THE INFLUENCE OF SUB-CRITICAL THERMOCHEMICAL PROCESSING ON FATIGUE RESISTANCE OF 42CrMo4 STEEL

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The machine parts, fasteners and many other components require high fatigue resistance as well as other properties. The paper aims to determine the influence of nitriding and nitrocarburizing realized at temperatures below the eutectoid transformation temperature in the Fe-N system on the fatigue resistance of 42CrMo4 steel. The effects of performing these thermochemical treatments both on annealed as well as quenched - tempered matrixes on change of fatigue resistance under rotary bending stresses are taken into analysis. It was concluded that, independently of the matrix structural condition, the subsequent sub-critical thermochemical treatments applied after heat treatments, will lead to the fatigue resistance enhance; the nitriding is constantly providing better results than nitrocarburizing performed in ammonia/endogas mixtures. Economic reasons, recommend however the nitrocarburising in atmospheres with high ammonia contents to be applied in order to provide appropriate increase of the fatigue resistance of 42CrMo4 alloy steel components.

Keywords: fatigue resistance, nitriding, nitrocarburizing

1. Introduction

The fatigue resistance of metallic components is strictly related to the repartition of stresses on their section: the presence of compressive stresses in superficial zones ensures a high level of durability and fatigue resistance implicitly.

The fatigue resistance limit is also dependent on mechanical resistance of components central zones and its enhancing causes the increase of fatigue resistance.

Following to the application of thermochemical treatments [1, 2, 3, 4], new phases with higher specific volumes compared to those of matrix has been developed in the superficial layers of metallic components; the residual stresses distribution epure on the component section has changed as well as the compressive stresses have continuously decreased from surface to center (fig.1).

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The mechanical resistance of component central zones should not been influenced by thermochemical processing therefore have to be chosen only those thermochemical treatment variants which involve isothermal holding temperatures lower than the tempering temperature of processed steel. Otherwise, a sequence of heat treatments after thermochemical treatments has to be used in order to re-establish the resistance characteristics required by the component central zones.
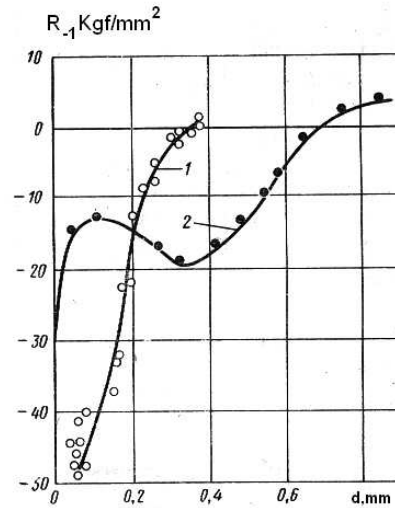

Fig.1 Distribution of residual stresses on the diffusion layer of case hardening steel with chemical composition: ~0.17%C; ~0.4%Mn; ~0.3%Si; ~1.5%Cr; ~4.2%Ni; ~1%W after:
1- nitriding at 500°C, nitriding case depth of 0.35mm; 2- carburizing+quenching+low temperature tempering [5]

In the presence of residual stresses, by loading the metallic components during exploitation with external stresses, the resulted stresses are determined by overlapping external stresses on residual stresses.

Moreover, in the presence of residual compressive stresses takes place a diminishing of tensile stresses in surface, zone where usually most of stresses are determined by the constructive and technological aspects related to component execution.

This combination of stresses explains the increase of fatigue resistance and therewith represents the cause for which the initiation of fatigue cracking happens frequently under the surface hardened zone and not at the surface level.

The higher the resistance of non-nitrided central zones, the greater the fatigue resistance of nitrided metallic components; by nitriding the source of cracking initiation is placed under the hardened layer and therefore the

augmentation of deformation resistance of these zones impede the cracks initiation under action of alternant stresses.

