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Current challenges in material choice for high-performance engine crankshaft

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Abstract

The segment of high-performance cars will progressively deal with the trade-off among cost saving, high performances and quality due to customers' higher expectations and the regulations requests for higher-power, safer, more intelligent and environmentally-friend cars. Dealing with these complicated systems requires additional designing phases and optimization of all components in terms of performances, reliability and costs. Among such mechanical parts assembled in an Internal Combustion Engine (ICE), the crankshaft is one that still requires extra attention regarding materials choice, thermal treatments, producing processes and costs. The aim of this work is to analyze the actual and future scenarios about the material choice for the crankshaft of high-performance engines. In particular, what is considered here is the actual development and improved quality reached by base materials and manufacturing technologies for this critical component of the engine. In this context, different materials are analyzed, together with surface hardening techniques, thermal treatments and their technical and cost saving potentials.

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Keywords: ; mechanical component, material selection, crankshaft, steel

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1. Introduction

The need to deepen the aspect of costs savings while designing and manufacturing mechanical components is becoming a feature of hard management by automotive manufacturers. In fact, they must offer products that not only

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should guarantee high performances and elevated standards of quality, but also be attractive for a demanding clientele asking for safer, more powerful and intelligent cars. Moreover, all these aspects must be compliant with the more and more stringent regulations for vehicles imposed by governments and with the new procedures for the control of emissions, such as the adoption of new Real Driving Emission (RDE test) and Worldwide Harmonized Light Vehicle Test Procedure (WLTP test) (as Commission Regulation 2016/427suggests). Internal Combustion Engines (ICE) solution is still the main power technology adopted for urban vehicles, and plays a critical role on the matters presented above; therefore, when it comes to ICE development, OEMs need to carefully consider their design and construction. On one hand engines should develop high powers and torques, while on the other hand they have to keep low levels of fuel consumption and emissions (95 g/Km $\mathrm{CO_2}$ emission by 2021, which means fuel consumption equal to 4.1 l/100km of gasoline and NO_x), as well as being cost-effective for OEMs. Therefore, the way that is currently going to be followed by automotive companies is to produce engines with higher specific powers, low weight and optimized thermal performances. Nowadays, hybrid supercharged/turbocharged ICE coupled with electric machines are more and more compulsory options among OEMs because they allow the use of compact and downsized thermal units, thus lighter (although electric machine systems are considerably heavy), or in any case better weight-balanced.

This is true also for high-performance car makers, which are heading towards the production of sophisticated hybrid vehicles with electromechanical systems that affect both the powertrain behavior and the vehicle dynamics. Moreover, time schedule issues sum up to these technical complications, causing to rush not only the design phase of components themselves, but also the production processes as well as the overall quality (Arcidiacono (2004)).

Considering all the above, the crankshaft is one of the most complex and functional component when dealing with ICE, and requires strategic investments in its production. This is a critical component for the ICE due to the high loads coming from the mixture combustion, the inertia of pistons and connecting rods and from the transmission assembly. In order to safely avoid the shaft to catastrophic failures caused by stresses, a very robust and proper design project has to be done.

Crankshafts for road vehicles are generally made by casting irons or forged steels. Considering high performance engines, the choice often falls on forged steels because they guarantee high mechanical properties, as studies have shown (Williams and Fatemi (2007), Zoroufi and Fatemi (2005), Nallicheri et al. (1991)). However, Menk et al. (2007) and Druschitz et al. (2006) revalued the cast irons due to improved casting processes and developed new type of austempered iron (MADI machinable austempered ductile iron) respectively – the article will take into consideration the steel forged crankshaft only. More specifically, the aim of this article is to highlight the current design and implementation scenario of a component such as the crankshaft, considering the entire production process from the design phase to the realization one, giving prominence to the technical aspects, volume of production and costs.

The design phase of the components is guided by several constraints. Basically, the first steps of the project are related to the definitions of the crankshaft configuration, starting from the engine layout – that means linear or V shape, the stroke length value and the maximal length of the crankshaft. The values of the combustion pressures, thus the value of the generated forces, must be well defined in the early stages, as well as the inertia forces of the piston, those of the connecting rods and the maximum revs. At this stage, the values of the mechanical characteristics needed for the project are at least identified. Moreover, other several critical points shall be considered for the best design of the crank; the vibration modes generation is relatively important, but this aspect will be no further investigated. Anyhow, it is interesting to concentrate on the possible solutions related to the development of a crankshaft with high mechanical properties. The simplest way to counteract high loads would be working on the geometry of the crankshaft and increase its dimensions. This is a hazard because in such way the moment of inertia and the mass become higher, and so are the friction losses and the power required for the acceleration of moving components, as reported by Cevik et al. (2009). A second option is related to the possibility of shaft elongation to increase the resistant section, avoiding the modification of the journals in terms of diameter size. This is a risk because of the decrease in rigidity of the shaft and the extension of the length of the engine affecting the room available. In literature many scientific papers developed some design approaches using methodologies such as TRIZ (Arcidiacono et al. (2016)) and Axiomatic Design (Arcidiacono et al. (2017)) to guarantee the reliability and robustness of the system during design phase. Through these approaches it could be possible to develop an optimized design solution for the chranshaft. Otherwise, the designers can concentrate their efforts on multi-objective optimization in materials selection (Cavallini et al. (2013), Giorgetti et al. (2017)) or deal with material, choosing for better and stronger materials while keeping and optimizing the geometry of the components with very few modifications.

In this paper, the use of new forged steels among the actual high-performance vehicles present on the market is investigated. In particular, Quenched and Tempered (QT) steels, Microalloy (MA) steels, and steels with Bainitic structure with different surface conditioning (e.g. thermal nitriding, induction hardening or conditioning through rolling fillets) are considered. Other technologies such as casting or wrought machining will not be considered.

2. Current technologies and materials utilized

2.1. Quenched and Tempered steels

As said, the variety of steels used for the realization of crankshafts includes QT, MA, and Bainitic. Within these categories of steels for high performances engines, it is possible to restrict the field of options and focus onto some examples, per each category, that are representative of the state of art of actual world engines production.

QT steels are the most widely adopted solution for crankshafts, characterized by high mechanical properties (over 900 MPa for UTS) – and high fatigue performance. These steels are developed through an austenitization treatment combined with rapid quenching, followed by one or more tempering heat treatments. As a result, these steels feature a hard and tempered martensitic structure with high mechanical strength.

Raedt et al. (2012) suggest that for applications requiring deep hardenability, chromium, molybdenum or nickel might be added. In table 1 some typical steels of this category and their chemical compositions are summarized.

Table 1. Examples of QT steels with chemical composition ranges.

	C%	Mn%	P%	S%	Si%	Cr%	Ni%	Mo%	V%	Fe%
AISI4340	0,38-0,43	0,60-0,80	≤0,035	≤0,040	0,15-0,35	0,70-0,90	1,65-2,00	0,20-0,30	-	bal.
42CrMo4	0,38-0,45	0,60-0,90	≤0,025	≤0,035	≤0,40	0,90-1,20	-	0,15-0,30	-	bal.
31CrMoV9	0,27-0,34	0,40-0,70	≤0,025	≤0,035	≤0,40	2,30-2,70	0,15-0,25	-	0,10-0,20	bal.

