Development of low tungsten substitute tool steels

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TUNGSTEN is a very important alloying element in high speed tool steel, hot and cold work die steel and permanent magnet alloys, but its ore deposits are limited to a few countries. Continuous development over the years to reduce tungsten content in conventional 18-4-1 high speed steel i.e. 18% tungsten, 4% chromium and 1% vanadium, has led to increase of molybdenum, cobalt, chromium or vanadium. These steels have a hyper eutectoid structure in the fully hardened state in which complex carbides are embedded in martensite matrix. Both of these constituents in high speed steel retain higher hardness at high temperature than their counterpart in plain carbon steel. Many such high speed steels with low amount or without tungsten have been developed. These low tungsten steels[1] apart from replacing the non-available alloying elements have the additional advantage of requiring lower hardening temperature than high speed tool steel containing 18% tungsten, thus avoiding the formation of coarse grain size in steel.

The use of molybdenum-vanadium tool steels[2] without tungsten was reported to give good performance comparable to molybdenum tungsten type high speed steel. Development work started with high vanadium content of about 5%, but it was later on found that even at 2·5% vanadium content the red hardness was quite good. It has been shown that as molybdenum content increases there is improvement in the performance. Optimum conditions are reached with molybdenum content of about 3%. A decrease of molybdenum content to about 2% is desirable if the performance of material is to be kept up.

If we consider the influence of vanadium content for a molybdenum content of 3%, it has been shown that the performance is apparently independent from vanadium content in a wide alloying range of 2–3%. For higher than 3·5% vanadium content the performance decreases sharply. For lower vanadium contents less than 1·7%, the performance decreases considerably. This fall in properties starts with the decrease in vanadium content. From the melting technique point of view it is not easy to keep within a narrow alloying range and therefore the higher alloying range is good which is less susceptible to variations in compositions and gives good uniformity in properties.

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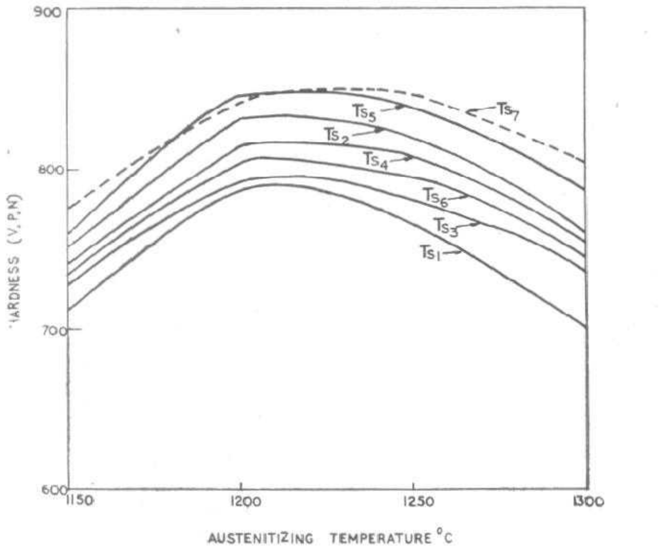
An addition of tungsten can considerably increase the cutting properties of molybdenum-vanadium steels. For high vanadium contents of 5% a small addition of 1% tungsten is not effective. Only higher tungsten contents bring in the effects. However, for vanadium content of 2·5% a tungsten addition of 1% brings in an improvement in properties, which further increases with increasing tungsten content up to 4%. The usual alloying content of molybdenum-vanadium steels is 2–3% tungsten.

For the usual high speed steels chromium content is between 3·5% and 4·5%. In Russia several investigations[3] were made on the basis of a higher chromium content of 7–14% to produce high speed steels low in tungsten or free from tungsten. A review of the older publications[4] shows that under high addition of tungsten of about 5% such steels also show properties similar to high speed steels. This is also true for steels with 1·5% vanadium to 2·5% vanadium in steel. By decreasing the tungsten content to 3% the cutting performance is improved. There is the possibility to decrease this tungsten content when this is compensated by an increase of vanadium content. For steel with 3·3% and 4·5% vanadium the relationship between cutting strength and tungsten content is similar to that of steel with 2·5% vanadium in the range of 3–5% tungsten. Moreover, it is observed that in these steels an increase of chromium content from 4–8% brings about a remarkable improvement in performance which is further improved by a chromium content of 11%.

