Microalloyed steel applications in high-rate hot forging processes

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Abstract
Worthwhile process savings are obtained in the hot-forging of components by using automated high-rate plants and microalloyed steels that do not require subsequent quenching and tempering. This paper describes and discusses the mechanical and fatigue properties of a series of microalloyed steels. Present and foreseen applications are also reviewed with regard to the automotive industry.
Lastly, some suggestions are made concerning the correct choice of materials and components to ensure reliability in the application of this class of steels.

Riassunto
L'adozione di impianti automatizzati ad elevata cadenza, insieme con l'utilizzo di acciai microlegati che non necessitano di trattamenti termici post-fucinatura, consentono di ottenere interessanti economie di processo nella fabbricazione di componenti stampati a caldo.
Nel presente lavoro sono presentate e discusse le proprietà meccaniche e a fatica di una serie di acciai microlegati ed esaminate, per quanto riguarda il campo autoveicolistico, sia applicazioni già consolidate che future possibilità di impiego.
Alcune indicazioni sono infine fornite, a livello di scelta del materiale/componente, per garantire una applicazione affidabile di questa classe di acciai.

Introduction

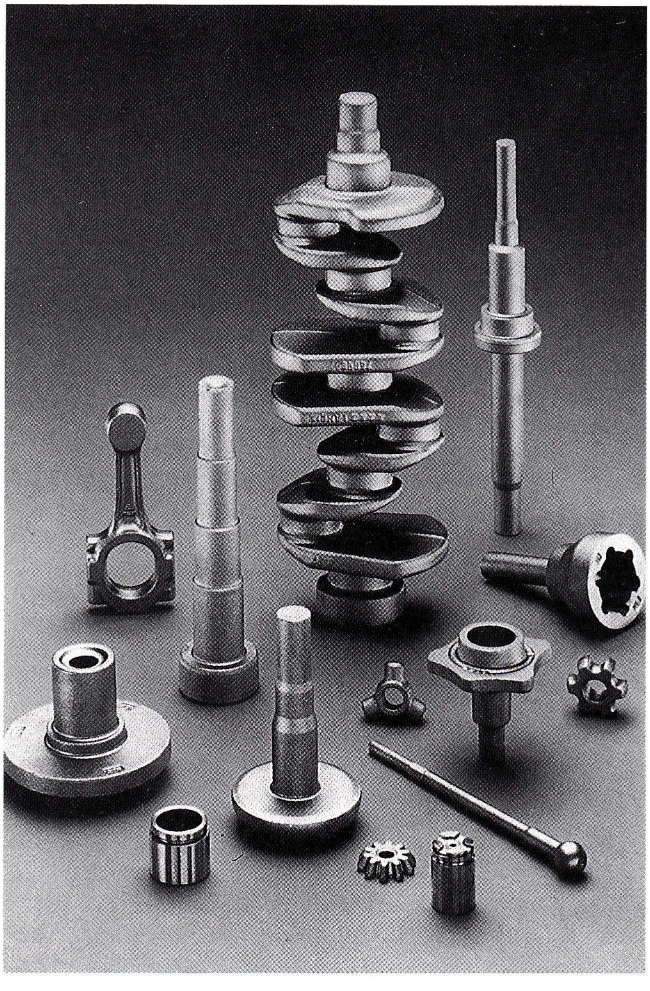
Plunging production figures and the introduction of alternative technology materials, such as nodular irons, light alloys and metal matrix composites, have thrown the hot-forging into a state of crisis in recent years. Great efforts have thus been made in the way of restructuring and technological innovation with a view to recovering the competitiveness of forged steel.

Some typical automotive components conventionally made by hot forging quenched and tempered (Q & T) steels are illustrated in fig. 1. A common feature of such components is mass production, where there is an increasing demand for them to be of high quality and able to be manufactured at a low overall cost. Excellent cost/performance ratios can thus be obtained by using innovative steels in conjunction with technologically advanced plants.

Modern computer-controlled automated presses with their high-rate closed-die forging rhythms (typically 70-80 pieces/min) result in lowering the manufacturing times and costs. Furthermore, the process parameter values can be monitored so as to achieve maximum plant reliability.
These innovations have a direct influence on the quality of the finished product. They also ensure reliability even when materials conventionally regarded as more critical for applications such as microalloyed steels, are used.

