Production and service properties of micro-alloyed steel components for the motor industry

M. BAFFIGI and S. CORSO, Fiat Auto S.p.A., Turin, Italy
A. GIACCONE and L. INFANTE, Deltasider S.p.A., Turin, Italy

Abstract

In the mechanical engineering sector, there is now a marked trend towards the use of micro-alloyed steels in the form of long products as cost-effective substitutes for hardened and tempered steels. In addition to laboratory tests on the initial steels to check verifiable properties which can provide a first-step indication of properties in use, it is also important to ascertain the suitability of steels for various end applications by direct tests on components in actual service.

The case of crankshafts considered in this paper represents the start of a comprehensive programme of tests on components initiated by Fiat Auto and can be regarded as one example of an approach to the problems of using micro-alloyed steels which was brought to a successful conclusion.

Riassunto

Fabbricazione e caratterizzazione all'impiego di componenti in acciai microlegati per l'industria automobilistica

L'impiego degli acciai microlegati in prodotti lunghi quali sostituti economici degli acciai da bonifica per le applicazioni nel settore delle costruzioni meccaniche, è in piena fase evolutiva. Al di là dei riscontri sulle proprietà verificabili con prove di laboratorio sul materiale di partenza e che possono servire di orientamento iniziale all'impiego, è importante verificare l'adeguatezza dell'acciaio sperimentandolo direttamente sul componente e valutandolo nelle condizioni reali di impiego. Il caso degli alberi a gomito considerato in questo lavoro rappresenta l'inizio di un ampio programma di sperimentazione su componente intrapreso dalla Fiat Auto e può essere considerato un esempio di approccio alle problematiche d'impiego degli acciai microlegati conclusosi positivamente.

Micro-alloyed steel as a substitute for hardened and tempered steel

Highly stressed mechanical parts are normally produced from medium-carbon or low-alloy steel forgings in hardened and tempered condition. These steels, which, in service condition, have a sorbitic microstructure (spheroidized carbides in ferrite), show strengths of some 800-1000 N/mm^2 and offer maximum integrity as regards strength, fatigue endurance and resistance to sudden impact loads.

The production cycle involving hardening and tempering gives rise not only to the direct costs for heat treatment but also to indirect costs for straightening to correct quench-induced distortions (with the risk of cracking) which makes this processing route rather uneconomical particularly with energy costs on top.

Before the development of micro-alloyed steels, user attention was also focussed on iron castings which, in addition to removing the need for forging, offered good machinability.

Despite the inherent brittleness of cast iron, its service reliability was thought to be comparable to that of hardened and tempered steel in applications where toughness and ductility were not essential for the sound functioning of the components.

Crankshafts and camshafts are examples of components for which cast iron came to be used on a regular basis.

The possibility of using hardening and tempering steels in the as-forged condition, which would provide ductile properties superior to those of cast iron, was hampered by the difficulty of achieving adeguate tensile properties.

There are various potential methods for improving the tensile properties of steel produced direct from forging temperature, namely:

- relatively rapid cooling after forging (structural transformation hardening);
- cooling of certain steel compositions in air (solid-solution hardening);
- cooling of micro-alloyed steels in air (precipitation hardening).

The third method is the most practicable as the quantity of additions required is small and easily handled in the steelworks. Provision of the level and consistency of strength is also relatively easy to arrange in view of the restricted mass effect (ruling section) of the mechanical components usually produced.

When using micro-alloyed steels, it is nevertheless essential to take account of metallurgical aspects associated, firstly, with micro-alloying itself and its effects and, secondly, with the influence of heating, mechanical working and cooling operations on the microstructure. The following section of the report will discuss these metallurgical aspects.

Micro-alloying and metallurgical factors associated with cooling after forging.

Mechanism of influence of micro-alloying additions

Micro-alloying refers to small additions of elements which remain in solution in the steel above a certain temperature in the austenite phase and precipitate during cooling, combining with other elements in the steel after reaching their solubility limits. If precipitation is coherent with the matrix, the precipitates act as obstacles to the movement of dislocations and contribute to improving steel hardness.

The elements normally used for steel micro-alloying are vanadium and niobium which, on cooling, precipitate as carbides, nitrides and/or carbonitrides of composition and proportions which vary according to the equilibrium conditions dictated by the contents of C, N, Al, V and Nb in the steel (Fig. 1).

The curves in Fig. 2 give an indication of the precipitation of V and Nb according to temperature in a steel with about 0.2% C and 1.20% Mn.

It is interesting to note that, whereas Nb starts to precipitate at around 1250°C, V stays in solution down to about 900°C.

In view of the fact that the range of forging temperatures is approximately from 900 to 1250°C, it is evident that, whilst V precipitates mostly towards the end of forging, Nb starts to precipitate during forging and even during heating. This behaviour is exploited in current use of these two elements by allocating a predominant precipitation hardening role to V (coherent precipitation) and a predominant grain growth-inhibiting role to Nb. This second role, developed as a parallel to aluminium nitrides, is very important because a relatively coarse ferrite-pearlite structure is one of the negative features of micro-alloyed steels which, to a large extent, determine impact strength (the same adverse effect on toughness arises with precipitation hardening itself).

To achieve the hardening effect, the precipitates must have an effective maximum size which has been calculated to be of the order of 50-100 Å (3). To obtain this type of precipitate, the cooling rate between 1000 and 700°C has to be between two limits, i.e. between a maximum rate, above which cooling is too rapid for precipitation to occur and a minimum rate, below which precipitates coalesce even in the γ-phase and are too big and too limited in number to initiate hardening (1). In the case of niobium, for example, the maximum cooling rate has been calculated to be 80°C/min and the minimum rate, 10°C/min (3).

Fig. 1 - Solubility products of some nitrides and carbides in austenite (1).