The maximum level of fatigue resistance is achieved for relatively low nitrided layer case depths (fig.2a).
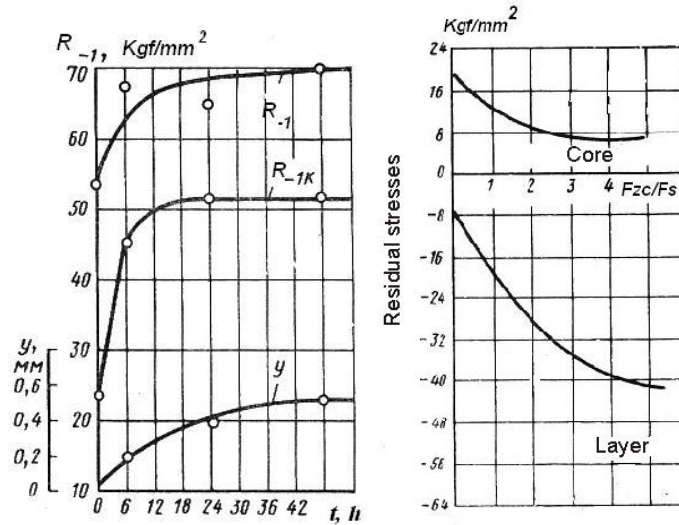

Fig.2 The dependence of fatigue resistance of steel with chemical composition mentioned in fig.2, nitrided at 520°C on isothermal maintaining time at nitriding (a); the dependence of residual stresses level of the same steel on (F_{zc}) deep zone area/(F_s) layer area ratio (b) [5, 6]
Note. R_{-1K} - is the fatigue resistance determined on notched specimens

The increase of fatigue resistance takes place for nitrided layer case depths (y)/component radius (r) ratios of y/r=0.1÷0.2 in case of specimens without stresses concentrators, respectively the maximum fatigue resistance is reached for much lower ratios of about y/r=0.01 in the presence of stresses concentrators [5].

It was observed that the ratio between the area of not nitrided central zone (F_{zc}) and the area of nitrided layer, (F_s) plays a major role in the fatigue resistance reached. Thus, in the case of steel taken previously into analysis (with chemical composition mentioned in fig.1), for $F_{zc}/F_s<4$ (fig.2b), the layer compressive stresses are rapidly decreasing and the tensile stresses of central zone are increasing. At higher nitrided case depths, the fatigue resistance could decrease due to excessive amplification of tensile stresses in the component central zones and due to related reduction of those from layer [6].

These observations are further supported by other work [7] where the roles of compressive residual macrostresses and microstresses in the nitride surface layer on the fatigue limit increase are highlighted.

The thermochemical processing temperature influences the fatigue resistance too: the higher the temperature, the lower the fatigue resistance; this phenomenon is determined by the reduction of mechanical resistance of component central zone and of the layer compressive stresses

Similar observations are also outlined in [8] where it was concluded that nitriding at lower temperatures has no obvious effect on the fatigue limit of unnotched specimens while has a significant influence on notched specimens of investigated steels (24CrMo13 and 42CrMo4).

The ε - nitride (9÷11%N) is characterized by high brittleness. To increase the plasticity of superficial layers and generally to improve their exploiting characteristics it is necessary to add carbon bearing gases in the nitriding atmosphere. Thus, the layer oversaturation with nitrogen is impeded and the brittleness of the zone with nitrides is avoided.

In the presence of the endogas additions in the nitriding gaseous atmospheres (50%NH_3/50%endogas), layers of oxi-carbonitrides with case depths of 2.5÷25μm and low porosity will develop on the component surface.

To reduce the size of these layers, it is recommended at the end of nitriding cycle to decrease the ammonia content at about 40%vol. in the endogas/ammonia mixture [9].

2. Experimental

The purpose of the experimental researches is to evaluate the effect of subcritical thermochemical treatments (nitriding and nitrocarburizing in endogas/ammonia gaseous mixtures) on the fatigue resistance and tensile strength levels of alloy steel for quenching and tempering - 42CrMo4 in different structural conditions. Were performed:

- mechanical tests with dynamic loads - rotary bending fatigue tests in order to determine the fatigue resistance, R_{-1};

- mechanical tests with mechanical loads which are increasing progressively in time in order to determine the tensile strength, Rm.

Specimens with standardized shapes and sizes [10] were used to assess these resistance characteristics, their specific sizes being 12.5 mm (size of the calibrated zone according to SR EN 10002-2:96) for the tensile strength tests respectively Φ=4mm (size of the active zone) for the fatigue resistance tests; in the case of tensile strength tests, specimens with dimensional factor of n = L_o/d_o = 5 (L_o - initial length) have been used.