Components made with this family of materials have strength and fatigue properties comparable with those of conventional steels. Their great advantage, however, is that they do not require a subsequent quenching and tempering treatment. Apart from the economic and

Fig. 1 - Hot forged automotive components.



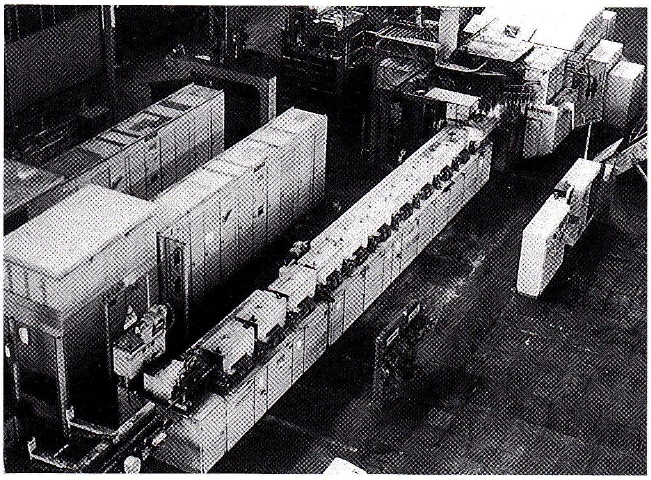
energy savings involved, this allows full exploitation of the high productivity of automated presses by cutting out the waiting times needed for such treatments.

The fact that automated presses forge in closed dies should not be overlooked when optimising cost/performance ratios must be reached. Greater precision conferred by reduction of the allowed tolerances is couples with lower fabrication times and costs, since less finishing is required.
The purpose of this paper is to describe the ongoing development of automotive component hot-forging technology and the interest devoted by steelmakers to the elaboration of new microalloyed steels with optimised compositions suitable for this field of application.

Innovations in hot-forging technology

A general view of a modern high-rate hot-forging plant used for the production of high-quality mechanical components is shown in fig. 2.
The reheating furnace is fed by an automatic bar loader. It consists of 10 induction-type reheating stations powered by static converters giving a total power of 6000 kW.
A computer-controlled optical pyrometer in each station ensures that forging temperatures of 1250° C are kept within a tolerance of ± 20° C. The bar (45 ÷ 70 mm diameter and 7 ÷ 10 m in length) passes into the furnace at a speed near to 10 metres/min. It is sheared by means of a computerised system into stock, with a weight tolerance of ± 5 g, for insertion in the die.

Fig. 2 - High rate forger (courtesy by TEKSID S.p.A.).



Stock out of weight and/or temperature tolerance is automatically rejected before it enters the forger.
The forger is of the horizontal type and the most powerful in tis category. It has a maximum thrust of 1500 tonnes and can produce pieces weighing up to 5 kg and measuring up to 180 mm in length and 150 mm in diameter at a rate of 70 to 80 a minute, i.e. ten times faster than a hand-operated press.

As already mentioned, this automatic forger works with closed dies, i.e. without the formation of burs, and with reduced machining allowances and tight dimensional tolerances. In addition, supplementary finishing operations usually done by mechanical machining can be performed, such as the grooving of oil ducts in a gear sleeve hub. High-rate horizontal forgers were initially introduced for the hot-forging of simple, axially symmetrical parts, e.g. gears, sleeves and rings. Their application to the production of more intricate components with considerable variations in diameter and configurations that are not solely axially symmetrical, e.g. knuckles and differential half-shaft flanges, are now under consideration.

Components of this kind must be manufactured by extrusion. During this process, considerable changes in shape and diameter are imposed lengthwise on a billet by a punch, which drives the material through an appropriately shaped die at a temperature of 1200-1250° C. Optimisation of the process is rendered extremely difficult, because parameters such as temperature, deformation rate, friction and lubrication conditions and the shape of the component, have a decisive influence on the distribution of the deformation and local stresses within the die.

For this reason, a specific finite elements program must be adopted on a CAD station when designing the individual pressing stations so as to simulate the extrusion process under the forger's working conditions, and hence optimise the distribution of deformation and stresses, check the completion of the figure in each station, and determine the effective pressing force. This analysis also results in optimum tool design. Forger start-up times are greatly reduced and tool performance and working life are improved.