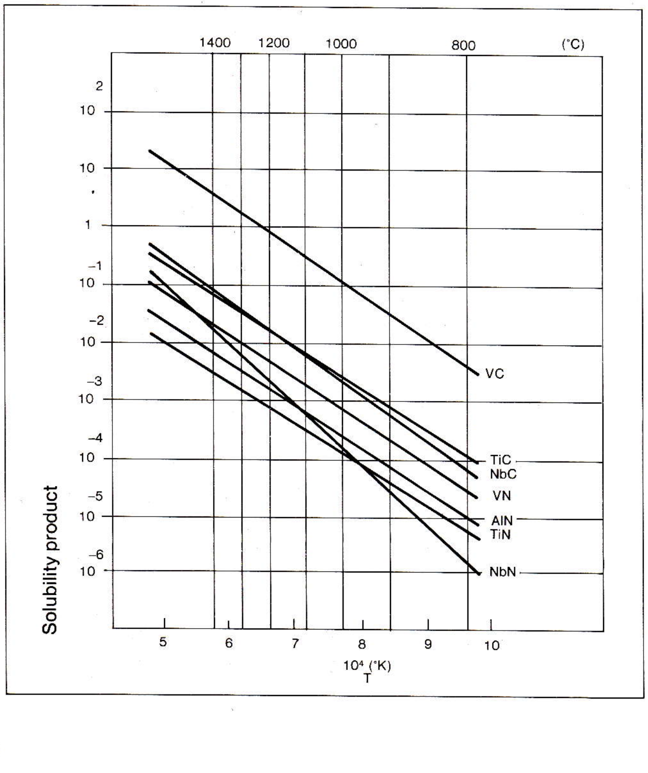
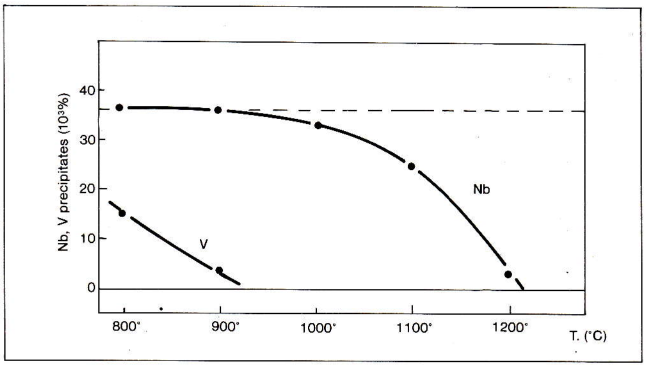


Fig. 2 - Niobium- and vanadium carbonitrides in austenite determined by electrolytic extraction in a steel with (%): C = 0.20; Mn = 1.22; Si = 0.34; P = 0.016; S = 0.017; N = 0.009; Al = 0.004; Nb = 0.038 and V = 0.033 (2).



The contents of V and Nb normally used in micro-alloyed steels are, respectively, 0.08-0.15% and 0.04-0.06% and provide increases in tensile and yield strength of 80-150 N/mm^2 as compared with steels of the same composition but without micro-alloying additions.

Influence of heating, plastic deformation and cooling on microstructure and mechanical properties of micro-alloyed steel

As micro-alloyed steel is used directly after hot working, the attainable properties are influenced, with identical compositions, by the conditions of heating, working and cooling. These conditions can affect, firstly, the mechanism of precipitation and, secondly, the microstructural characteristics associated with recrystallization and γ→α-transformation (amount of ferrite and pearlite, ferrite grain size, pearlite aggregate size, interlamellar spacing and thickness of cementite plates in the pearlite).

As regards effects on precipitation, the most critical aspect is the cooling rate referred to in the preceding paragraph. It should, however, be noted that, with most of the sizes used for components cooled naturally in air after forging (30-100 mm dia.), there is, in practice, always an effective cooling rate for the purpose of precipitation hardening. The only precaution necessary in this case is that the component should be cooled in static air down to about 600°C to avoid formation of a few large precipitates which would lower hardness. Beyond this point, however, cooling can be carried out in batches.

As regards property variations due to influences exerted on the microstructure, mention can be made of the equations formulated by Gladman et al. (4) for medium-to-high-carbon, ferrite-pearlite steels which can be used to calculate yield stress (Rs), tensile strength (Rm) and impact transition temperature for an impact strength of 27 J. These equations are as follows:

$$\begin{aligned}\text{Rs: yield stress} &= f_\alpha^{1/3}[2{\cdot}3+3{\cdot}8(\%\text{Mn})+1{\cdot}13\,d^{-1/2}]\\ (\text{tons/in}^2)\quad &+(1-f_\alpha^{1/3})\,[11{\cdot}6+0{\cdot}25\,S_0^{-1/2}]\\ &+4{\cdot}1\,(\%\text{ Si})+27{\cdot}6\,(\sqrt{\%\text{ N}_f})\end{aligned}$$

$$\begin{aligned}\text{Rm: tensile strength} &= f_\alpha^{1/3}[16{\cdot}0+74{\cdot}2(\sqrt{\%\text{ N}_f})+\\ (\text{tons/in}^2)\quad &+1{\cdot}18\,d^{-1/2}]+(1-f_\alpha^{1/3})\,[46{\cdot}7+\\ &+0{\cdot}23\,S_0^{-1/2}]+6{\cdot}3\,(\%\text{ Si})\end{aligned}$$

27 J impact transition temperature (°C) =

$$\begin{aligned}&f_\alpha[-46-11{\cdot}5\,d^{-1/2}]+\\ &+(1-f_\alpha)\,[-335+5{\cdot}6\,S_0^{-1/2}-13{\cdot}3\,p^{-1/2}\\ &+3{\cdot}48\times10^6\,t]+\\ &+48{\cdot}7\,(\%\text{Si})+762\,(\sqrt{\%\text{ N}_f})\end{aligned}$$

In these equations:

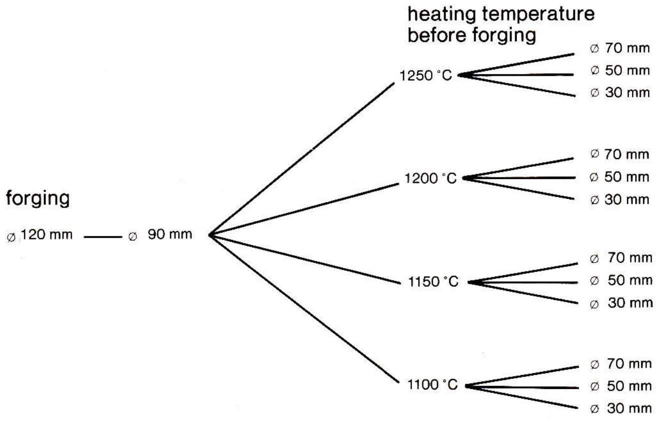
f_α = volume fraction of ferrite;
d = ferrite grain size (mm);
p = pearlite colony size (mm);
S_o = interlamellar spacing of the pearlite (mm);
t = cementite plate thickness in the pearlite (mm);
$\%\text{ N}_f$ = nitrogen content in solid solution.