The tensile strength tests were realized on Los 60 type universal testing machine. The rotary bending fatigue tests were performed on Schenck Punn machine which allows the permanent adjustment of load during operation and has variable loading speed in the range 0÷100Hz (the applied frequency was 47.5Hz).

The samples were cut from annealed bars of 42 CrMo4 (steel having the chemical composition of 0.41%C; 0.85%Mn; 0.31%S; 0.015%P; 1.15%Cr; 0.25%Mo in the compositional range of W.1.7225 steel grade) and were subsequently treated in chamber furnaces; the automat control of technological parameters including the control of ammonia and ammonia/endogas contents as well as ammonia dissociation adjustment are provided.

The mechanical resistance namely tensile strength and the fatigue resistance under rotary bending stresses have been evaluated on normalized, quenched and tempered or sub-critically annealed, samples as well as on samples with the previously mentioned heat treatment variants and subsequent thermochemical processing by nitriding or nitrocarburizing in ammonia/endogas gaseous mixtures.

The tests were repeated three times for each of mechanical characteristics concerned and the result taken into analysis is representing the arithmetic mean of experimental values.

The method used to estimate the fatigue resistance at rotary bending with uniform distributed load and trapezoidal moment was the Locati method. The specimens were subject to equidistant stages of fatigue testing with successive loading stresses and each stage is corresponding to a constant number of cycles $n=1 \times 10^5$; the first stage of fatigue testing is performed at 500 MPa, value which is below the fatigue limit of the material.

The metallographic investigations were performed using MF-2 Reichert optical microscope and Hanemann microhardness tester with load of 50gf in order to determine the microstructure and the compound layer and effective nitriding depths.

3. Results. Interpretation

The 42CrMo4 (W 1.7225) steel is a quenching and tempering steel with bainitic - martensitic hardenability (fig.3) and tensile strength in quenched and tempered condition of about 1100÷1300MPa (for reference specimens sizes ≤ 16mm) and with minimum fatigue resistance under cyclic bending testing of about 373MPa.

The structures of 42CrMo4 steel in normalized respectively quenched and tempered condition (fig.4) highlight aspects which are closely correlated with the information provided by the diagram of anisothermal phase transformation of the sub-cooled austenite: directly, for the normalizing and quenching and indirectly for high tempering of which result can be anticipated based on the results of cooling in oil performed from the austenite stability range.
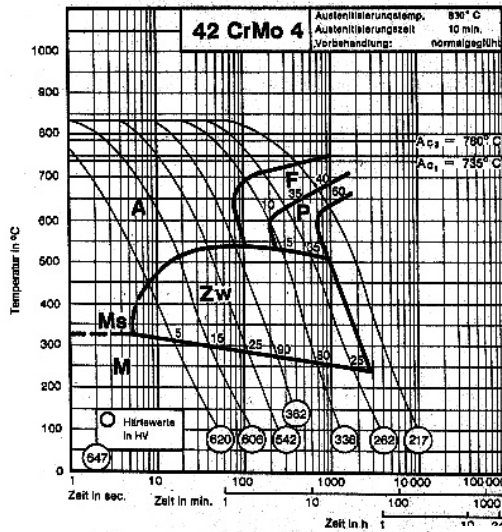
Fig.3 Diagram of anisothermal phase
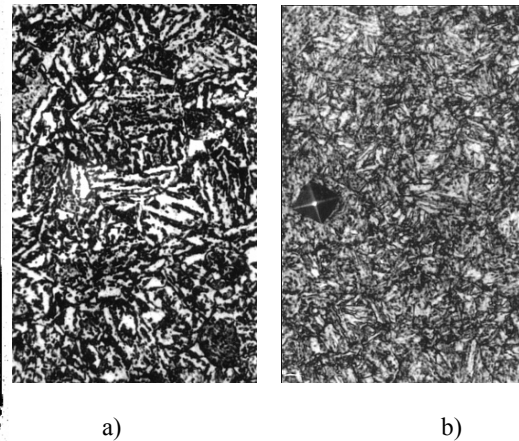transformation of the sub-cooled austenite
of 42CrMo4 steel [11]

Fig.4 Structures after normalizing (870°C/1h/air) (a),
respectively quenching and tempering (b)
(quenching 840°C/oil + tempering 580°C/water)
of 42CrMo4 steel. Etching reagent: nital 2%,
magnification 500:1

In the normalized steel structure can be observed ferrite, troostite type perlite, bainite and low proportions of martensite (below 5%) and the hardness is about ~265HB; the quenched and tempered structure is composed of bainite and martensite decomposition components - ferrite and carbides and the hardness is about ~388HB.