To increase the fatigue limit of such steels, for high-loaded crankshaft applications as in sport vehicles, a nitriding thermal treatment is done after the tempering treatment. The nitriding determines high surface hardness (above 750 HV) and increased mechanical properties on the surface, but maintains the same material alloy toughness in the shaft core. This is done mainly to improve fatigue resistance behavior as will be explain afterwards.

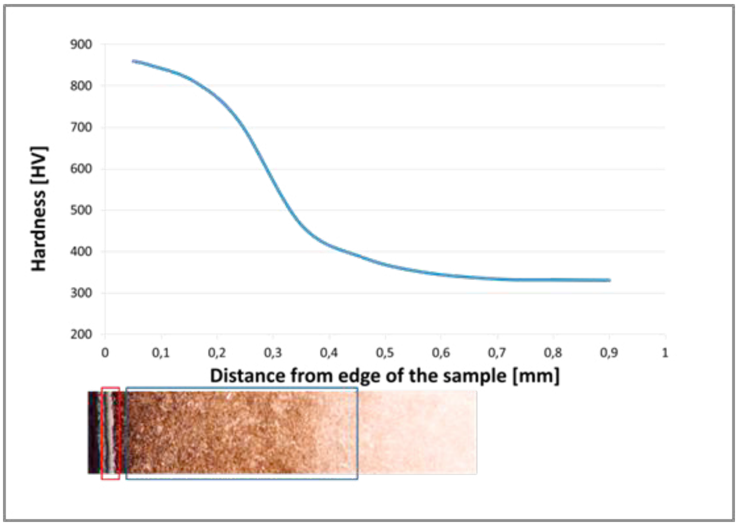

Fig. 1. Typical micro hardness curve example of a Quench and Tempered nitrided steel and corresponding microstructure; red area is the “white layer”, blue one is the “diffusion zone”.

The nitriding process involves the use of nitrogen as a diffusing element, which forms some intermetallic compounds with ferrite and cementite when the material is left between 500 and 580 °C for some tens of hours (nitrides and carbonitrides: γ_Fe_4N phase or ε_Fe_2N phase) in the so-called compound layer or "white layer". This external layer is generally removed from the surface by a grinding process because it is brittle. In fact, if some small debris is detached from the surface of a journal, it can generate the seizure of the bearing, thus compromising the rotation of the shaft. Moving inwards from the material surface edge, typically for a depth of 0,1–0,5 mm, the nitrogen diffuses and generates a modified structure or "diffusion zone". This region, according to Biró (2013), is made up of stable nitrides generated by the reaction of the nitrogen with the nitride-forming elements, such as chromium, vanadium, molybdenum, tungsten, and aluminum. In Fig. 1 a typical micro-hardness curve of a nitrided steel is drawn together with the corresponding microstructure; red and blue colors are used to highlight the "white layer" and the "diffusion zone" respectively.

One of the techniques used for the nitriding process entails controlling a gas flow of ammonia, dissociated ammonia ($NH_3 \leftrightarrow N + \frac{3}{2}H_2$), hydrogen, and nitrogen into a batch furnace that encloses the components, allowing the diffusion of the nitrogen into the steel. This thermochemical process is not easy due to the number of parameters involved (temperature of treatment, steel alloy chemical components, amount of nitrogen available) as Weymer (2009) and Mittemeijer (2013) explained; however, it is possible to say that the factor allowing for the nitriding is the nitriding chemical potential that is established by controlling the flow of $NH_3 - H_2$, which is at fixed chemical composition in the oven. This potential is defined as

$$r_n = \frac{p_{NH_3}}{{p_{H_2}}^{3/2}} \tag{1}$$

where p_{NH_3} and p_{H_2} are the partial pressures of the gas components. As said, the gas must be kept into a constant stream; if the generated atmosphere is stationary, NH_3 will locally decompose at the surface in a way that will allow it to realize its equilibrium with its thermal decomposition in the atmosphere, thus losing control of the nitriding process.

Because nitriding does not involve neither heating into the austenite field nor quenching, nitrided components exhibit minimum distortion and excellent dimensional control (Schneider (2013)), although for high depth of nitriding treatment some distortions in long shafts may be present, causing movements in the forms of twisting and bending. In such cases, a pre-treatment of stress relief (at higher temperature than those of the nitriding process) must be done for some hours to minimize those effects. The depth of the nitriding layer, after the final grinding procedure to remove the white layer (which is very brittle and hard, especially after long treatment when it is affected by high porosity), can vary from 0,2 to 0,4 mm but may also reach 1 mm for very high-power engines such as those for sport applications; to reach these depths, nearly 100 hours of gas treatment could be required. Fig. 2 from Rakhit (2000) shows the nitriding depth growth, which is a logarithmic function of time.

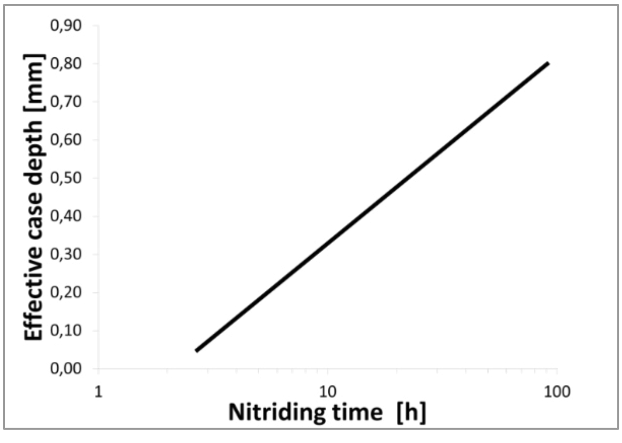

Fig. 2. Relation between time of treatment and effective nitriding case depth.

The main advantage coming from the nitriding process in terms of fatigue resistance, particularly with rotating bending, is the generation of a compressive state into the first cents from the surface due to the diffusion of nitrogen and the creation of precipitates. As explained before, the gas nitriding is the most diffused method, but there are other techniques as the salt bath method (whose utilization is limited due to the presence of toxic cyanide into the solution) or a plasma-based process that is growing up in its applications because of lower process temperatures compared to gas nitriding, resulting in much less distortion problems and the possibility to nitride materials which would result difficult to process using other methods, e.g. stainless steel (Holm and Sporge (2009)).

Since nitrogen diffuses into the whole surface of the shaft and it is a thermochemical treatment, the geometry nearby webs and journals should be a very simple fillet. In Fig. 3 a longitudinal section view of a pin from a QT crankshaft is shown: the area was surface treated by nitriding process.