The high chromium steel with 9% tungsten has got certain disadvantages as far as its production is concerned; it is difficult to shape it, it should be forged before rolling after annealing in stages.

Mitsche and Onitisch[5] and Prosvirin and co-workers have reported the application of aluminium as a substitute for tungsten in high speed tool steel. It was reported by Mitsche that an addition of 0·5% aluminium to



1 *Effect of austenitizing temperature on the hardness of steel*

chromium-molybdenum-vanadium tool is equivalent to an addition of 2·3% tungsten in tool steel.

Aluminium containing low alloy tool was found by Mitsche and Onitisch to be very sensitive to slight variation on heat treatment. A double tempering at 1040°F was necessary to aluminium containing steel instead of single tempering used for aluminium-free tool steel quenched from 1260°C.

Prosvirin[6] and co-workers published a monograph in which they reported in detail the results of tests on tool steel in which aluminium up to 3% and nitrogen up to 0·2% were used as an alloying element. The results permitted them to reduce the tungsten content and develop substitution tool steel, which gave very satisfactory service performance.

Nitrogen has long been known to act as an interstitial-type alloying element in steel, similar to carbon. It is logical, therefore, to look to nitrogen[7] as a possible matrix hardener when searching for means to make high speed tool steel harder. The value of nitrogen as a supplement to carbon has long been recognized in other high alloy and stainless steels.

Nitrogen[8] has also been reported to be an effective alloying element in steel, and has been added as much as 0·7% in tool steel containing 6–7% tungsten in addition to vanadium and chromium. Titanium[9] has also been found to improve the structure of tool steel, and being a very strong carbide and nitride former, it can also be added as an effective alloying element in tool steel.

TABLE I Chemical composition of steels

Steel No.	C %	Mn %	Si %	W %	Cr %	V %	Al %	Ti %	N %	B %	Zr %	Cb %
Ts 1	0·81	0·54	0·23	6·4	4·50	1·35	0·3	—	0·08	—	—	—
Ts 2	0·83	0·43	0·20	6·6	4·42	1·41	0·6	—	0·12	—	—	—
Ts 3	0·80	0·54	0·34	6·3	4·48	1·5	0·8	—	0·13	—	—	—
Ts 4	0·85	0·59	0·28	6·7	4·40	1·56	—	0·1	—	—	—	—
Ts 5	0·84	0·54	0·31	6·6	4·5	1·52	—	0·3	—	—	—	—
Ts 6	0·82	0·53	0·32	6·8	4·45	1·49	—	0·48	—	—	—	—
Ts 7	0·85	0·53	0·35	18·1	4·6	1·56	—	—	—	—	—	—
Ts 8	0·78	0·48	0·25	6·4	4·3	1·2	1·0	0·5	—	—	—	—
Ts 9	0·80	0·51	0·27	5·3	4·2	1·15	—	—	—	0·09	—	—
Ts10	0·81	0·58	0·31	5·96	4·1	1·4	—	—	—	0·17	—	—
Ts11	0·79	0·57	0·29	6·9	4·3	1·2	—	—	—	0·26	—	—
Ts12	0·82	0·61	0·28	6·5	4·3	1·1	—	—	—	—	0·16	—
Ts13	0·85	0·55	0·23	6·4	3·96	1·5	—	—	—	—	0·43	—
Ts14	0·90	0·57	0·25	6·1	3·4	1·3	—	—	—	—	—	0·40

Experimental result

Heats were made in 25 lbs high frequency furnace with mild steel and different ferro-alloys as base material. In exploring the use of nitrogen to increase hardness in tool steel it was found that there is a definite limit on its solubility in the molten steel. No matter how much nitrogen (in the form of high nitrogen ferro chrome) was added to the heat the maximum recoverable level was found to be at 0·12% containing 0·6% aluminium, as compared to ·02 to ·04% nitrogen normally residual in 6% tool steel to which nitrogen and aluminium have not been purposely added. Thus its potential utility in increasing hardness in the matrix is severely limited. The ingots were poured in 2″ × 2″ sq. moulds with hot tops. The ingots were slowly cooled to room temperature and were tested for as-cast hardness.