The occurrence of reversible brittleness at tempering, phenomenon which is specific to Cr and Mn low alloyed quenching and tempering steels (including 42CrMo4 steel) is suppressed by the presence of Mo in the chemical composition and thus the rapid cooling from tempering temperature (580°C) to avoid the brittleness is not theoretically justified (tensile stresses can develop and cause deformations during subsequent mechanical processing as well as the fatigue resistance decreases).

During experiments, the claims of the standards in force (STAS 791/88, respectively SR EN 10083-AI :1995) [12, 13] have been followed, however, the cooling after tempering maintaining was chosen to be performed in water in order to avoid the brittleness.

The cooling in water after maintaining at 580°C/1h (high temperature tempering) led to higher hardness in comparison with that currently attained by

tempering of this steel at the same temperature; another advantage of rapid cooling is related to the acceleration of the mass transfer processes during subsequent thermochemical processing determined by the stresses status created in the metallic matrix.

It was observed that in the case of quenched+tempered+nitrided specimens (tempering temperature 550°C/air cooling and nitriding time 50h) the R_{-1}=980 MPa while in the case of quenched+tempered+nitrided specimens (tempering temperature 550°C/water cooling and nitriding time 50h) the R_{-1}=804MPa.

These observations are in good agreement with the results shown in the reference [14] where the influence of tempering temperature on fatigue resistance at rotary bending of 42CrMo4 steel is analyzed; the decreasing of the fatigue resistance from R_{-1}=840 MPa (tempering temperature 550°C and nitriding time 16h) to R_{-1}=745 (tempering temperature 690°C and nitriding time 16h) was reported.

The tensile strength and fatigue resistance of 42CrMo4 steel as quenched and tempered were Rm=1220MPa and R_{-1}=578.5MPa (arithmetic means) and are accepted as reference values for this steel condition.

The applying of subcritical thermochemical treatments to the 42CrMo4 steel in normalized or in quenched and tempered condition causes substantial change of the stresses epure which is strictly correlated with the thermochemical processing parameters (fig.5).

The highest fatigue resistances are observed for quenched, tempered and nitrided matrixes, followed by normalized and nitrided matrixes and finally by quenched, tempered and nitrocarburized matrixes in gaseous mixtures composed of ammonia and endogas (fig.6).

Nitriding applied after quenching and tempering provided the highest shift of fatigue resistance at rotary bending, 69.5%, followed by nitrocarburizing in rich ammonia/endogas mixtures, which was 18.5-20%.

The inconvenient of use of nitriding is the long processing time required to attain case depth of 0.6 mm (50 hours of isothermal holding); the use of nitrocarburising in high ammonia atmosphere (60-70%) for max. 3 hours of isothermal holding lead to fatigue resistance increase of max. 20% against that attained without thermochemical processing.

The ratio between the fatigue resistance at rotary bending and tensile strength of 42CrMo4 steel in quenched and tempered condition is $\frac{\overline{R_{-1}}}{Rm}$=580/1220=0,47; this ratio registers significant increase by further application of nitriding, $\frac{\overline{R_{-1}}}{Rm}$=980/1220=0,8 (of about 1,7 times) and relatively low increase

by application of nitrocarburizing in ammonia/endogas mixtures ($\frac{\overline{R_{-1}}}{Rm}$=633,12/1220=0,51).