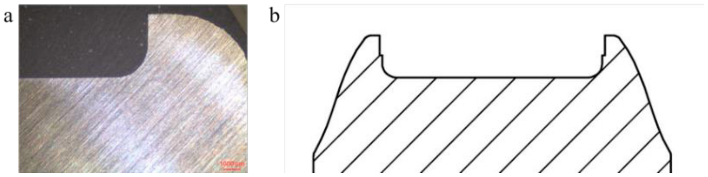

Fig. 3. Geometry of QT and nitrided steel crankshaft journal; (a) real pin section, (b) longitudinal section view of a pin.

It is interesting to schematize the whole flow process of realization of a typical crankshaft considering the technologies presented before, from raw material to finished product. Looking at Fig. 4, the process for a QT nitrided is quite complex. Firstly, there is a thermal treatment chain after forging that generally requires a normalizing procedure to allow the microstructure grain control, then a quenching and tempering treatment to achieve the final desired tempered martensite. After the first gross machining phases, a stress relief is performed to cut off the internal stresses generated by the quench and machining operations. After that, the first grinding machine is needed to mechanically activate the surface for the nitriding process. After the nitriding, the finishing operations are performed with second grinding and lapping of mains and pins journals. This is a summary of the macro phases of the process: it is easy to see how the flow process is constantly interrupted, going from the machining line to the thermal batches.

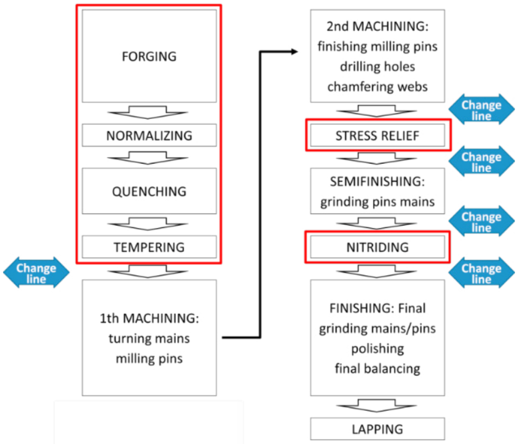

Fig. 4. Flow chart for a QT and nitrided steel from forging phase to final lapping. Squared in red are the thermal treatment phases. "Change line" label means that the workpiece goes out from a production line and enters a one that is different from the previous, or that is delivered to a supplier.

2.2. Microalloy steels

Another family of steels that is deeply different in terms of chemical properties, production process and microstructure compared to the QT family is the MA one. These manganese steels are ferritic pearlitic, and are realized mainly by adding small amount of niobium, vanadium or titanium (less than 0,10%) to carbon-iron alloy, which form precipitates (carbides, nitrides or carbonitrides) that prevent dislocations to further move, act as grain refinement, and possibly control transformation temperature, allowing for higher mechanical properties as Davis (2001) explained in his work. Titanium forms stable nitrides which are insoluble in austenite phase, and keeps the grain growth controlled at the same time ((Halfa (2014)). It is important not to exceed with the addition of titanium in presence of nitrogen because excess of it can be detrimental for the creation of titanium nitride (TiN) which affects material toughness; the limit ratio between these elements is $\mathrm{Ti} \div \mathrm{N} = 3{,}42$ as suggested by Li and Milbourn (2013).

In table 2 some examples of typical MA steels used in crankshaft applications are reported.

Table 2 Examples of MA steels with chemical composition ranges.

	C%	Mn%	Si%	N%	P%	S%	Nb%	Ti%	V%	Fe%
38MnVS6	0,34-0,41	1,20-1,60	0,15-0,80	0,01-0,02	≤0,025	0,020-0,060	-	-	0,08-0,20	bal.
48MnVS3	0,42-0,49	0,60-1,00	0,15-0,80	0,01-0,02	≤0,025	0,020-0,060	0,04-0,06	≤0,01	0,08-0,20	bal.

Vanadium can be fully dissolved in austenite (so lower reheating temperatures are needed during forging, compared to other additives) and precipitates in form of carbonitrides (V-C,N) particles in pro-eutectoid ferrite as well as in ferrite lamellae of pearlite during cooling. It can provide significant increase in strength regardless the carbon content (Sage 1986). This is an important property because it allows to keep the carbon content low, thus avoiding embrittlement and promoting weldability.

Finally there is niobium, which modifies the mechanical properties of the alloy by means of three methods. As previously said, these methods are the grain refinement, the formation of carbonitrides (which precipitate in austenite) and the decrease of the austenite-to-ferrite temperature transformation (allowing for the increase of tensile and ultimate tensile strengths). As highlighted in Fig. 5 by Klinkenberg (2007), niobium determines a strength increase of the steel also with low levels of alloying element compared with others.

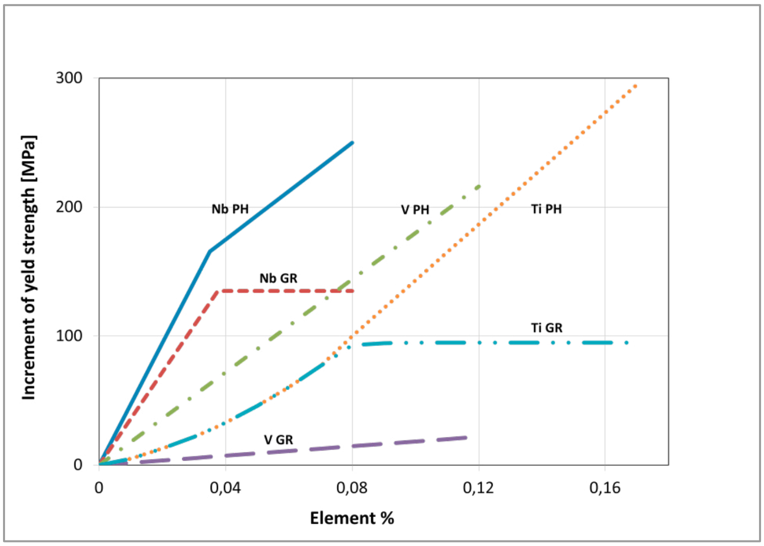

Fig. 5. Effect of alloying element in the increment of yield strength. “PH” indicates the effect due to precipitation hardening; “GR” indicates the effect due to grain refinement. Notice the niobium efficiency, which reaches the same results in strength compared to other alloying elements even with less percentages of addition to the base material.

The combined addiction of niobium and titanium controls the austenite grain size during the austenitization phase. Studies done by Klinkenberg (2007) on optimized MA steels showed that dispersion hardening reduces the toughness of the forged part, which can be compensated by control of both the grain size and carbon content. The drawback effect (steel's reduced strength) was compensated by an addition of niobium which supported the precipitation together with vanadium and doubled the total quantity of precipitates (Zhang et al., (1988)).
The thermal treatment that allows the realization of such structure with the desired characteristics is different from the many ones adopted in QT steels. Indeed, after the forging phase a single controlled cooling is performed instead of several heating and cooling phases. This gives an important advantage in terms of energy saving, time needed for the process and, as a direct consequence, costs. In Fig. 6 the two example schemes of the thermal treatment phases for a QT and MA steel are reported, in which an appreciable difference in number of heating and cooling phases is evident, as well as the time needed for the two processes. Since this type of steels do not need to be quenched during the microstructure formation, the level of distortion that can be present into the crankshaft after the following machining phases is less compared to that of QT forged parts. This is an important aspect to be considered for the design phase as well, since it allows the designer to diminish the number of overstocks. Less material as stocks means that there are two types of savings: the first one is related to reduced raw material utilization, while the second is about the chance to facilitate the machining operations.