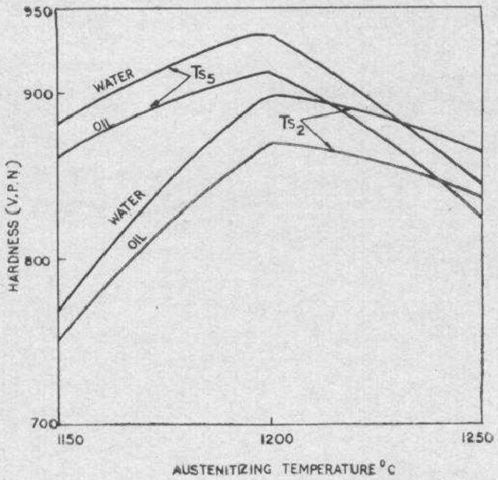
Hardnesses of ingots in annealed condition were also taken. These annealed 2″ × 2″ ingots were forged in ½-ton hammer to ½″ square section in several heating operations after cutting the hot top portion of the ingots. The forged ½″ square sections were packed in lime and homogenised at 950°C. The homogenised bars were analysed.

Table I shows the compositions of the steels investigated.

Tool ingots from Ts1 to Ts7 were successfully forged and annealed whereas ingots Ts10 to Ts12 were very difficult to be forged due to boron and extreme precaution was taken for the forging of these ingots. Table II shows the hardness of all steels from Ts1 to Ts7 in the ingot condition as well as after annealing and forging and of Ts8 to Ts14 in the ingot as well as annealed conditions.

It is seen from the table that in case of Ts1 and Ts2 hardness is increasing with increase in aluminium from 0·3–0·6%, but with further increase from 0·6 to 0·8% aluminium there is decrease of hardness in the steel. Hardness of Ts4 has increased in case of Ts5, as the titanium content has increased from 0·1 to 0·3%, but further increase of titanium from 0·3 to 0·48% has led to the decrease in hardness from 644 to 632 VPN. It is interesting to note that hardness as in the annealed and after forging has followed more or less similar pattern to the hardness of Ts7 which is conventional 18/4/1 steel as shown in Table II. It is clear from the table that hardness values of Ts2 and Ts5 compare favourably to the hardness of steel Ts7.

It is interesting to note that in the ingot condition hardness as of steels Ts2 and Ts5 are 680 and 685 VPN respectively compared to 695 of steel 18/4/1 in cast condition. Similarly the hardness values of Ts2 and Ts5 are 347 and 334 in annealed condition and 375 and 385 VPN in forged condition compared to 350 and 418 VPN of conventional high speed steel in similar set of conditions.



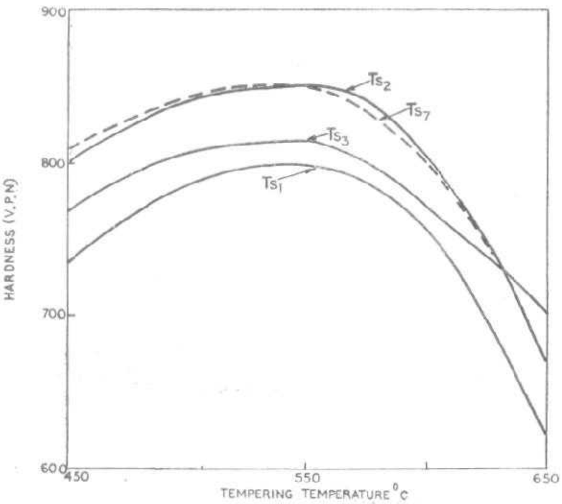
2 *Effect of quenching media on the hardness of steels Ts_2 and Ts_5*