The explanation is related to the lower increase of fatigue resistance in case of applying of nitrocarburizing by comparison with applying of nitriding. This aspect can be further substantiated by the differences registered between the sizes of the layers saturated by diffusion as well as by the fact that in the nitrocarburized layers can be found isolated microcracks which could represent the sources for breaking under rotary bending.
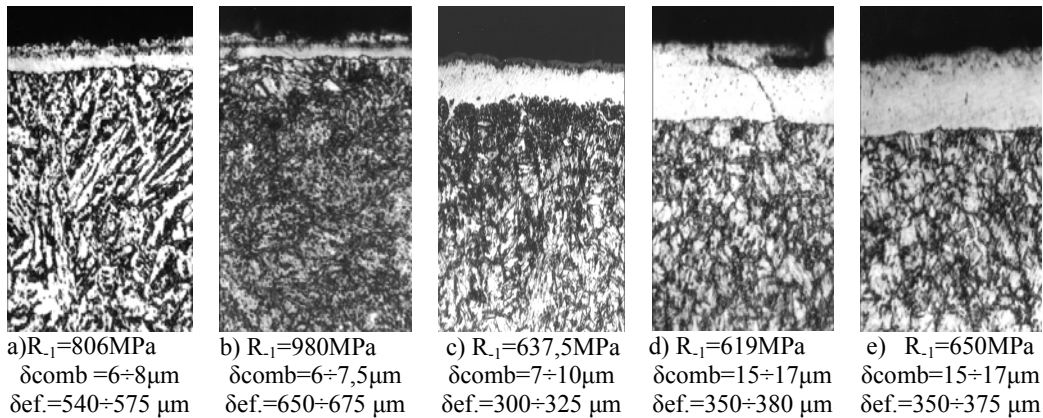

a)R_{-1}=806MPa
δcomb =6÷8μm
δef.=540÷575 μm

b) R_{-1}=980MPa
δcomb=6÷7,5μm
δef.=650÷675 μm

c) R_{-1}=637,5MPa
δcomb=7÷10μm
δef.=300÷325 μm

d) R_{-1}=619MPa
δcomb=15÷17μm
δef.=350÷380 μm

e) R_{-1}=650MPa
δcomb=15÷17μm
δef.=350÷375 μm

Fig.5 Microstructures of 42CrMo4 steel in different structural conditions: after normalizing and nitriding at 520°C/50 h,   in atmosphere of 75%N_2+25%H_2 (a); quenching, tempering and nitriding at the same parameters (b); quenching, tempering and nitrocarburizing at 580°C/3h in ammonia/endogas mixtures of: 50%/50% (c); 60%/40% (d) 70%/30% (e). Etching reagent: nital2%; Magnification 1000:1

It is interesting to remark the effect of nitriding on normalized matrixes of 42CrMo4 steel which lead to the obtaining of fatigue resistances higher than those of quenched, tempered and nitrocarburized in ammonia/endogas matrixes (R_{-1}=806MPa - nitrided matrixes, respectively 619-650MPa nitrocarburized matrixes); the shift of fatigue resistance in rapport with the tensile strength is superior to that registered in the case of quenched, tempered and nitrided matrixes (0.84 by comparison with 0.80).
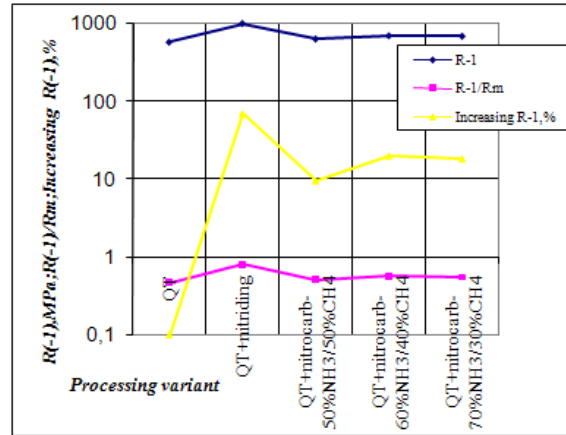
Fig.6 The effects of applying of sub-critical treatments on fatigue resistance of 42CrMo4 steel, on fatigue resistance increase against the reference value (in quenched and tempered condition), respectively on the evolution of fatigue/ mechanical resistances ratio.

It is interesting to remark the effect of nitriding on normalized matrixes of 42CrMo4 steel which lead to the obtaining of fatigue resistances higher than those of quenched, tempered and nitrocarburized in ammonia/endogas matrixes (R_{-1} =806MPa - nitrided matrixes, respectively 619-650MPa nitrocarburized matrixes); the shift of fatigue resistance in rapport with the tensile strength is superior to that registered in the case of quenched, tempered and nitrided matrixes (0.84 by comparison with 0.80).