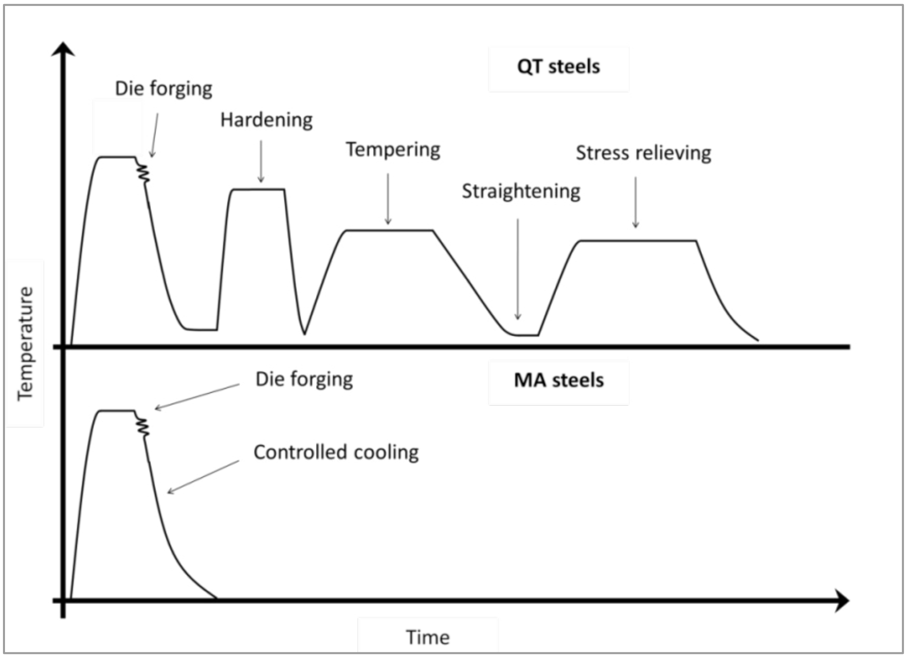

Fig. 6. Time and temperature history of a quench and tempered steel (top scheme) compared to a microalloy one (bottom scheme).

Generally, it is possible to locate the MA in the 750-1100 MPa class for tensile strength, very close to the QT steels (Korchynsky and Paules (1989)). Moreover, vanadium MA steels have reached comparable strength levels equivalent to QT steels thanks to improved design and forging process (Milbourn 1988). Similarly, vanadium MA steels present fatigue resistance levels comparable to QT steels, keeping the same hardness level but a lower toughness value, although it is enough for crankshafts, which are cyclically fatigue-loaded in service (Naylor (1998), Engineer and Huchtemann (1996)). The good fatigue resistance behavior of these steels was also underlined by a study of Hoffmann and Turonek (1992), showing that fatigue strength of two vanadium (0,06-0,08%V) MA grades reached the fatigue strength of the QT carbon steel (SAE 1050) and QT alloyed steel (SAE 4140). In table 3 the fatigue results from complete reverse bending test are reported. Each data point was the average of six to eight samples.

Table 3 Reverse bending fatigue strength comparison among QT and MA steels.

Steel grade	Steel family	Fatigue strength [MPa]
SAE 1050	QT	520
SAE 4140	QT	785
MA1	MA	490
MA2	MA	461
MA1 and fillet rolled	MA	706
MA2 and fillet rolled	MA	579

In crankshaft applications, whenever material from this steel family are deployed, induction hardening is generally applied as well to generate an external hard phase by martensitic transformation, which makes the component strong enough to support wear and increase mechanical characteristics. The area affected by the treatment is present both in the center of the journal (where the bearing works) and in the fillet area. The hardening also affects the fatigue resistance behavior by generating a compression state in the surface layer that prevents nucleation and crack propagation (Hayama (1975), Medlin et al. (1999), Grum (2003)). In Fig. 7 an example of an induced tempered pin of eight-cylinder crankshaft is reported. The key elements in this picture are the tempered area affecting the central zone of the pin and the area of the groove. This mechanical feature is typical of a crankshaft that has undergone a rolling process acting as reinforcement; however, in this case, since the martensite is extended also to this area, the groove was probably used for the tools passage only. Another possibility could be that the groove was machined in a previous crankshaft project which was designed for a rolling process, which was changed later on to induction hardening.

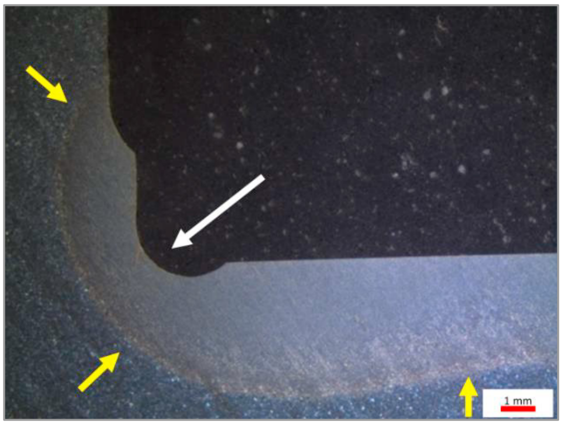

Fig. 7. Stereoscopic image of an induction hardened journal pin section etched with Nital 2%. Yellow arrows point at the reinforced area by martensitic transformation that follows the bearing profile and the groove. Notice the geometry of the groove.

As mentioned before, another technique in the crankshaft production for the reinforcement of the fillet area is the rolling process. This is done through plastic deformation of the alloy due to rollers action. They push with high loads, sometimes above thousands of newtons all around the journal.

Specifically, it is possible to attribute the beneficial effect of the rolling to an increased plastic deformation in the rolled zone which ensures both a compression state on the surface (preventing crack nucleation) and a work hardening effect (that brings along also a martensitic transformation of retained austenite with high hardness values). Also, rolling on the fillets has a leveling action of the surface peaks, thus determining higher surface quality and less stress-concentrated zones ((Cevik et al. (2012)).

All these effects contribute to the increase of the fatigue limit, as many studies have shown (Ko et al. (2005), Matsuda et al. (2011), Schaal et al. (2003), Bao and Liao (2013), Bao et al (2011)).

Also in this case, it is interesting to report the phases of the crankshaft production done by MA and induction hardened steel. Fig. 8 immediately shows significant differences from the QT flow process (Fig.4). The number of thermal treatment phases is drastically reduced and the machining operations result simpler. The process flow is more constant, with a few interruptions only due to the change. The big advantage of the induction hardening as a surface treatment is that it can be done in line, thus crankshafts made with this solution can be done with a takt time of few minutes allowing for high volumes applications.