Fig. 3 offers an illustration of the strain and stress distribution predicted for a hot-forged car component on a CAD station (1). Quite apart from the undeniable increase in productivity provided by closed-die forging as opposed to conventional press forging, it also results in an improvement in quality, whose essential features are:
— a higher degree of finish conferred by tighter tolerances
— greater component strength conferred by the

continuous fibre pattern typical of the extrusion process.

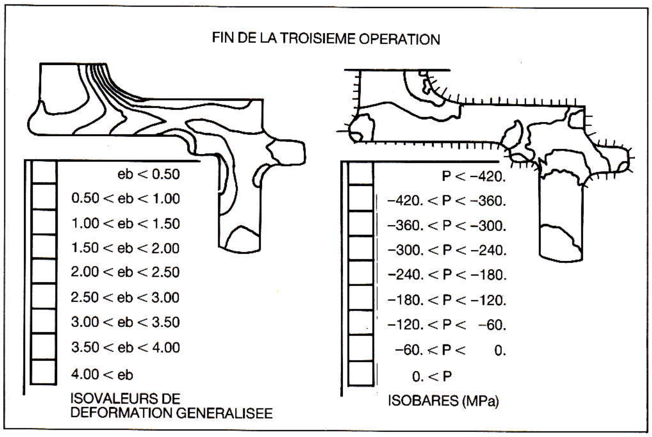


Fig. 3 - F.E.M. analysis of a hot forged component.

Applications of microalloyed steels

Steels microalloyed by a small addition of Vn, Nb and Ti to a basic C-Mn composition, have a mainly perlite and ferrite structure. They are designed to exploit the precipitation hardening that occurs during cooling of a hot-worked piece.

Skilful employment of this reinforcement mechanism results in crude forging, or hot-rolled components whose strength levels are similar to those Q & T low and medium-alloyed steels.

Elimination of these heat treatments and hence the reduction of distortion and residual stresses, more uniform properties across the thickness, and better machinability are the key fabrication advantages offered by this class of steels. Their toughness is generally lower than that of Q & T steels. This factor, however, does not constitute a serious restriction to their general application, since it is only of real importance for the relatively few components required to display an excellent resistance to impact loadings (2, 3).

At the design stage particular attention must thus be devoted to the settlement of the expected in service mission of the component. In other words, microalloyed steels are acceptable candidates for the manufacturing of all components requiring high strength and a correspondingly good fatigue resistance. Their use is thus linked to a " purpose-oriented " choice of the correct steel for a given component so as to ensure its maximum reliability.

Increasing use is now being made of sophisticated calculation techniques, such as the finite elements method, in the design of mechanical components, so that a complete and reliable picture can be obtained of the stresses to which they will be subjected. The material can thus be rationally " distributed " over the more critical areas where fatigue failure is more likely to occur.

Effective use of the results provided by these calculation methods is dependent on the availability of fatigue life prediction criteria that make provision for both the properties of material employed and the load cycle to which the component will be subjected in service (fig. 4). Knowledge of the fatigue properties of the material to be employed is thus a key prerequisite to obtaining significant and reliable results.

These properties must be determined on test specimens whose microstructural, geometrical and surface features represent those of the component itself.

Table 1 compares the chemical composition of some microalloyed steels indicated by M and Q & T steels conventionally used for manufacturing of automotive components.

The results of tensile, toughness and fatigue tests (4) of specimens whitdrawn from bars subjected to heat and mechanical treatments simulating the conditions to which a hot-forged component is likely to be exposed are illustrated in Tables 2, 3 and 4.

The main microstructural parameter values of microalloyed steels are set out in Table 5.

Fig. 4 - Schematic of procedure used to predict the fatigue life of mechanical components.

