yield and tensile strength and corrosion resistance in seawater than the conventional grades tested in the same medium [5]. This was achieved by corrosion and oxidation resistant alloying elements, such as Mo, Ni and Cr, which were replaced by high amounts of Mn (1.34-1.6 wt%), which is an austenite stabilizer, and Si (0.34-0.70 wt%), which is a ferrite stabilizer. Although the MS3 and MS6 alloys had higher Mn and Si contents than any conventional grade, their material costs were cheaper due to the lower costs of Mn and Si compared to Ni, Mo and Cr. The MS3 and MS6 alloys also had lower proportions of cementite than most of the conventional grades with V as the strong carbide former.

The characteristic microstructure of rail axle steels is ferrite-pearlite and its strength is increased by increasing the volume fraction of pearlite. Pearlite is harder than a proeutectoid ferrite due to the hard $Fe_3C$ in pearlite, and the amount of $Fe_3C$ is proportional to the carbon content [11]. When ferrite-pearlite steels are mechanically stressed, the load-bearing phase is $Fe_3C$ in pearlite and since ferrite is softer than cementite, higher proportions of ferrite decrease strength. High strength in HSLA steels is partly due to precipitates and strong carbides which are formed from the strong carbide formers (Cr, Mo, Nb and V), which are in negligible amounts in medium carbon rail axle steels. There is higher affinity of Cr, Mo, Nb and V contents for C than Fe [11, 13], which produced the lower proportions of $Fe_3C$ compared to low carbon steel grades (Table 3). The effect of pearlite proportions on the strength (yield strength and UTS) of rail axle steels showed a scattered distribution (Figure 6) with no discernible trend. The pearlite did not have significant effect on the axle steels with yield strength below 450 MPa, which were mainly medium carbon steels. However, rail axles from high strength low alloy steels with similar pearlite volume fractions had much higher yield and tensile strengths than the low carbon steels, due to the alloying elements (Cr, Ni, Mo and V) promoting grain refinement and increased solid solution strengthening. Other factors that affect strength of steels are prior austenite grain size, interlamellar spacing, pearlite colony size and fine precipitation, which are the result of heat treatment [4, 5, 6, 11].

Figure 7 shows direct proportionality between carbon equivalent and the pearlite weight fraction, although within a wide band. Most of the axle steels (especially low carbon steel grades) have carbon equivalents between 0.4 and 0.8, with their pearlite weight fractions ranging between 0.3 and 0.7. Alloy steels used for high speed trains tend to have much higher carbon equivalents due to their higher alloying elements contents, promoting more carbides. The relationship between strength (yield strength and UTS) with carbon equivalent was a scattered distribution (Figure 9).

Generally, alloyed steels have better mechanical and corrosion properties due to the effect of alloying elements [5, 11]. The effect is seen on transformation temperatures, fine precipitates in the microstructure, increasing the strength of the steel through precipitation hardening, solid solution strengthening and grain refinement, which was not the subject of discussion in this paper, since it could not be calculated with Thermo-Calc. However, there is increased material and production costs (higher energy requirements) as the alloying elements increase the melting temperature and full austenitic transformation temperature during heat treatment. There was a correlation between the phase proportions, carbon equivalents and yield stresses with the material costs of the rail axle steels.

These data aided the optimisation and design of new rail axle alloy compositions for alloys with improved corrosion resistance, which is the main challenge for most South African rail axle steels. After the phase proportions of the standard rail axle steels were calculated from Thermo-Calc, new compositions were proposed based on the standard grades with moderate contents of Cr, Ni, Mo, Nb and V. The phase proportions of over 27 proposed alloys were calculated, analysed and three alloys were chosen for experimentation.

## CONCLUSIONS

The effect of phase proportions, yield stress and UTS and carbon equivalent on material cost of the rail axle steels was studied. From the phase proportion calculations of Thermo-Calc, the rail axles were classified as medium carbon and low alloy steels. High strength low alloy axle steels with more alloying elements had twelve phases calculated, whereas an average six phases was calculated for the medium carbon steels, with minimal alloying elements. Secondary carbides of Mo, V, Nb and Cr were calculated for low alloy steels due to the higher affinity of these elements to C than Fe.

The general trend of the material cost with pearlite weight fraction and strength of the axles showed a scattered distribution, although the yield and ultimate tensile stresses, carbon equivalents and phase proportions of the rail axle steels increased with increasing alloying elements. High alloying elements increased material cost and resulted in better properties. Some medium carbon steels with little or no strong carbide formers had low cementite proportions due to increasing Mn and Si contents, making them more cost effective in developing new alloys for rail axle applications.

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