The benefits in costs saving have been evaluated by Hoffmann, J. H., Turonek (1992) who compared two vanadium MA steels with carbon steel SAE1050 and alloy steel SAE 4140 for high-performance four and six cylinder crankshafts. Fig. 9 (Hoffmann, J. H., Turonek (1992) reports the distribution of costs among material, forging, heat treatments, and machining for a 6-cylinder crankshaft per 3 yearly volume class production. The material cost of the MA (30MnVS6) steel is about 2% less than the QT (SAE4140) grade. The forging cost is about 7% less for the MA steel. The significant cost saving for the MA steel is to be found in the machining, especially with increased production volume. At an annual volume of 300,000 parts, the machining cost of the MA steel is about 28% lower than that of the SAE 4140. This study concluded that the use of MA steel could reduce the cost of the finished part by 11-19% compared to the same part made with QT alloy steel.

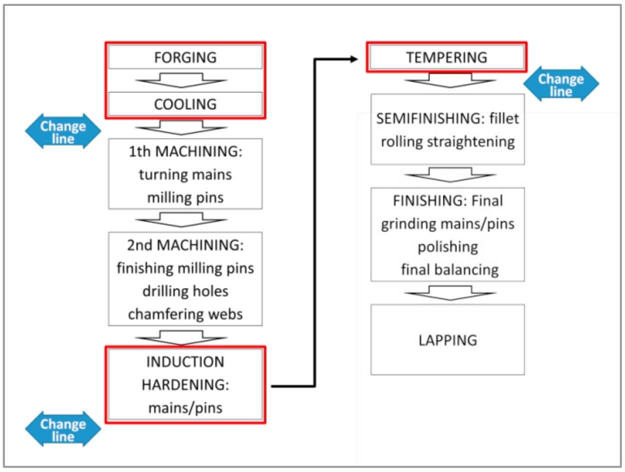

Fig. 8. Flow chart for a MA and induction hardened steels from forging phase to final lapping. Squared in red are the thermal treatment phases. “Change line” label means that the workpiece goes out from a production line and enters a one that is different from the previous, or that is delivered to a supplier.

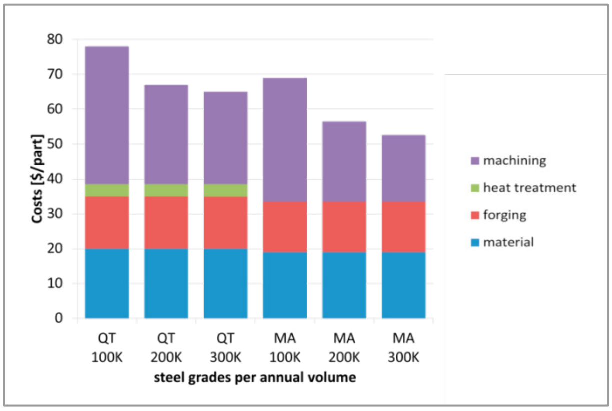

Fig. 9. Costs saving potential of a MA steel compared to QT one, detailed per class per each annual volume production of a 6-cylinder engine.

2.3. Microalloy steels: critical factors

To sum up, the state of art of technology available to produce crankshafts in vehicles is between QT plus nitriding steels and MA plus reinforced surface treatments. This last solution has several advantages compared to the QT steels, like the possibility to cut down the thermal treatments for forging, the possibility to speed up the process by using in-line surface reinforcement techniques properly tuned, the opportunity by the designers to reduce the overstocks due to less distortion (since no quenching phase is required) and increase the volumes of production. However, soon MA steels could be not enough for the realization of crankshafts. This is especially true when considering the trend of increased specific powers of new ICEs that will certainly require higher mechanical characteristics for their components. Thus, at this stage the only available alternative is the utilization of QT and nitrided steels together with the losses in terms of energy, cost and time due to the thermal treatments and the higher number of productive process interruptions. Thinking about suitable steels for crankshafts production from a cost perspective, it could be interesting to focus on the utilization of bainitic structures. These steels can be found in applications for crankshaft production in low performance engines, in some gears with nitriding reinforcement (or induction hardening) and engine rails.

2.4. Bainitic steels

Bainitic transformation has both the features of martensite transformation and perlite transformation; the former is developed between two specific temperature limits inside which bainite can develop, that are Bs (bainite start) and Bf (bainite finish), while the latter is a time depending transformation. This means there is an incubation time and a completion time for the bainite generation. All these parameters are strongly affected by the alloying element concentration. When increasing the carbon content, the Bs temperature decreases as demonstrated by Steven and Haynes (1956) and Garcia-Mateo et al. (2005), while reducing alloying element concentrations speeds up the time of transformation – which means accelerating the kinetics of transformation.

There are several studies dealing with the classification of bainite microstructures (Irvine and Pickering (1957) Habraken and Economopoulos (1967), Lui, et al. (1987), Oblak and Hehemann (1967)), from which the standard definition for upper bainite and lower bainite can be retrieved. The former consists into a gross microstructure of non-lamellar ferrite plates and carbides of cementite Fe_3C that develop a lath structure together. The plates grow without a diffusion mechanism, and the excess of carbon is then portioned into the remaining austenite (Hehemann (1970), Takahashi and Bhadeshia (1990)). The latter is finer and generated by ferrite and carbides at different chemical compositions and distribution; in fact, the ferrite cluster forming evolves into shaves, inside which a precipitation of carbides in acicular shape (with characteristic angle of 50-60 degree) orientation appears.

Unfortunately, dealing with these types of steels is a problem when the application demands high fatigue properties and toughness, because the cementite is brittle. It is found that by increasing the amount of silicon, a bainite microstructure free of carbide can be obtained (Bhadeshia (2005)). The carbon, together with the silicon, can be solved into austenite, bringing it to room temperature.

The mechanical characteristics of these kinds of steels are very good. Depending on both the chemical composition and how the steel is cooled down from the austenite zone, the yield strength can range from 450 to 950 MPa and the UTS from 530 to 1200 – which is very close to the values reached by QT steels (Dedier (1997) and Raedt (2012)). However, for crankshaft application the mechanical characteristics are into a narrow range, as can be easily checked from Fig. 10, in which the areas covered by the different types of steels are reported, considering the UTS and Yield strengths.

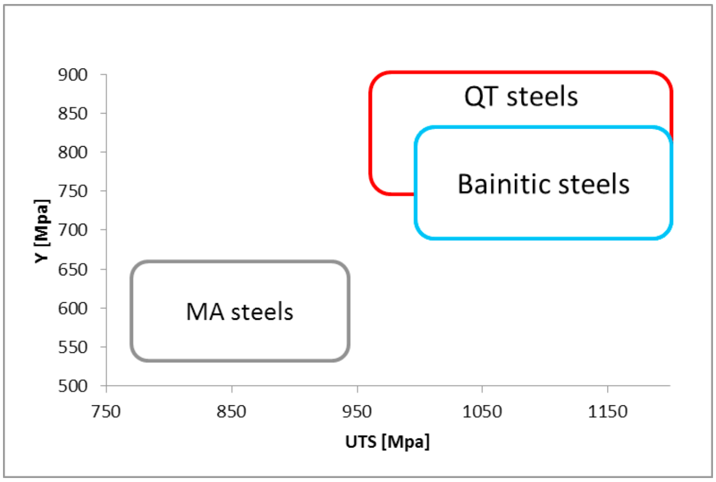

Fig. 10. Mechanical ranges for UTS and Yield for QT steels, MA steels and bainitic steels.