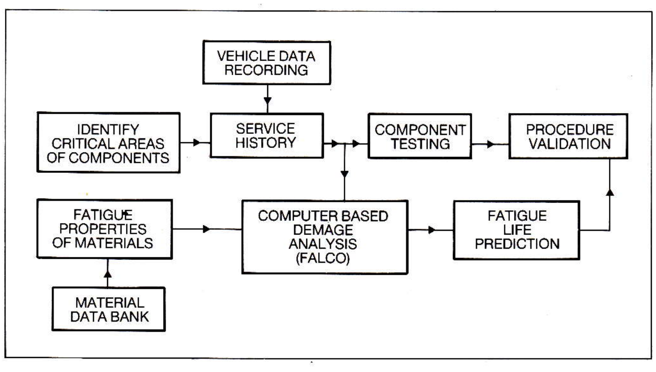


TABLE 1 - Chemical composition (weight %) of some microalloyed and Q & T steels

STEEL	C	Mn	Si	P	S	Cr	Ni	Mo	V	Nb	N
M2	0.21	1.54	0.46	0.012	0.005	0.08	0.11	0.02	0.18	0.030	0.013
M3	0.22	1.68	0.40	0.010	0.020	0.08	0.06	—	0.13	0.026	0.018
M4	0.54	0.96	0.31	0.010	0.026	0.10	0.04	0.01	0.11	0.040	0.014
M5	0.38	1.46	0.34	0.016	0.030	0.20	0.12	0.03	0.10	0.037	0.014
M10	0.31	1.30	0.55	0.019	0.028	0.35	—	—	0.11	0.067	0.012
41Cr4	0.41	0.78	0.28	0.024	0.016	1.0	0.14	0.03	—	—	—
42CrMo4	0.41	0.80	0.25	0.020	0.018	1.0	0.16	0.16	—	—	—
42CrMo4 + S	0.40	0.73	0.23	0.018	0.040	1.0	0.13	0.20	0.016	—	—

TABLE 2 - Mechanical properties of the steels

STEEL	TENSILE PROPERTIES									CHARPY IMPACT TEST			
	Rm MPa	Rp MPa	A5 %	Z %	σ_f MPa	ε_f	n	K MPa	Rp/Rm	KCU$_L$ J/cm^2		KCU$_T$ J/cm^2	
										−40° C	T.A.	−40° C	T.A.
M2	800	590	21	67	—	1.108	0.130	1250	0.74	40	80	—	—
M3	875	580	21	48	1208	0.654	0.153	1381	0.66	75	80	15	24
M4	930	575	19	45	1254	0.597	0.192	1654	0.62	4	11	4	7
M5	940	620	19	54	1335	0.786	0.166	1575	0.66	10	35	—	—
M10	905	623	17	57	1545	0.844	0.123	1325	0.69	10	50	—	—
41Cr4	930	800	19	62	1390	0.967	0.112	1350	0.86	60	96	16	28
42CrMo4	940	840	19	64	1440	1.022	0.094	1300	0.89	117	140	32	47
42CrMo4 + S	960	840	23	65	1500	1.050	0.100	1340	0.87	100	110	28	34

TABLE 3 - Elastic fatigue parameter values

STEEL	S_A	k	N_A	Rp/Rm
	MPa		cicli $\times 10^5$	
M2	385	11	39.8	0.48
M3	370	13	41.6	0.42
M4	370	14	31.8	0.40
M5	420	12	5.9	0.45
M10	405	28	9.5	0.45
41Cr4	450	16	5.0	0.48
42CrMo4	450	15	5.4	0.48
42CrMo4 + S	440	14	4.2	0.46

TABLE 4 - Low Cycle Fatigue behaviour results

STEEL	n'	K'	σ'_Y	ε'_f	c	σ'_f	b	E_{cicl}
		MPa	MPa			MPa		MPa
M2	0.098	1210	660	0.677	−0.675	1170	−0.068	209000
M3	0.098	1195	650	0.363	−0.584	1280	−0.079	206900
M4	0.133	1400	600	1.044	−0.689	1290	−0.081	207700
M5	0.150	1610	635	0.931	−0.686	1390	−0.085	205900
M10	0.141	1530	635	0.439	−0.602	1400	−0.088	204800
41Cr4	0.124	1300	600	0.835	−0.664	1255	−0.078	207300
42CrMo4	0.113	1240	610	2.900	−0.800	1170	−0.069	208700
42CrMo4 + S	0.124	1335	615	0.755	−0.662	1155	−0.067	208400

TABLE 5 - Microstructural parameters of microalloyed steels

STEEL	Ferrite	Perlite	Bainite	d_α	d_Y	So
	%	%	%	μm	μm	Å
M2	68	29	3	15.7	58.5	1605
M3	59	31	10	7.4	15.5	905
M4	15	85	—	3.6	48.5	2030
M5	12	88	1	7.2	55.0	1945
M10	29	71	—	8.6	—	1495

A generalised representation of their fatigue behaviour in a substantially elastic field, as obtained from statistical analysis of the results of tests carried out (inter alia) in previous characterizations, is shown in fig. 5 in the form a " uniform scatter band " (5, 6).