TABLE II Hardness of the steels in as-cast, annealed and after forging

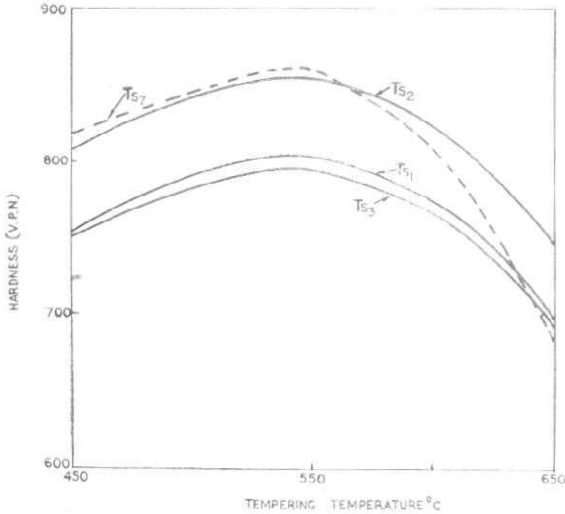
Steel No.	In the cast condition VPHN	Annealed condition VPHN	Forged condition VPHN
Ts 1	640	330	360
Ts 2	680	347	375
Ts 3	630	320	355
Ts 4	644	318	358
Ts 5	685	334	385
Ts 6	632	315	360
Ts 7	695	350	418
Ts 8	690	585	—
Ts 9	764	594	—
Ts 10	763	504	—
Ts 11	804	523	—
Ts 12	605	547	—
Ts 13	710	537	—
Ts 14	695	602	—

Effect of austenitising temperature on the hardness

To establish the correct hardening temperature, the specimens of all the steels were austenitised at different temperatures between 1150° and 1300°C. After austenetising the specimens were oil-quenched. Specimens of high speed tool steels were also austenitised and oil-quenched. The as-quenched hardness values obtained in first seven steels after austenitising at 1100°, 1200°, 1250° and 1300°C have been plotted in Fig. 1. It is clear from the figure that maximum hardness in case of low tungsten steels was obtained when austenetising temperature was 1200°C whereas in case of high speed tool steel the maximum hardness was obtained at about 1250°C. It is further observed from the curve that steels Ts2 and Ts5 gave maximum hardness amongst the low tungsten tool steels.



3 *Effect of single tempering on the hardness of steels Ts_1, Ts_2, Ts_3 and Ts_7*



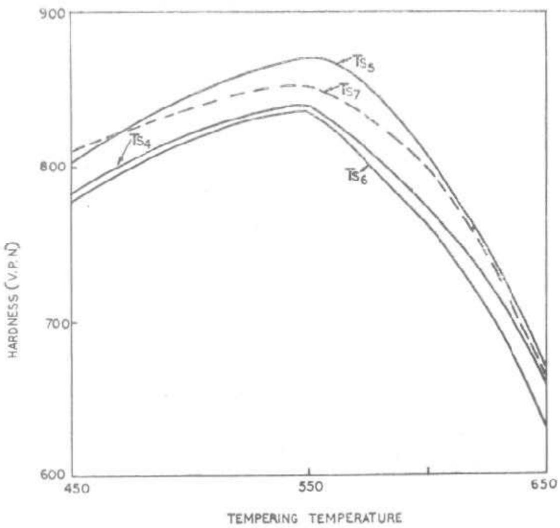
5 *Effect of double tempering on the hardness of steels Ts_1, Ts_2, Ts_3 and Ts_7*