The microstructural parameters inserted in the equations such as grain size, volume fraction of ferrite etc. are controlled by process variables like composition, austenite grain (and therefore heating and finish-forging temperature) and rate of cooling after forging. The effects of these variables are interdependent and cannot be considered in isolation from each other (5).

For a single composition, the effects of other process variables on the properties were investigated during forging of HVO80LS micro-alloyed steel (steel with a minimum tensile strength of 800 N/mm²) produced at Deltasider using different temperatures and section sizes. The experimental verification was obtained from a work carried out under ECSC Contract 7210 MA/412 currently in progress. This is a V + Nb, resulphurized, calcium-treated steel with the following composition in the case in point:

C = 0.42
Mn = 0.77
Si = 0.33
P = 0.025
S = 0.025
Ni = 0.11
Cr = 0.17
Mo = 0.03
Cu = 0.12
V = 0.11
Nb = 0.04
N = 98 ppm
Al = 0.017

The steel was worked by drop forging using the same sequence of reductions for each size produced. The combination of forging conditions used is shown in the following outline:



The graphs in Figs. 3 to 8 show the change in grain size, area fraction of pearlite, impact strength, tensile strength, yield stress and percentage elongation. Although the effects of variables acting in opposition to each other to varying degrees and possible omissions in control of the experimental conditions can lead to certain undefined changes in the various parameters shown in the graphs, the behaviour as regards microstructure shows quite good agreement with the effects anticipated in heating and forging conditions.

The higher the heating temperature, the greater is the austenite grain size (Fig. 3) and the higher the reduction in forging, the smaller is the austenite grain size due, to the protracted effect of grain fragmentation at lower temperatures at which grain recrystallization slows down (Figs. 9 and 10). The grain refining effect of the micro-alloying additions can be seen by comparing the micrographs in Figs. 9 and 10 with those in Figs. 11 and 12 referring to a steel of the same composition without micro-alloying additions in the same forging conditions. It is to be noted that the austenite grains can be equated with the areas enclosed by the proeutectoide ferrite network.

The percentage of pearlite decreases with the size of the forging. It also tends to decrease with decreasing austenite grain size (Fig. 4).

The most apparent influence of microstructure on properties here concerns impact strength. Impact strength tends to decrease with increasing grain size and pearlite content i.e. with increasing forging temperature and forging size (Fig. 5).

With reference to tensile properties, the curve plots show that tensile and yield strength increase with the degree of reduction and, to a certain extent, with heating temperature (Figs. 6 and 7). There is evidently a relationship with the degree of reduction since grain size decreases with increasing forging reduction. As regards the heating temperature, a greater precipitation hardening effect could be envisaged with an increase in this temperature (more micro-alloying elements in solution during heating especially in the case of niobium).