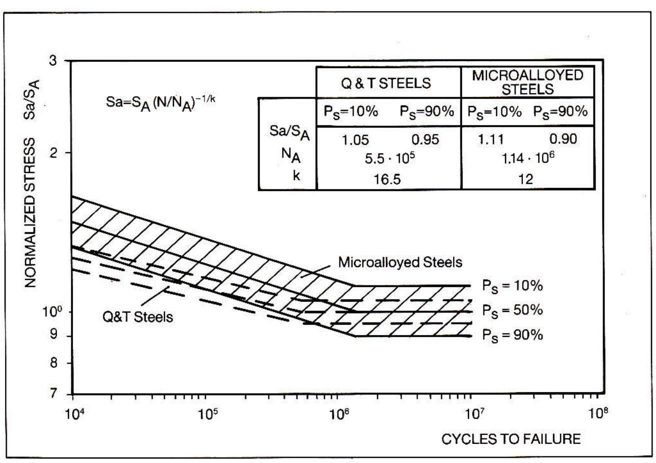
The patterns observed, standardized with respect to the fatigue limit S_A of each set of homogeneus data, and the characteristic constant values calculated for various probability of survival values, enable a direct comparison to be made between microalloyed and Q & T steels.

Fatigue behaviour patterns can compared across the entire endurance range by using the parameter SWT = $(\sigma_{max} \cdot E \cdot \varepsilon)^{1/2}$ as proposed by Smith et al. (7). This parameter is often employed as a " damage parameter " in fatigue life prediction models using " local approach " concepts (8).

The curves in fig. 6 illustrate the similarity of the fatigue behaviour of the three 900 MPa strength class Q & T steels. This is fully in agreement with results of the tensile stress tests (Table 2), and the fatigue parameter values set out in Tables 3 and 4.

Fig. 7, too, shows that microalloyed steels M2 to M5 have a virtually identical fatigue life expressed in terms of SWT parameter.

Fig. 5 - Uniform scatter band of microalloyed and Q & T steels.



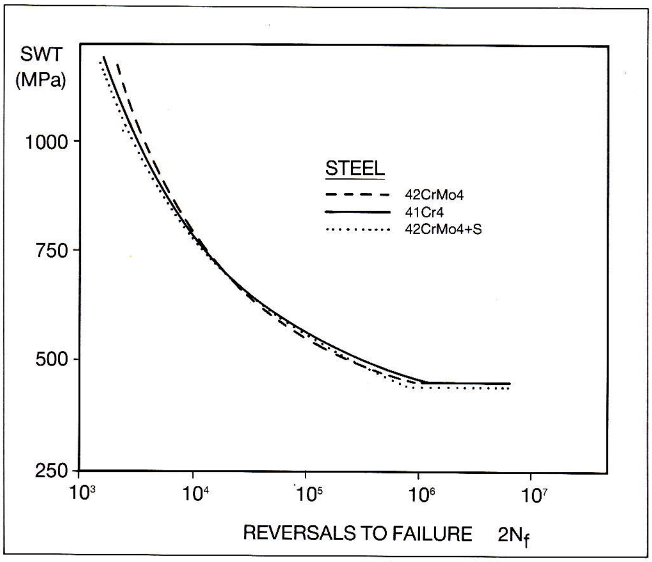
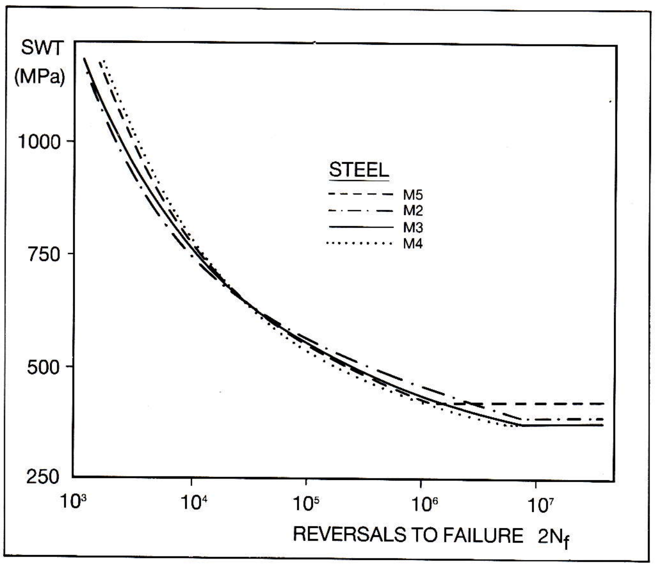


Fig. 6 - Relation between S.W.T. parameter and reversals to failure fot Q & T steels.