Effect of quenching media

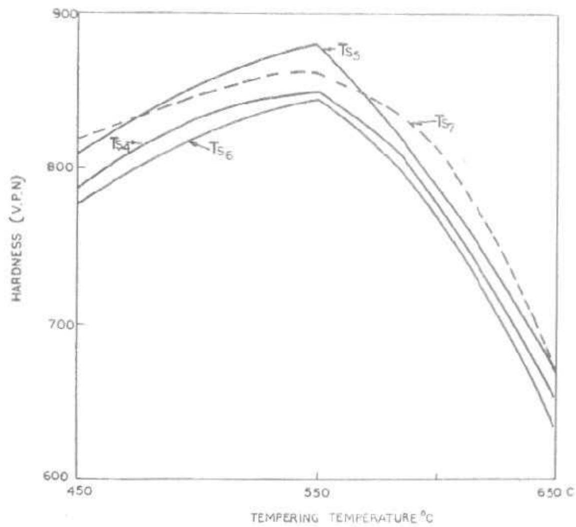
Steels Ts_2 and Ts_5 gave the best and comparable hardness to 18/4/1 when quenched in oil from 1200°C. To find out the best quenching media, which may not introduce any internal stresses and at the same time, may develop full hardness after quenching, it was decided to water-quench and oil-quench specimens of steels Ts_2 and Ts_5, which gave the best result after oil quenching. From the hardness values plotted in Fig. 2, it is seen that specimens of steels Ts_2 and Ts_5 gave higher hardness in case of water quenching as compared to oil quenching. Air cooling of both the set of specimens gave very erratic results. It is further interesting to note from Fig. 3 that specimen of steel Ts_5 gave higher hardness than steel Ts_2 in either oil-quenched or water quenched condition. It was however, observed that water-quenched specimens developed some cracks on the surface. No such cracks were observed in case of oil-quenched specimens.

Effect of single and double tempering on the hardness of low tungsten-high speed steel

Specimens after quenching in oil from 1200°C, were tempered at various temperatures and time to find out the best condition for getting optimum hardness. Table III shows the hardness of all steels after single



4 *Effect of single tempering on hardness of steels Ts_4, Ts_5, Ts_6, Ts_7*



6 *Effect of double tempering on the hardness of steels Ts_4, Ts_5, Ts_6 and Ts_7*

TABLE III Hardness after tempering (V.P.N.)

Steels	at 450°C		at 550°C		at 600°C		at 650°C	
	Single	Double	Single	Double	Single	Double	Single	Double
TS1	735	755	804	810	755	790	625	700
TS2	800	810	851	856	805	825	670	750
TS3	770	750	790	804	770	765	700	695
TS4	785	790	842	850	775	775	655	655
TS5	802	812	870	880	806	790	675	670
TS6	776	775	841	845	760	770	635	635
TS7	810	820	852	862	800	815	670	675

and double tempering at 450, 550, 600 and 650°C. Figs. 3–4 and 5–6 show the effect of tempering temperature in the range of 450°C to 650°C on the hardness after single and double tempering respectively. Hardness after similar treatments given to 18/4/1 type of standard steel is also shown in all the curves. It is seen that after single tempering, peak hardness was obtained in the tempering range of about 550°C in case of titanium as well as aluminium-nitrogen containing steel similar to 18/4/1 steel. It is seen from the curves that maximum hardness was obtained in case of steel Ts5 containing 0·3% titanium, similarly maximum hardness was obtained in case of steel Ts2 containing aluminium and nitrogen. Similar hardness trend was observed in case of double tempering. It is interesting to note that hardness of 18/4/1 high speed steel after giving similar treatments is also comparable to the hardness of steels Ts2 and Ts5.

Microstructure

Microstructural studies of the steels Ts7, Ts2 and Ts5 in the as-quenched condition show that some undissolved carbides are present along the grain boundaries as can be seen in photomicrographs Nos. 1, 2 and 3. Photomicrographs Nos. 4, 5 and 6 show microstructures in the tempered condition for one hour at 550°C. In case of Steel Ts5 bainite needles are shown along with tempered martensite and undissolved carbides. Microstructures developed by double tempering at 550°C are also shown in photomicrographs Nos. 7, 8 and 9. Amount of tempered martensite and bainite have increased considerably in steel Ts2 after double tempering.