In table 4 some typical bainitic steels utilized for the realization of crankshafts are reported, while Fig. 11 shows the optical and SEM micrographs of the bainitic steel 18MnCrSiMoVB6.

Table 4 Examples of Bainitic steels with chemical composition ranges.

	C%	Mn%	Si%	Cr%	S%	Ni%	Mo%	Cu%	Others%	Fe%
25MnCrSiVB6	0,23-0,32	1,20-1,80	0,60-1,30	0,60-1,20	≤0,10	≤0,40	≤0,30	≤0,40	0,2V, Ti, B	bal.
40SiCrMoB4	0,32-0,42	0,50-1,30	0,60-1,30	0,60-1,20	≤0,10	≤0,40	≤0,30	≤0,40	Ti, B	bal.
18MnCrSiMoVB6	0,19-0,23	1,3-1,85	0,60-1,30	1,30-1,90	≤0,10	≤0,40	≤0,30	≤0,40	0,2V, Ti ,B	bal.

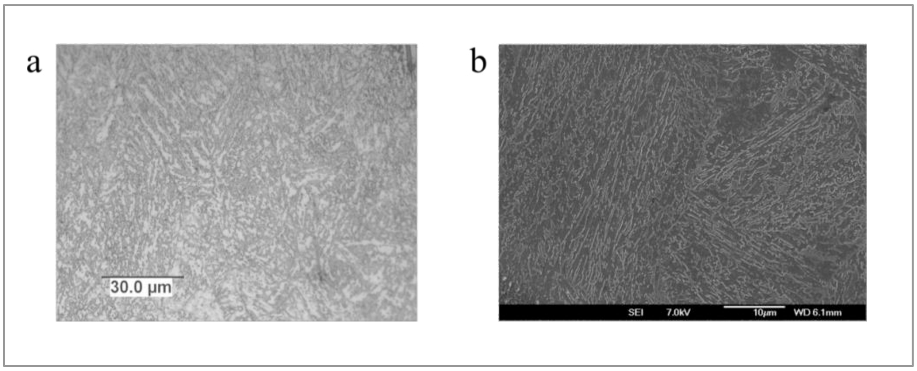

Fig. 11. Microstructure of bainitic steel 18MnCrSiMoVB6; (a) optical image; (b) SEM image.

Like MA steels, also bainitic grades can be cooled down to the formation of the desired microstructure to avoid the costly thermal treatment of the QT steels.

Unfortunately, the cooling phase can be a very critical point for the realization of a forged crankshaft. Indeed, the different thicknesses of the component with massive and slim zones, process interruptions that can freeze a piece under a cooling fan or totally out of its influence, different industrial equipment as conveyor belts, cooling box or fans can alter the scheduled cooling ramp, affecting the mechanical characteristics. Sourmail and Smanio (2013) critically analyzed the effect of cooling conditions on some bainitic grades, evaluating their mechanical properties and transformation kinetics. They demonstrated that fast transformation kinetics is less sensitive to cooling conditions.

This basically means that manufacturers can easily reach the same final mechanical characteristic of crankshafts no matter the type of industrial equipment used or the size of forged parts, when bainitic grades are optimized for low sensitivity to cooling rate. This is reached by lowering the level of alloying elements to increase kinetics of transformation and limiting segregations, as they have showed.

On the other hand, since the quenching phase is eliminated (and so is the risk to have distortions on pieces), a new chance to reduce the oversize of the stocks and save material arises. Furthermore, less material means quicker machining phases and less consumptions of tools, although one potential disadvantage related to the bainitic steels is the machinability, particularly for application like crankshafts in which the machining phase has a relevant impact.

When dealing with surface treatments, these steels can be both surface-reinforced by the nitriding process or induction hardening.

This last technique allows high production volumes in less time compared to the nitriding surface, even if it needs special care during the quenching phase. Indeed, there is the possibility to destroy the bainitic microstructure nearby the martensite in the so called “Thermal Affected Zone”. This fact could generate an annealing of the material, resulting in a strong reduction of the mechanical properties in that area.

While dealing with the gas nitriding process, bainitic steels respond very well to the treatment, reaching higher depths of nitrides diffusion compared to QT steels. In a study done by Lemaitre et al. (2005) three different steels were tested for a gear application. A gas nitriding treatment was done over two QT steels specimens (42CMo4 and 23MnCrMo5mod) and over a bainitic one (25MnCrSiVB6). Table 5 presents the values of the nitriding depth reached by the three steels and the increment of diffusion compared to the 42CrMo4.

Table 5. Nitriding depth at 450 HV 0.3 for three steels.

Steel grade	Steel family	Depth (mm)	Increment on 42CrMo4
42CrMo4	QT	0,33	--
25MnCrSiVB6	Bainitic	0,58	+75%
23MnCrMo5mod	QT	0,42	+27

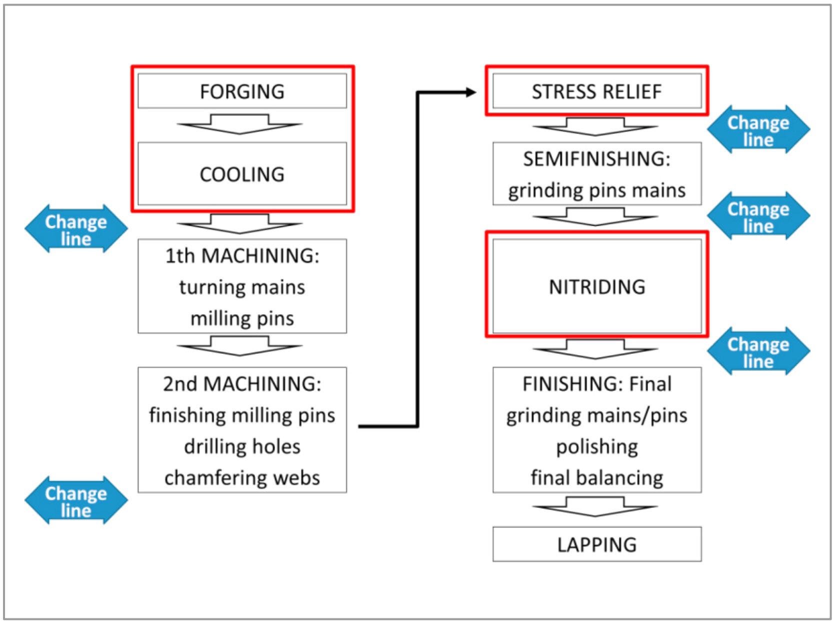

Fig. 12. Flow chart for a bainitic steel from forging phase to final lapping. Squared in red are the thermal treatment phases. “Change line” label means that the workpiece goes out from a production line and enters a one that is different from the previous, or that is delivered to a supplier.