Fig. 7 - Relation between S.W.T. parameter and reversals to failure for microalloyed steels.



This is not predictable directly owing to the significant difference in their strengths (Rm = 800 to 940 MPa), ductility (Z = 45 to 67%) and microstructural values (Table 5).
Steels M2 and M3, in particular, with their low C and high Mn and their satisfactory toughness in KCU (Table 2), display almost identical fatigue behaviours despite their microstructural differences in bainite and ferrite content, ferrite grain size $d\alpha$, and perlite lamellar interspacing So (Table 5). Lastly, figs 6 and 7 provide further evidence of the similar behaviour of microalloyed and Q & T steels.

The conclusion to be drawn from these experimental results, therefore, is that an automated plant offering easy control of the process parameter values can be used to obtain from materials of suitable composition a good compromise between strength (i.e. fatigue endurance) and toughness. As a result, this family of steels can also be used in the manufacture of components subjected to particularly heavy stresses.

Purpose-oriented choice of a microalloyed steel component

A new design philosophy neatly summed up in the expression " fitness for purpose " has been making great headway in recent years, in the automotive field as elsewhere.
According to this approach, which is widely adopted in the aircraft industry, the selection of materials for the main mechanical components of a vehicle are determined by the mission they will be required to perform during their service life.
Sophisticated calculation methods and experimental techniques have offered the designer this possibility, since in both the investigation and the monitoring stage they provide him with an extensive coverage of the " environment " (stress field loads, temperature, ambient conditions, etc. as a function of time) within which critical vehicle components will be operating.
Precise definition of these boundary conditions enables purpose-oriented choices to be made between commercially available materials in terms of their cost-performance ratios.

As far as the microalloyed steel in bars forming the subject of this paper are concerned, it has already been shown that their main tensile and fatigue characteristics are similar with those of the Q & T steels normally used as a benchmark. Their typical metallurgical structure, however, being mainly composed of perlite, does not allow them to attain toughness values comparable with those typical of Q & T steels (Table 2), and in some cases essentially brittle failures may occur even at room temperature. On this subject it is interesting to note that, particularly in Italy with its long-standing foundry tradition, nodular iron, thanks (inter alia) to the adoption of effective surface treatments (e.g. rolling) capable of upgrading an intrinsically weaker material, has in many cases replaced Q & T steels in the automotive industry (e.g. the crankshafts and con rods used in low-stress engines illustrated in fig. 1). Even parts regarded as " safe from attack " by cast iron, such as front suspension components, have been made out of this material which, by comparison with steel, is intrinsically defective and more brittle.

Designers therefore, with the backing of prediction methods and " reassured " by appropriate experimental checks, are adopting " brittle " materials such as nodular iron, not only for components whose brittleness is not enhanced by the type of stresses to which they are normally subjected, but even those, such as suspension components, for which impulsive loads are part of the usual pattern of the forces acting on them.
Microalloyed steels with a carbon content of more than 0.4% and thus able to ensure adequate strength and surface hardness levels after either nitriding or induction hardening can be used to a sufficient extent as substitutes for Q & T steels for both crankshafts and con rods, where fatigue resistance is the decisive requirement.

More complicated situations are presented by suspension parts, such as wheel hubs, steering, knuckles. The toughness levels currently required of the quenched and tempered steels employed for most of these components, however, are virtually beyond the reach of the microalloyed steels now available. It is obvious, therefore, that continued application of today's specifications greatly prejudices the use of these materials on a massive scale.

Particular procedure are thus needed to assure an a priori assessment of the minimum toughness level required to the material, as a function of its application on a given component whose operating conditions are known or can be reasonably supposed.
The influence of repeated impact loads on endurance can be evaluated experimentally on components (9) or test specimens representing their significant areas.