Discussion

Among the large number of steels investigated with the base composition containing 6–7% tungsten, 4–5%

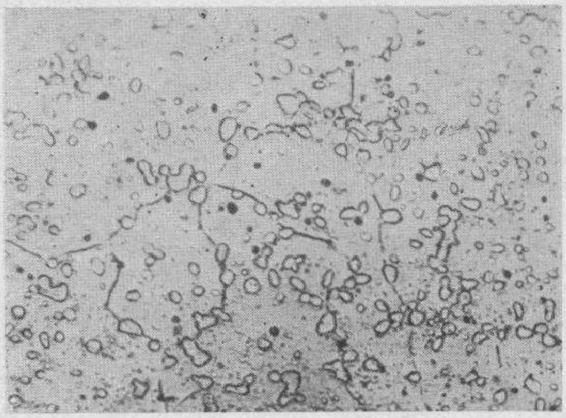


Photo 1 *Microstructure of the as-quenched specimen of 18/4/1 high speed steel (Ts7) Nital etch* × 760

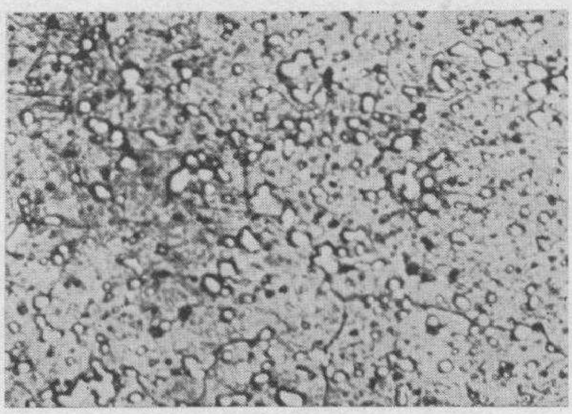


Photo 2 *Microstructure of the as-quenched specimen of steel Ts2 Nital etch* ×760

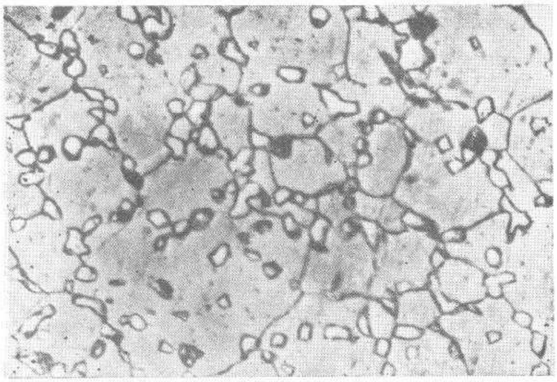


Photo 3 *Microstructure of the as-quenched specimen of steel Ts5 Nital etch* × 760

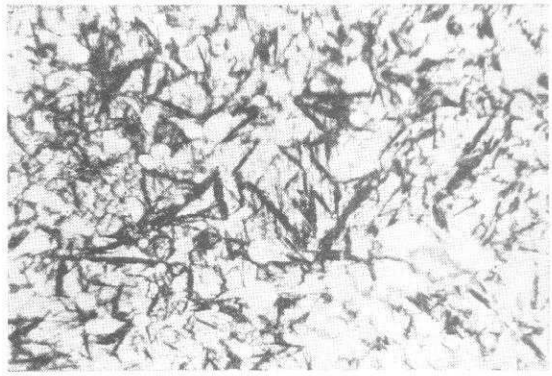


Photo 5 *Microstructure of the specimen of steel Ts2 after single tempering at 550°C Nital etch* × 760

chromium, 1–1·5% vanadium and containing other alloying elements, it was observed that addition of aluminium, nitrogen and titanium developed adequate hardness in annealed as well as in quenched and tempered condition and results obtained were comparable favourably with 18/4/1 conventional high speed steel in the respective heat treated condition.