In Fig. 12 a typical process for the realization of a bainitic microstructure crankshaft plus a gas nitriding is schematized. It is possible to appreciate the difference from the QT and MA processes. The cycle is similar to the MA one in the first part (forging and cooling phases) and to the QT one in the second part (nitriding process). Thus, the production process for the crankshaft of a high-performance engine made with bainitic steels presents many of the advantages of the other two class of steels from a process point of view as well.

2.5. Bainitic steels: critical factors

The main critical aspect in the use of bainitic steel is the difficulty of the machining operations. To deal with this aspect, some steel makers decided to utilize sulphur added steels to find a trade-off between machinability and mechanical properties. In fact, the possibility to use a sulphured solution is allowed only if the sulphur level and the direction and distribution inside the part is well controlled. Otherwise, a concentration of sulphurs can drastically affect the fatigue behavior of the component generating a nucleation zone for cracks (Pessard et al. (2009) Cyril et al. (2009)). The other choice involves a modification of the machining process by changing the tools, as reported by Bushmayer (2016). The modifications consist into using different inserts and tuning the machining parameters. Unfortunately, the relationship between these modifications and the productivity and cost of the process has not been yet analyzed in sufficient detail.

An industrial use of the bainitic steels for the crankshaft of high-performance engine needs a deeper characterization of the speed of nitrogen diffusion, of the resulting hardness and of the residual compression state reached after a gas nitriding process. In this way, the potential in terms of fatigue behavior and the nitriding efficiency could be confirmed and managed with precision during the design phase.

3. Conclusions

In this paper, the current and future scenarios about the possible choices of material for crankshafts of high-performance engines have been analyzed, also with an overview on surface hardening techniques, thermal treatments and their technical and cost saving potentials. The state of art dealing with high performance engines is, currently, contended between the QT and nitrided steels and the MA steels. QT and nitride steels, combined with two surface hardening techniques (induction hardening and rolling of fillets) present the top potential in terms of mechanical characteristics and fatigue resistance. On the other hand, the MA steels and induction hardening assure high volumes of production and give advantages in terms of distortion and machining of pieces, due to absence of the quenching phase, while cannot reach higher mechanical characteristics compared to QT steels.

The current trend in increased powers of the future ICE will require stronger components, meaning that the current technologies available for crankshaft production will not be able to satisfy all the projects requirements (e.g.: performance, productivity and costs). In this scenario, the utilization of bainitic steel for forged parts of engine components appears fairly mature. In fact:

- some OEMs have already decided to use these steels for crankshaft production, yet limited to low-performance engines;
- there are studies and real applications of both bainitic steels associated with induction surface hardening or nitriding thermal treatment (this aspect allows the designer to choose for the best solutions without be constrained by technologies themselves);
- the stability of material, which is no more thermally stressed, gives the advantage to save material and help machinability due to less oversized stocks.

For these reasons, the use of this kind of steels for the ICE crankshaft presents a very high potential. Currently, the main aspect that needs further investigation is related to the machinability, which is worse compared to other solutions. Specifically, a study on the impact of the modification in machining parameters or tools, as well as on the relationship between addition of sulfur and fatigue limit, has to be done in future work.

References

Arcidiacono, G., Wang, J., 2004. Automotive Reliability. Quality and Reliability Engineering International 20(2), March 2004, Pages iii-iv.

Arcidiacono, G., Bucciarelli, L., 2016. TRIZ: Engineering Methodologies to Improve the Process Reliability. Quality and Reliability Engineering International Journal, doi:10.1002/qre.1955

Arcidiacono, G., Giorgetti, A., Ciappi, A., 2017. An Axiomatic Design framework for reliability improvement. Proceeding of ICSCA '17 in ACM International Conference Proceeding Series, pp. 214-217. doi:10.1145/3056662.3056707

ASM Handbook, 2008.Volume 15: Casting. AMS international 1-8.

Bao, K., Liao, R. D., Zuo, Z. X., 2011. Stress Calculation of Fillet Rolled Crankshaft in Bending Fatigue Tests. Applied Mechanics and Materials 44-47, 2798-2804. Doi:10.4028/www.scientific.net/AMM.44-47.2798

Bao, K., Liao, R. D., 2013. Bending Fatigue Life Prediction of Fillet Rolled Crankshafts. Applied Mechanics and Materials 275-277, 174-178. Doi:10.4028/www.scientific.net/AMM.275-277.174

Bhadeshia, H.K.D.H., 2005. High Performance Bainitic Steels. Materials Science Forum 500-501, 63-74. Doi:10.4028/www.scientific.net/MSF.500-501.63

Biró, A. S., 2013. Trends of nitriding processes. Production Processes and Systems 6(1), 57-66.

Bushmayer B., 2016. Critical Assessesment 22: bainitic forging steels. Mater. Sci. Technol. 32, 517-522. Doi: 10.1080/02670836.2015.1114272

Cavallini, C., Giorgetti, A., Citti, P., Nicolaie, F., 2013, Integral Aided method for Material Selection based on Quality Function Deployment and Comprehensive VIKOR algorithm, Material & Design 47, 27–34. Doi: 10.1016/j.matdes.2012.12.009.

Cevik, M., Rebbert, M., and Maassen, F., 2009. Weight and Friction Optimized Cranktrain Design Supported by Coupled CAE Tools. SAE Technical Paper 2009-01-1452. doi: 10.4271/2009-01-1452.

COMMISSION REGULATION (EU) 2016/427, 10-3 2016.

Cyril, N., Fatemi, A. and Cryderman, B., 2009. Effects of Sulfur Level and Anisotropy of Sulfide Inclusions on Tensile, Impact, and Fatigue Properties of SAE 4140 Steel. SAE Int. J. Mater. Manf. 1(1), 218-227. doi:10.4271/2008-01-0434.

Davis, J., R., 1997. ASM Specialty Handbook: Heat-Resistant Materials. AMS 243,244.

Davis, J. R., 2001. Alloying: Understanding the Basics. AMS 193-202.

Dedier, G.E., 1997. AMS Handbook Volume 20: materials Selection and Design. AMS International.

Engineer S., Huchtemann B., 1996. Review and Development of Microalloyed Steel for Forgings, Bars, and Wires. In: Fundamentals and Applications of Microalloying Forging Steels. (Ed.) TMS, Matlock, Warrendale (PA), pp. 61–78.

Garcia-Mateo C., Sourmail T., Caballero, F. G., Capdevilla C. and de Andres C.G., 2005. New approach for the bainite start temperature calculation in steels. Mater. Sci. Techn., 934-940. doi:10.1179/174328405X51622.

Giorgetti, A., Cavallini, C., Arcidiacono, G., and Citti, P., 2017. A Mixed C-VIKOR Fuzzy Approach for Material Selection during Design Phase: A Case Study in Valve Seats for High Performance Engine, International Journal of Applied Engineering Research 12, 12, 3117-3129.