Tests on this kind on specimens of type 48 MnV3 microalloyed steel (10) have shown that, despite its much lower toughness compared with Q & T steels, the number of impacts it can withstand is sufficient to allow it to be used in the manufacture of reliable components. The amplitude and frequency of these impacts were worked out experimentally as a function of the vehicle's mission. In the case of a commercial vehicle steering knuckle, an analysis conducted with prediction models and then checked experimentally (11), showed that it could be made of microalloyed steels with strength levels on a par with those requested for Q & T steels (fig. 8). In terms of fatigue resistance, indeed, it can be seen from fig. 8 that the component is actually oversized, since it can be used over very long distances (> 10^6 km), even on particularly severe conditions (corrugated road).

In this specific case, therefore, reduction of the minimum strength level required on the drawing (say from 880 to 800 MPa) would not result in fatigue life problems, and would allow the use of microalloyed steels, e.g. M2 and M3 (Table 2), whose toughness (KCU = 58 J/cm^2 at room temperature) meets the standards set by the Q & T steels used in the manufacture of this safety component.

It can thus be asserted that application of microalloyed steels in the automotive industry will be accorded greater recognition if an optimised choice of the material to be used for a given component is always sought.

In Germany, for example, where these steels are extensively employed, type 49 MnV3 (Table 6) has completely replaced Q & T steel in the production of VW, Audi and Daimler Benz (car) crankshafts, while one-third of those used on commercial vehicles were already being made in this material as long ago as 1982, thanks to the advantages it offered in terms of process economies and better machinability (12).

In France, too, there has been a growing application of microalloyed steels on the part of the automotive industry (Table 6), while in Italy they have been used for car crankshafts and differential shaft for several years, and new applications (wheel hubs, knuckles, conrods) are at an advanced stage of experimentation (13).

Fig. 8 - Comparison of predicted fatigue lives of steering knuckle.

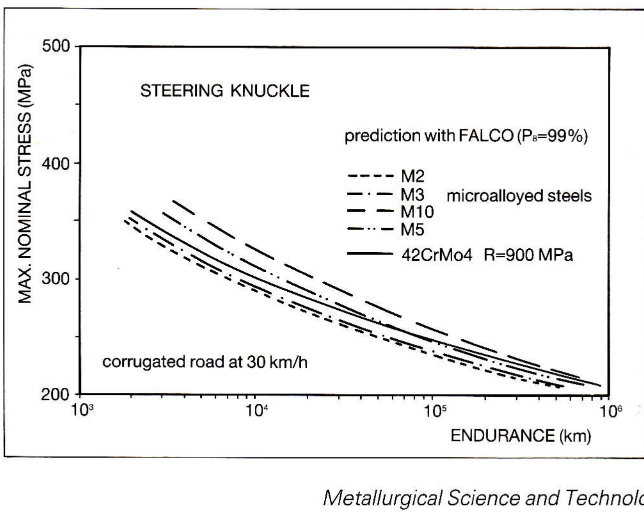


TABLE 6 - Microalloyed steel automotive components already being manufactured or at the stage of experimentation

STEEL	COMPONENT	CUSTOMER
HV080	crankshaft	FIAT
	conrod	
	U-bolt anchorage	
48MnV3	conrod	FIAT
	differential. shaft	
	steering knuckle	
49MnVS3	crankshaft	AUDI DAIMLER BENZ VOLKSWAGEN FORD Europe
	conrod	
SAE 1045+V	conrod	MITSUBISHI Motors
	steering arm	
METASAFE S800 METAFE S1000 METASAFE F1200	reaction road	RENAULT
	Wheel hub	
	Anti-sway bar	

Conclusions

The results offered by experimentation and the use of prediction methods in the study of various materials and individual components have shown that there is a good case for the replacement of Q & T steels with microalloyed steels (provided their microstructure is appropriate) in hot-forging applications. This step requires the adoption of automated presses to obtain optimized material specifications through close monitoring of the main process parameters.

Purpose-oriented selection of the right material for a given component, therefore, allows this class of steels to be employed in innovative applications without prejudicing the quality and reliability of the final product.

The potential thus assured by the optimum choice of these three elements (material, component and plant), however, can lead to the levels of innovation possible and awaited in the automotive sector only through integration of the activities of producers, processors and users.

To this end, the Centro Sviluppo Materiali (CSM), the Fiat Research Centre (C.R.F.), ILVA steel and Teksid's Hot-forging and Cold-Forming Division are currently working together to explore the possibility of obtaining substantial economic benefits from the use of microalloyed steels also in other technological sectors. This collaboration has been established within the framework of a multipolar programme.