It was observed from the present investigation that as the aluminium content was increased in medium tungsten high speed steel containing 6–7% tungsten, there was marked improvement in hardness after oil quenching and double tempering at 550°C. Best hardness was obtained at round about 0·6% aluminium content. Leoben[10] developed low alloy tool steels containing aluminium. It was assumed by Leoben that alloy carbides are formed more slowly than iron carbide hindering alloy depletion and consequent softening of the matrix and in this the action of tungsten is two-fold. More atomic species are necessary for the alloy carbide and relatively large tungsten atoms create diffusion impeding distortion in the matrix lattice, so it was felt that diffusion-impeding distortion action of matrix lattice could be duplicated by other large atoms even though the species did not form carbide. In the light of this hypothesis it is felt that aluminium whose atomic radius is 1·4 Å (compared to 1·27 Å of iron), has better prospect as alloying element in tool steel. Maximum improvement in cutting efficiency was observed when aluminium content was 0·4%. Moreover it was further observed that if the aluminium content was more than 0·6% abnormal grain growth and consequent embrittlement of the ingot took place. Similar observations were made in the present investigation. Steels with more than 0·6% aluminium were made, but due to embrittling effect the ingot could not be forged properly. Steel Ts3 which contained 0·8% aluminium was extremely difficult to forge at 6·3% tungsten.

Other advantages of these steels having 0·6% aluminium is that they require the same quenching temperature, but tempering time should be more to get optimum

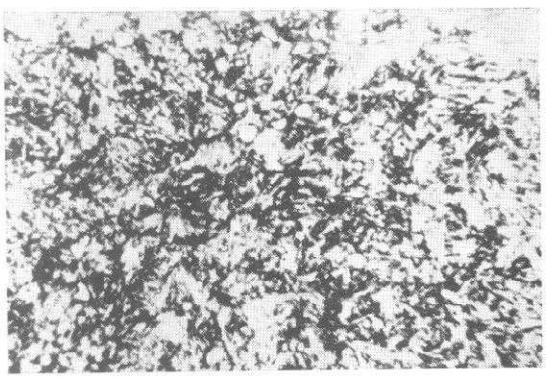


Photo 4 *Microstructure of the specimen of steel Ts7 after single tempering at 550°C Nital etch* × 760

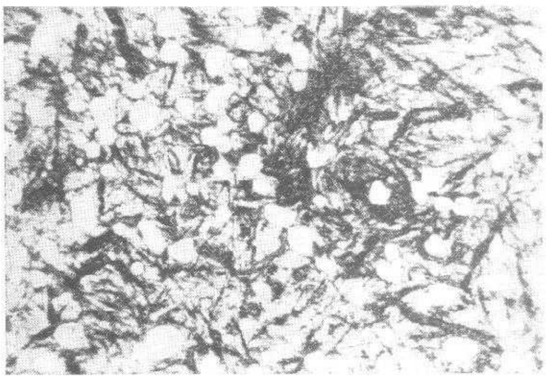


Photo 6 *Microstructure of the specimen of steel Ts5 after single tempering at 550°C Nital etch* × 760

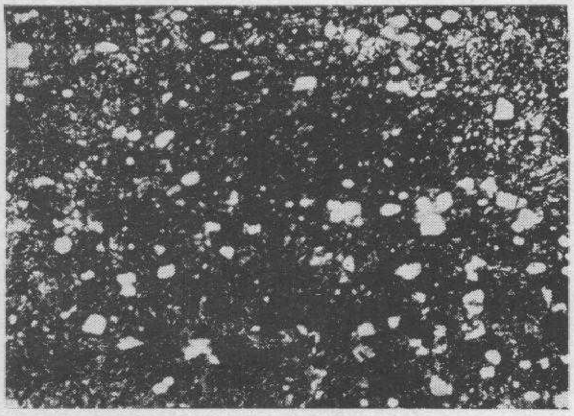


Photo 7 *Microstructure of the specimen of steel Ts7 after double tempering at 550°C*
Nital etch × 760