Fig. 3

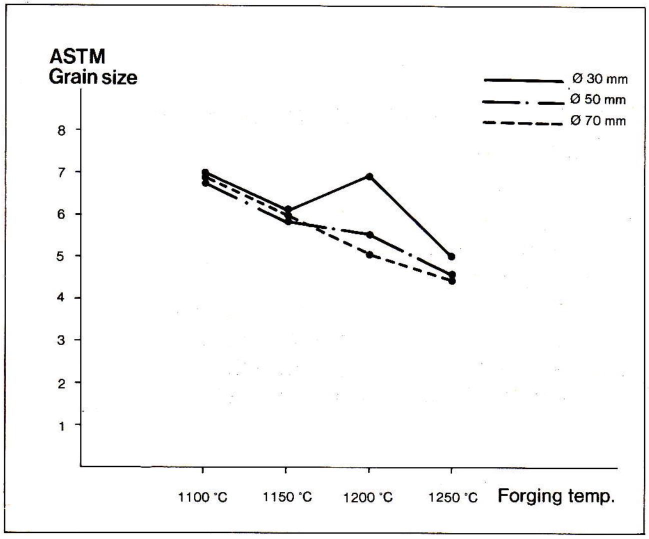


Fig. 4

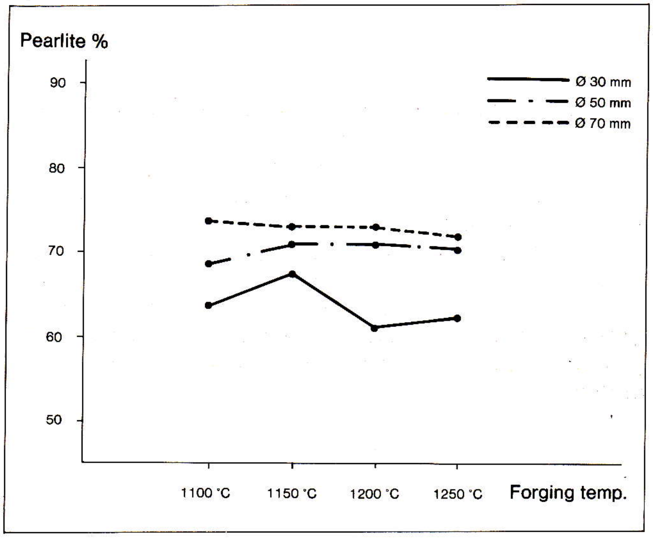


Fig. 5

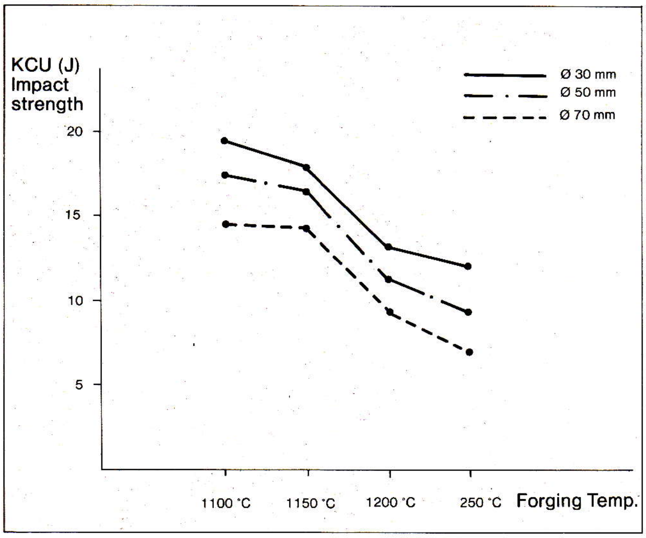


Fig. 6

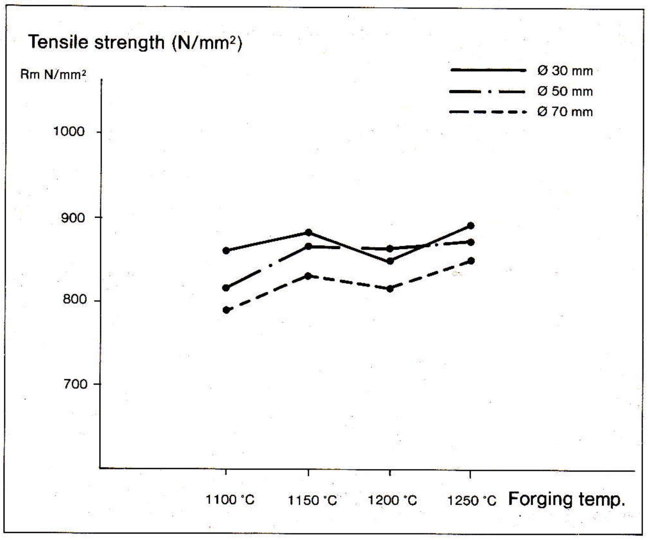


Fig. 7

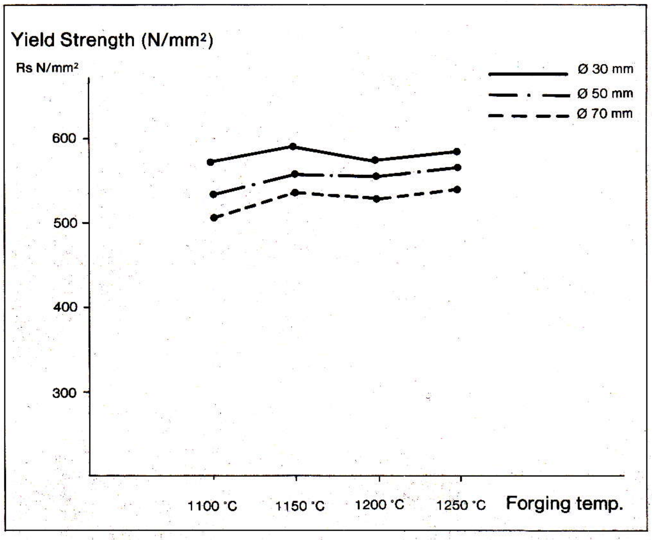
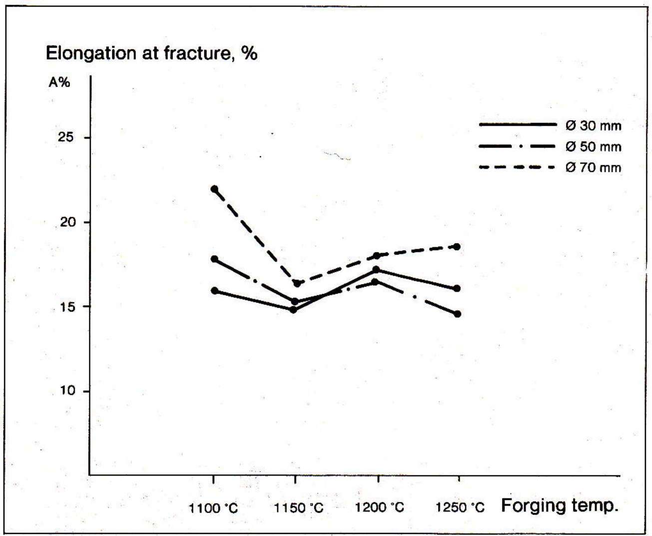


Fig. 8



Figs. 3 to 8 - Variations of the microstructural and mechanical properties due to different forging temperature and section sizes.

Elongation tends to decrease as the tensile properties increase (Fig. 8).

Within the experimental conditions and with the obtained forging results, the tests appear to show that the best compromise between tensile and impact properties can be obtained through use of low heating temperatures and high degrees of reduction in forging (low finish-forging temperatures). The finish-forging temperature must, of course, be high enough to ensure grain recrystallization to prevent the onset of residual work hardening.

Micro-alloyed steels produced at Deltasider

There are currently two trends in the choice of compositions for production of micro-alloyed steels for mechanical components.

The first, which originates from the development of this type of steel, involves the addition of vanadium to carbon steels containing not more than 1% Mn. This is the case with 49 Mn VS3, a steel of German origin, with

Fig. 9 - HVO80LS micro-alloyed steel, ∅30 mm, forged at 1100 °C (x100).

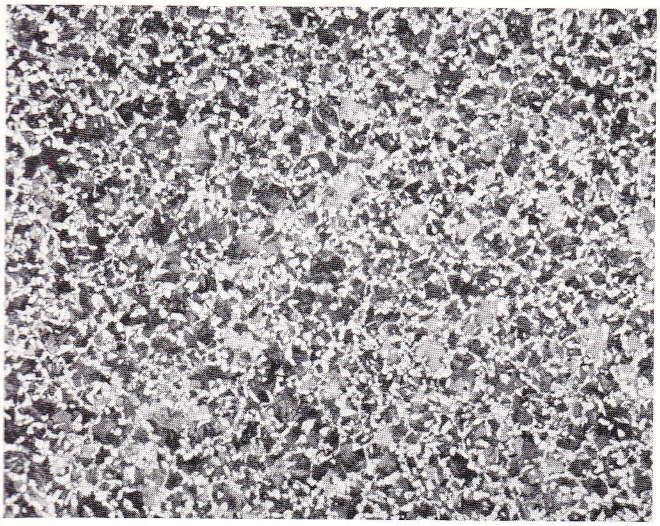


Fig. 10 - HVO80LS micro-alloyed steel, ∅70 mm, forged at 1250 °C (x100).