Grum, J., 2003. Analysis of residual stresses in main crankshaft bearings after induction surface hardening and finish grinding. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 217(3), 173-182.

Habraken, L.J. and Economopoulos, M., 1967. Bainitic microstructures in low carbon alloy steels and their mechanical properties. Transformation and Hardenability in Steels, Climax Molybdenum, 69–108.

Halfa, H., 2014. Recent Trends in Producing Ultrafine Grained Steels. JMMCE 2, 5. doi:10.4236/jmmce.2014.25047

Hayama, T., 1975. Effect of Residual Stress on Fatigue Strength of Induction-Hardened steel. Bulletin of JSME 18, 125, 1194-1200. doi:10.1299/jsme1958.18.1194

Hehemann, R.F., 1970. The bainite Transformation. Phase transformation, ASM , 397-432.

Hoffmann, J. H., Turonek, R. J., 1992. High Performance Forged Steel Crankshafts - Cost Reduction Opportunities. SAE Technical Paper 920784. doi:10.4271/920784.

Holm T, Sproge L., 2009. Nitriding and nitrocarburizing..Furnace Atmos. 3:1–10.

Irvine, K.J., Pickering, F.B., 1957. Low carbon bainitic steels. J. Iron & Steel Inst. 187, 292-309.

Klinkenberg, C., 2007. Niobium in Microalloyed Structural and Engineering Steels. Materials Science Forum 539-543, 4261-4266. doi:10.4028/www.scientific.net/MSF.539-543.4261

Ko, Y., Park, J., Bhan, H., Park, H. et al., 2005. Fatigue Strength and Residual Stress Analysis of Deep Rolled Crankshafts. SAE Technical Paper 2005-01-0988. doi:10.4271/2005-01-0988.

Korchynsky, M., Paules, J., 1989. Microalloyed Forging Steels-A State of the Art Review. SAE Technical Paper 89080. doi:10.4271/890801

Lemaitre, C., Dierrickx, P., Robat, D., et al., 2005. Wear, base tooth fatigue and pitting tests on nitrided steels 25MnSiCrVB6/L (METASCO) and 23MnCrMo5-mod-1 (JOMASCO) – dimensional reliability, manufacturing savings and automotive filed applications. In "IFHTSE-AIM 2nd international conference on heat treatment and surface engineering in automotive applications", Riva del Garda, Italy, 20–22 June 2005.

Li, Y., Milbourn, D. J., 2013. Vanadium Microalloyed Forging Steel. Proceeding of The 2nd International Symposium on Automobile Steel, Anshan, 47-54.

Lui, D.K., Cai, G., Lui, L., 1987. The granular bainite in V, Ti containing Fe-C alloys. Proc. Int. conf. "Phase transformation '87".

Oblak, J.M., Hehemann, R. F., 1967. Structure and growth of Widmanstatten ferrite and bainite. In "Transformation and hardenability in steels", Ann Arbor, Michigan.

Matsuda, M., Ootsuki, E., Kajihara S., Hanawa Y., Hamada T., 2011. Predicting Effect of Cold Rolling on Fatigue Strength under Combined Loading. KOBELCO TECHNOLOGY REVIEW NO. 30 DEC.

Medlin, D., Cornelissen, B., Matlock, D., Krauss, G., Filar, R., 1999. Effect of thermal treatments and carbon potential on bending fatigue performance of SAE 4320 gear steel.SAE Report 1999-01-0603. doi:10.4271/1999-01-0603

Menk, W., Kniewallner, L., Prukner, 2007. Cast crankshafts as an alternative to forged crankshafts. MTZ Worldwide.

Milbourn D. J., 1988. Air-cooled Forging Steels for Automotive Applications. Steel Time, 351-352.

Mittemeijer, E., J., 2013. Fundamentals of Nitriding and Nitrocarburizing. ASM Handbook, vol. 4A, Steel Heat Treating Fundamentals and Processes, (Ed.) Dossett J. and G.E. Totten.

Nallicheri, N. V., Clark, J. P., and Field, F. R., 1991. Material Alternatives for the Automotive Crankshaft; A Competitive Assessment Based on Manufacturing Economics. SAE Technical Paper 910139. doi:10.4271/910139

Naylor, D. J., 1998. Microalloyed Forging Steels. Materials Science Forum, vols. 284-286, 83-94.

Pessard, E., Morel, F., Morel, A., 2009. The anisotropic fatigue behavior of forged steel. Advanced Engineering Materials, Wiley-VCH Verlag, 11(9), 732-735. doi:10.1002/adem.200900040

Pichard, C., Tomme, C., and Rezel, D., 1993. Alternative Materials for the Manufacture of Automobile Components: Example of Industrial Development of a Microalloyed Engineering Steel for the Production of Forged Crankshafts. In Proceedings of the 26th ISATA International Symposium on Automotive Technology and Automation, Aachen, Germany.

Raedt, H.W., Speckenheuer, U., Vollrath, K., 2012. New forged steels - energy-efficient solutions for stronger parts. ATZ Automobiltechnische Zeitschrift, 114(3), 4–9. doi:10.1365/s35595-012-0089-9

Rakhit, A.K., 2000. Heat Treatment of Gears: A Practical Guide for Engineers. ASM International 6, 133–158. doi:10.1361/htog2000p033

Sage A. M., 1986. The Effect of Some Variations in Composition on the Properties of Vanadium Forging Steels. Conference Proceedings of Fundamentals of Microalloying Forging Steels, Colorado, 239-253.

Schaal, R., Kaiser, B., Pyttel, B., Berger, C., 2003. The influence of fillet rolling on fatigue strength - experiment and calculation. Computational and Experimental Methods 7, 205-212.

Schneider, M. J., The Timken Company, Chatterjee, M. S., 2013. Introduction to Surface Hardening of Steels. ASM Handbook, vol. 4A, Steel Heat Treating Fundamentals and Processes J. Dossett and G.E. Totten, editors.

Sourmail, T. and Smanio, V., 2013. Optimisation of the mechanical properties of air cooled bainitic steel components through tailoring of the transformation kinetics. Materials Science and Engineering: A 582, 257-261. doi:10.1016/j.msea.2013.06.040

Steven, W. and Haynes, A. G., 1956. Journal of the Iron and Steel Institute 183. 349-359-

Takahashi, M., Bhadeshia, H K. D. H., 1990. A Model for the Transition from Upper to Lower Bainite, Materials science and technology 6,592-603. doi:10.1179/mst.1990.6.7.592

Weymer, P., 2009. Principles of gas nitriding. Heat Treat. Prog.

Williams, J. and Fatemi, A., 2007. Fatigue Performance of Forged Steel and Ductile Cast Iron Crankshafts. SAE Technical Paper 2007-01-1001. doi:10.4271/2007-01-1001.

Zhang, H et al., 1988. THERMEC-88. ISIL, Tokyo, 527-534.

Zoroufi, M., Fatemi, A., 2005. Literature review on durability evaluation of crankshafts including comparisons of competing manufacturing processes and cost analysis. Published in Proceedings of the 26th Forging Industry Technical Conference. Chicago.