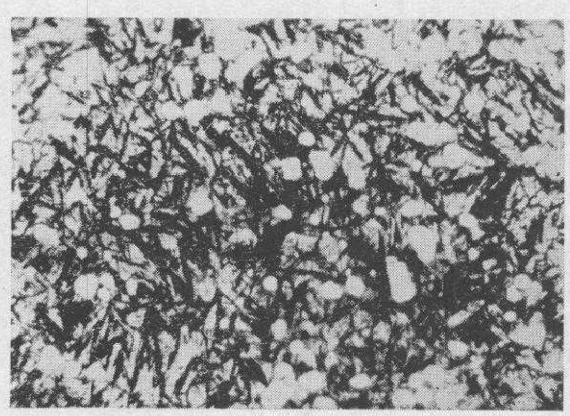


Photo 9 *Microstructure of the specimen of steel Ts5 after double tempering at 350°C*
Nital etch × 760

hardness after heat treatment. It is known from nitriding steel that during gas nitriding in ammonia an addition of aluminium to steel increases absorption of nitrogen and leads to higher surface hardness. It was pointed by Leoben that high speed steel can be alloyed up to 0·6% Al and with higher content of aluminium, low alloy tool steel loses its hardness as well as the performance. It was observed during the heat treatment of aluminium containing low tungsten tool steels that these steels are very sensitive to variation in heat treatment, and it was essential to temper thrice to get the secondary hardening peak and to get most of austenite transformed—similar observations were made in case of aluminium bearing steel by Mitsche and Onitsch.[6]

It was observed from the present investigation that as titanium content increased there was marked improvement in the hardness of tool steel after quenching and double tempering. At 0·3% Ti maximum hardness was observed and there was found to be a decrease in hardness when titanium content was more than 0·3% as can be seen from Table III. This improvement in the steel might have been due to the modification of the steel. Ul'yanov and Pkus[9] have also found considerable grain refined structure of the steel containing titanium. It was observed by these authors that when the titanium content was more than 0·3% the red hardness and hardness after quenching and tempering was decreased, as was observed in the present investigation. The addition of titanium also decreases the amount of residual austenite in hardened condition. The addition of titanium accompanied by high cooling rate produces a fine grain structure in heat-treated tool steel. The possibilities of exploring boron, copper, zirconium and colombium as alloying elements in low tungsten tool steel are also being investigated. It is obvious from Table II that addition of aluminium along with titanium has given considerable improvement in hardness in both ingot as well as in annealed condition. It is also clear from Table II that addition of boron also gives quite good hardness, and these ingots are being rolled and forged for further work.

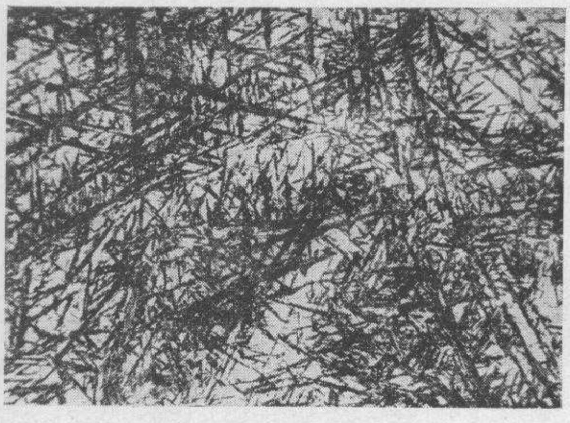


Photo 8 *Microstructure of the specimen of steel Ts2 after double tempering at 550°C*
Nital etch ×760

Conclusion

1. From the present investigation it was tentatively summarised that 6–7% tungsten, 4–5% chromium, 1–1·5% vanadium steel containing aluminium, nitrogen and titanium as alloying elements developed optimum hardness after oil-quenching from 1200°C and double tempering at 550°C.

2. It was further observed that aluminium containing steel developed maximum hardness when aluminium was about 0·6%. Similarly the titanium containing steel gives the best hardness with 0·3% titanium.

3. The hardness of aluminium and titanium containing low tungsten high speed steel developed comparable hardness to 18/4/1 high speed steel in respective heat treated condition.

4. Low tungsten steel containing boron, zirconium and aluminium-titanium in combination, developed adequate hardness in as-cast condition and steels are being rolled and forged for further studies.

Further work on these steels are under progress with regard to the red hardness, toughness, machinability, distortion and other desired properties in tool steel.

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