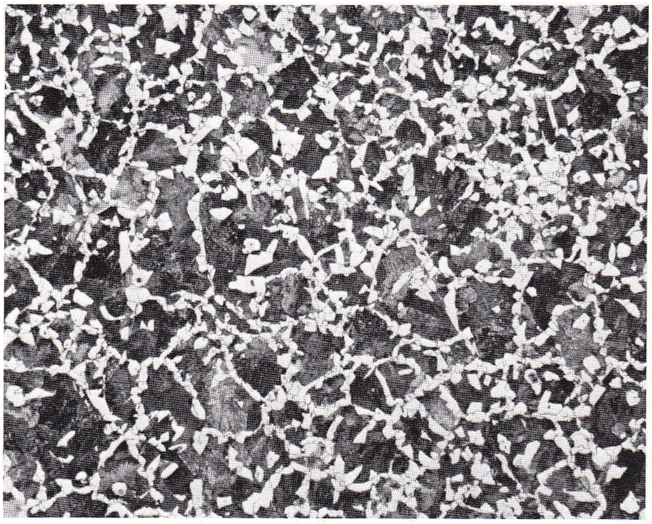


Fig. 11 - Carbon steel, ∅30 mm, forged at 1100 °C (x100).

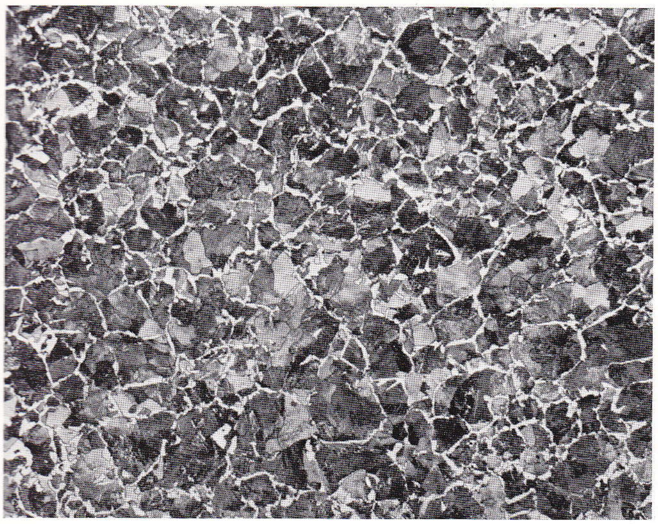


Fig. 12 - Carbon steel, ∅70 mm, forged at 1250 °C (x100).

TABLE 1 - Chemical composition (%) and mechanical properties of some micro-alloyed steels

Steel	C	Si	Mn	P	S	Micro-alloying additions	Tensile S. (N/mm^2)	Yield S. (N/mm^2)	Elongation (%)
49MnVS3	.44/.54	≤ .60	.60/1.0	≤ .035	.045/.065	.08/.13 V			
Metasafe D800	.15/.25	.10/.40	1.3/2.0	≤ .030	≤ .015	.10/.20 Nb + V	750/900		
Metasafe D900	.25/.30	.10/.40	1.3/2.0	≤ .030	≤ .015	.10/.20 Nb + V	850/1000		
Metasafe D1000	.35/.50	.10/.40	1.3/2.0	≤ .030	≤ .015	.10/.20 Nb + V	950/1100		
Vanard 850	.30/.50	.15/.35	1.0/1.5	.035 max	.05 max	.05/.20 V	770/930	540 min	18 min
Vanard 925							850/1000	600 min	16 min
Vanard 1000							930/1080	650 min	12 min
Vanard 1100							1000/1160	700 min	8 min

the composition ranges shown in Table 1. In these steels, the carbon content is medium-to-high and makes a major contribution to strength in combination with precipitation hardening. A ferrite-pearlite microstructure is formed using the range of cooling rates normally adopted after forging and hot rolling. The carbon content allows these steels to be used for components surface-hardened by induction hardening (crankshafts). The impact strength is however particularly low owing to the high percentage of pearlite which can give rise to a microstructure composed of pearlite aggregates (colonies) in ferrite networks.

The second trend, which has emerged more recently, involves restriction of the carbon content and provision of the required strength through the use of higher manganese contents. This route has been taken by S.A.F.E. for example (Metasafe steels: see compositions and mechanical properties given in Table 1) and also British Steel (Vanard steels: see compositions and properties in Table 1).

The advantages of these steels is that, for similar tensile properties, they have less pearlite and a finer grain which is beneficial as regards impact properties. The increased Mn-content and the higher hardenability it provides can, however, lead to the formation of a mixed ferrite-pearlite-bainite structure after cooling with incomplete utilization of the strengthening effect of the micro-alloying elements (6), whilst the reduced carbon content can exclude the use of surface induction hardening in manufacture of the components. These comments are particularly applicable to lower-strength steels since, in the case of higher strength levels, the carbon content has to be raised anyway.

Development at Deltasider, where the main requirement was to produce steel ideal for crankshaft forging for Fiat, followed the first of the trends mentioned above as the Fiat crankshafts need to be induction hardened. Nb was used in combination with V for improved control of austenite grain whilst controlled resulphurization (S = 0.040% max.) and Ca-treatment were used to ensure micro-cleanness and good machinability.

The produced steel has the designation HVO80SL with a minimum tensile strength of 800 N/mm^2. The composition ranges of the steel are shown in Table 2 together with typical minimum mechanical properties obtainable with controlled cooling after hot working (rolling or forging) in billets of up to 100 mm size.

TABLE 2 - Chemical composition (%) and indicative mechanical properties of micro-alloyed steels produced at Deltasider

Steel (Condition)	C	Si	Mn	P	S	N (ppm)	V	Nb	Tensile S. (N/mm^2)	Yield S. (N/mm^2)	Elong. (%)	Reduct. Area (%)
HVO80SL	.41 .48	.15 .35	.60 1.0	$\leqslant$ .035	.020 .040	90 120	.08 .13	.04 .06	800 min	500 min	15 min	35 min
HVO90SL	.48 .54	.20 .35	.80 1.10	$\leqslant$ .035	.020 .040	90 120	.08 .13	.04 .06	900 min	550 min	12 min	30 min
hot-rolled or forged												

Deltasider also produces a micro-alloyed steel with a minimum tensile strength of 900 N/mm^2 with the designation HVO90SL (see compositions and mechanical properties in Table 2) and a range of micro-alloyed drawn steel products known as "HL" products which can replace parts produced by machining of hardened and tempered bars.

Trial application phase

On the basis of the results obtained in the development of the above micro-alloyed steels, it was possible to initiate a trial programme for introduction of these steels in the motor industry for components such as crankshafts and connecting rods.
Fiat Auto, in collaboration with Deltasider and Teksid Drop Forging, initiated this programme with trials in wich this type of steel was used for crankshafts in the 131 and 132 models (2000 c.c. cylinder capacity). The steel normally used for these crankshafts was hardening and tempering quality 40CrMo4 which was surface-hardened by induction hardening and soft nitriding.

Production of crankshafts and metallurgical description

Two casts were produced via the conventional ingot casting route of micro-alloyed HVO80SL (800 N/mm^2 tensile) and HVO90SL (900 N/mm^2 tensile). The ingots were rolled into 90 and 95 mm-section billets. The chemical compositions were as follows:

	C	Mn	Si	S	P	V	Nb
HVO80SL	0.43	0.75	0.32	0.026	0.017	0.093	0.04
HVO90SL	0.48	0.67	0.29	0.031	0.013	0.11	0.06

Crankshafts were produced with both the above compositions.
The crankshafts were forged from billets heated to 1120-1150°C in an induction furnace using a 4000 t mechanical press.
The crankshaft temperature at the end of forging was about 1050°C. After removal of flash, the forging was cooled down to 800-850°C in about 10 minutes.
The hardness was measured in various areas of the crankshafts.
The uniformity of the determined hardness value can be seen from Fig. 13 which refers to HVO80SL steel.

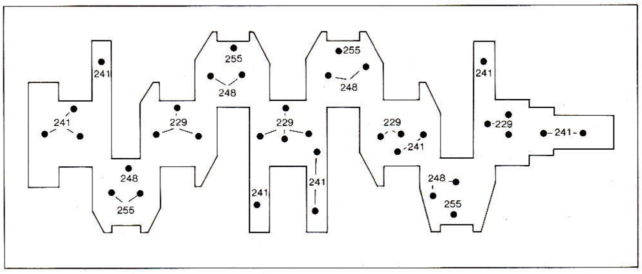


Fig. 13 - Brinell hardness determined on a crankshaft of micro-alloyed HVO80SL steel.

The pertinent microstructures are shown in Fig. 14.
The samples for determination of mechanical properties were taken from the journal end (tensile specimens) and crankpin webs (impact specimens).
Table 3 shows the results obtained in comparison with hardened and tempered 40CrMo4 steel.
The crankshafts were then finished by machining and soft nitriding to provide the component with higher fatigue resistance and improved wear resistance in the area of the lip seals. The hardening cycle was that normally used in production at Fiat Auto Mirafiori

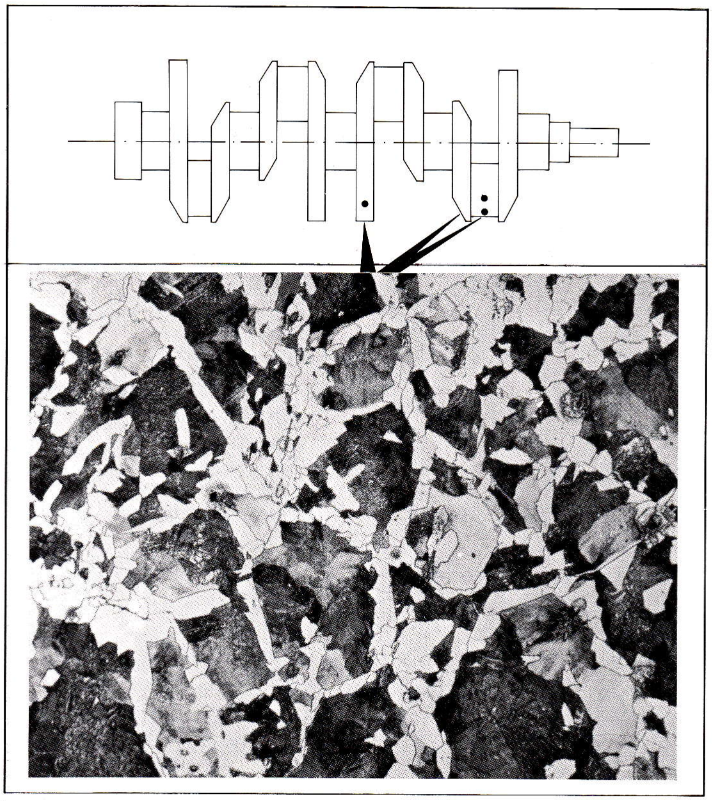


Fig. 14 - Microstructure determined in various zones of the shaft (lamellar pearlite distributed between ferrite grains).

Meccanica works in Turin. The changes in hardness obtained are shown in Table 4 and in the graphs in Fig. 15 which also include data for hardened and tempered 40CrMo4 as a comparison.

Fatigue tests

After analysis of the static mechanical properties of the above micro-alloyed steels in the form of forged products, it was then necessary to complete the picture with fatigue tests on both smooth and notched specimens.

The influence of soft nitriding on fatigue resistance and notch sensitivity was also monitored. Rotating-bending fatigue tests were performed on specimens with $K_t = 1$ and $K_t = 1.55$ (see specimen designs in Fig. 16).

To increase the level of significance, the test bars were taken directly from the crank web zone of the crankshafts. The soft nitriding cycle was a follows:

Heating: 570°C for 3 hours;

Atmosphere: EXOGAS: 50%
NH_3 : 50%

The microstructure in the nitrided zone is shown, by way of example, for HVO90SL steel in Fig. 17.

The thickness of the nitrided layers vary from 20 to 25 microns.

The fatigue tests were performed in a Schenck

TABLE 3 - Properties determined on a crankshaft

Steel	Tensile S. (kg/mm^2)	0.2%-Proof stress (kg/mm^2)	Elongation L = 5d (%)	KCU-Impact strength (J)
HVO80SL	84.5	54.6	15.5	16
HVO90SL	93.1	60.4	10.5	13
40CrMo4 (hardened + tempered)	105.8	96.4	16.1	32

TABLE 4 - Comparison of hardness obtained after "soft" nitriding and lapping for different steels

Type of steel	40CrMo4 (H + T)	HVO80SL - HVO90SL
Surface hardness on main journals, HV_1	614 - 685	687 - 713
Thickness of lapping compound layer (mm)	0.010 - 0.015	0.015 - 0.020

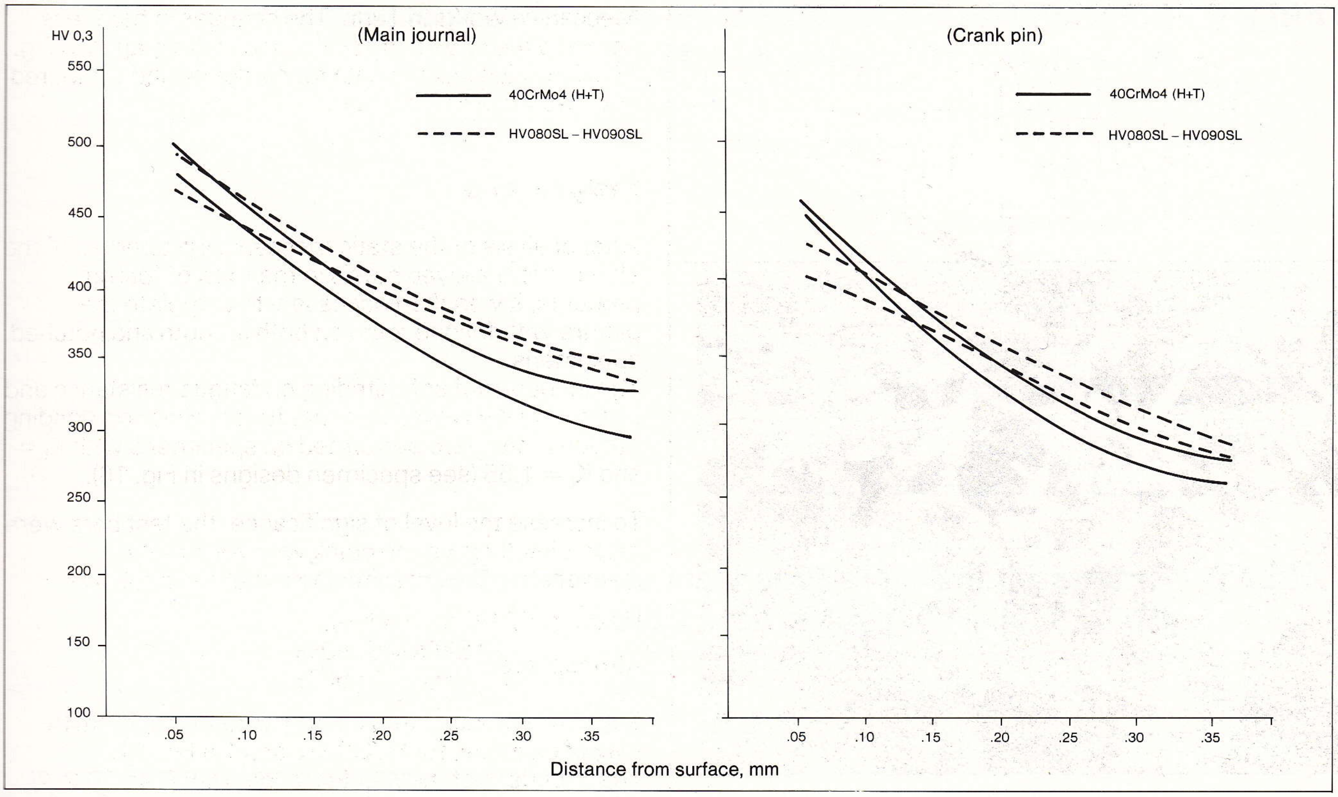
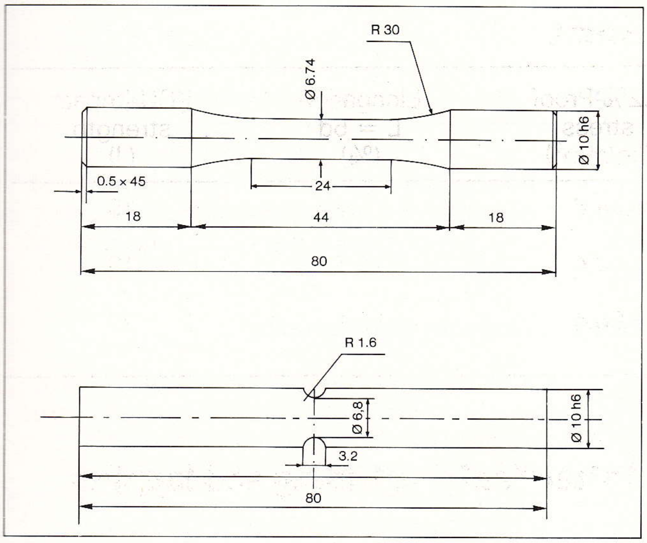


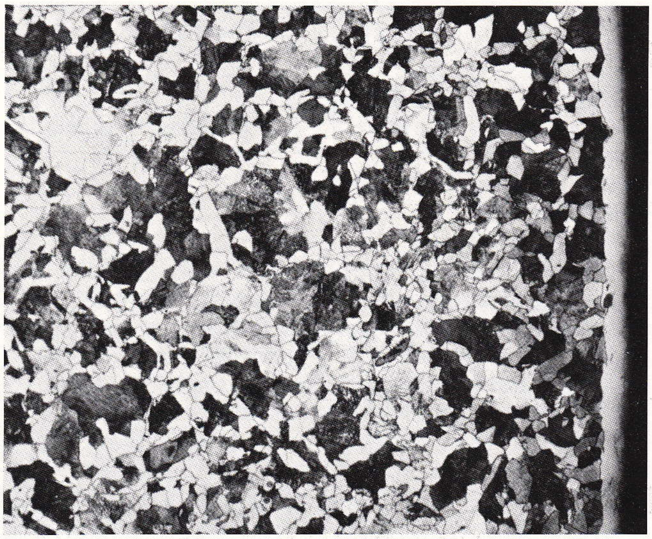
Fig. 15 - Hardness gradient after soft nitriding.

Fig. 16 - Rotating-bending fatigue specimens (dimensions in mm).



machine using a frequency of 12×10^3 cycles/min and the fatigue limits were calculated for 10^7 cycles duration with the aid of the staircase method. Tables 5 and 6 show the fatigue resistance σ_D for 50%

Fig. 17 - Nitrided zone in a specimen.



failure probability, the fatigue ratio $K = \dfrac{\sigma_D}{T.S.\ (R_m)}$

the notch factor $K_f = \dfrac{\sigma_D}{\sigma_{D_{notch}}}$

and the notch sensitivity factor $q = \dfrac{K_f - 1}{K_t - 1}$

TABLE 5 - Rotating-bending fatigue tests on smooth specimens ($R = -1$, $N = 10^7$ cycles, $K_t = 1$)

Steel	Heat Treatment	Fatigue Limit σ_D (N/mm^2)	Fatigue Ratio $K = \frac{\sigma_D}{Rm}$
HVO80SL	Controlled cooling	337	0.40
HVO80SL	Controlled cooling and soft nitriding	434	0.51
HVO90SL	Controlled cooling	391	0.41
HVO90SL	Controlled cooling and soft nitriding	513	0.54
40CrMo4	Hardening + tempering to HB 282 ÷ 320	473	0.44
40CrMo4	Hardening + tempering to HB 282 ÷ 320 + soft nitriding	615	0.58

TABLE 6 - Rotating-bending fatigue tests on notched specimens ($R = -1$, $N = 10^7$ cycles, $K_t = 1.55$)

Steel	Heat Treatment	Fatigue Limit σ_D (N/mm^2)	Notch Factor K_f	Notch Sensitivity Factor q
HVO80	Controlled cooling	306	1,10	0.18
HVO80	Controlled cooling and soft nitriding	484	0.89	—
HVO90	Controlled cooling	330	1.18	0.32
HVO90	Controlled cooling and soft nitriding	484	1.06	0.10
40CrMo4	Hardening and tempering to HB 282 ± 320	380	1.24	0.43
40CrMo4	Hardening and tempering to HB 282 ± 320 plus soft nitriding	608	1.01	0.018

Observations

The rotating-bending fatigue tests on unnitrided smooth specimens show that the micro-alloyed steels are comparable with the hardened and tempered steel and that the fatigue resistance data are closely dictated by the static test values. The fatigue ratio K is, in fact, identical within the experimental scatter range. Soft nitriding increases the fatigue resistance of the micro-alloyed steels by about 30% i.e. by about the same amount as observed in hardened and tempered steel. The tests on notched specimen showed a diminution in fatigue resistance which was lower in controlled-cooled, micro-alloyed steels than in hardened and tempered 40CrMo4. Both the notch factor and notch sensitivity were in fact lower in the tested micro-alloyed steels.
It can be seen from test results that the notch sensitivity factor is substantially reduced upon soft nitriding of micro-alloyed and hardened and tempered steels. It is well known, in fact, that such a treatment, in addition to increasing fatigue resistance, also reduces notch sensitivity of steels.

Fatigue tests on crankshafts

To check on the acceptability of crankshafts made of micro-alloyed steel instead of hardened and tempered 40CrMo4 quality, bench fatigue tests and engine tests (in both engine test beds with braking facilities and actual cars) were conducted on crankshafts made from controlled-cooled and soft-nitrided HVO80SL steel treated in the normal production cycle described earlier. In addition, all the tested crankshafts were surface ground on the crank pins, removing 0.127 mm of metal to simulate the most critical condition allowed in the production cycle.
The bench tests consisted of planar fatigue bending

tests in the crankshaft web plane with a constant moment along the axis of the shaft.

A symmetrical-alternating load cycle was used and the testing frequency was 30 Hz. The load/no. of cycles curve was plotted up to 10^7 cycles. This curve is shown in Fig. 18, in which the S-N-curve for conventionally produced 40CrMo4 crankshafts is also included for comparison. The micro-alloyed steel shafts have a fatigue resistance equivalent to that of hardened and tempered steel crankshafts. The fatigue limit, in particular, is 85 kgm as compared with 90 kgm for normally produced shafts. This difference is not considered significant from the point of view of good functioning of the shaft in service and crack initiation is restricted, with about the same frequency, to the fillet zones of the journal and crank pin.

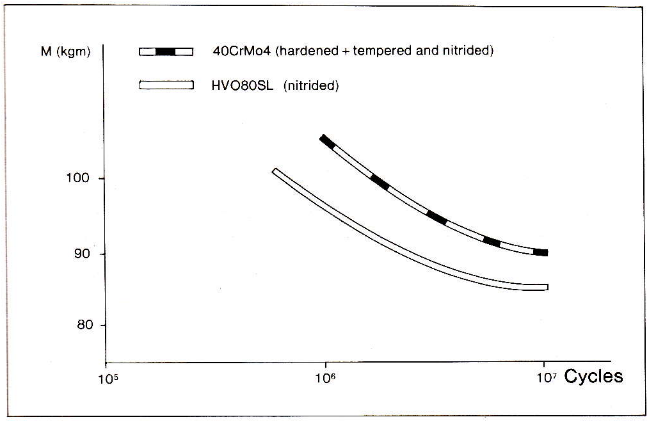
These bench tests were completed by tests on two crankshafts installed in two engines in the 2000 c.c. range. The first shaft was installed in a 132 class engine and subjected to a total test time of 700 hours according to standard procedures used in the Technical Engine Testing Department at Fiat Auto. At the end of this period, a further 25 hours was added on at 7000 r.p.m. which represented the outside critical r.p.m. limit. The second shaft was installed in a Ritmo 130 T.C.-type engine and the test was run for a total of 500 hours.

Finally, a third crankshaft was installed in a 132 I.E.-type engine and this car was run for another 100,000 km round the Fiat test track at Nardo.

In the course of the above tests, no anomalies or deterioration of the crankshaft properties was observed. The wear observed on the main journals and crank pins at the end of the tests was the normal amount and in no way prejudicial to the sound functioning of the shafts.

The results in general were regarded as positive and fully comparable with those obtained on crankshafts made from hardened and tempered 40CrMo4 steel.

Fig. 18 - Planar bending fatigue test (2000 c.c. motor crankshafts).



Conclusions

In the mechanical engineering sector, there is now a marked trend towards the use of micro-alloyed steel in the form of long products as cost-effective substitutes for hardened and tempered steels. In addition to laboratory tests on the initial steels to check verifiable properties which can provide a first-step indication of properties in use, it is also important to ascertain the suitability of steels for various end applications by direct tests on components in actual service. It must be borne in mind, in fact, where the steel does not need to be finally stress-relieved, the properties of the finished parts will be influenced not only by the chemical composition-imposed strength level but also by the practice adopted in the production cycle. This is especially applicable in respect of impact strength which is related to grain size and to the amount and distribution of ferrite and pearlite which, in turn, depend on the chemical composition and the production cycle used in making the product (heating, forging conditions and rolling conditions if the parts are to be used after controlled cooling direct from the mill etc.).

The case of crankshafts considered in this paper represents the start of a comprehensive programme of tests on components initiated by Fiat Auto and can be regarded as one example of an approach to the problems of using micro-alloyed steels which was brought to a successful conclusion.

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