It can be further observed that nitrocarburizing applied to the sub-critically annealed matrixes lead to fatigue resistances which are equal or higher than those registered for the quenched, tempered and nitrocarburized matrixes for this steel (fig.7).

The deviation between the fatigue resistance and tensile strength of the sub-critically annealed and nitrocarburized matrixes is systematically higher than that registered in the case of quenched, tempered and nitrocarburized matrixes of this steel. For example, the ratio between the two resistances is $\frac{\overline{R_{-1}}}{Rm}$=634.3/931=0,68 for sub-critically annealed matrixes and subsequent nitrocarburized in 50%NH$_3$/50%endogas mixtures and is 0,52 for quenched, tempered matrixes and subsequent nitrocarburized at the same parameters; these ratios are 0.75 and 0.51 for matrixes nitrocarburized in 60%NH$_3$/40% endogas mixtures respectively 0.74 and 0.53 for matrixes nitrocarburized in 70% NH$_3$/30% endogas mixtures).

a) R₋₁=633,5MPa
δcomb=6÷8μm
δef.=370÷400 μm

R₋₁=694,6MPa
δcomb=15÷17μm
δef.=360÷400 μm
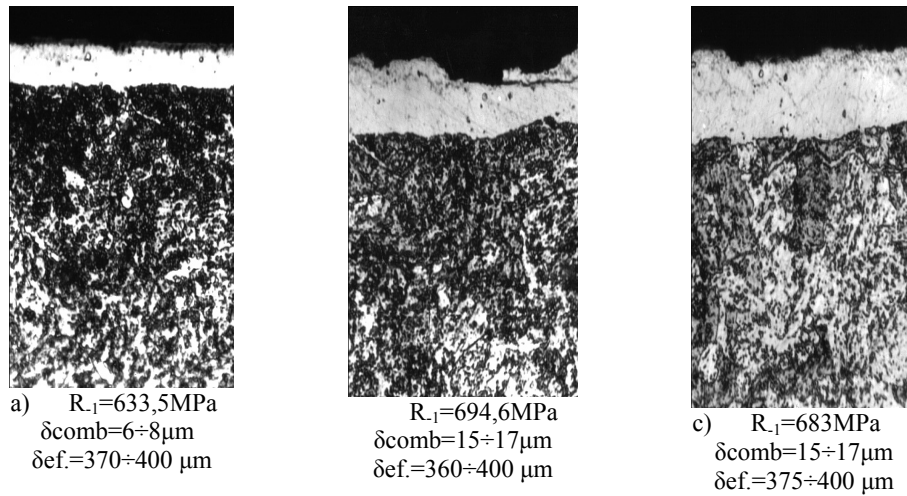
c) R₋₁=683MPa
δcomb=15÷17μm
δef.=375÷400 μm

Fig.7 The microstructures of 42CrMo4 steel after sub-critical annealing-700°C/1,5h/cooling in furnace and subsequent nitrocarburizing at 580°C/3h in different ammonia/endogas mixtures: 50%/50% (a); 60%/40% (b), 70%/30% (c). Etching reagent: nital 2%; Magnification 1000:1

The deviation is determined by the differences available between the matrixes tensile strengths of this steel caused by the phases combination in different structural conditions: Rm=931MPa for the subcritical annealed and nitrided matrixes where ferrite and globular cementite are observed, Rm=951MPa for the normalized and nitrided matrixes where ferrite (proeutectoid, bainitic or resulted from martensite decomposition) as well as carbides are included, respectively Rm=1220MPa in the quenched, tempered and nitrided or nitrocarburized matrixes where ferrite (bainitic or resulted from the martensite decomposition) and carbides are highlighted. The choosing of certain type of matrix necessary for specific application is possible obviously taking into consideration the demands in exploitation thus the minimum tensile strength.

6. Conclusions

1. The sub-critical thermochemical treatments ensure the enhancing of fatigue resistance of 42CrMo4 steel; the nitriding brings a shift of about 70% of this characteristic in comparison with that registered on the non-nitrided matrix, for the case where the processed steel has quenched and tempered structure.

2. It is more economically profitable to apply nitrocarburizing in order to increase the fatigue resistance; this type of thermochemical processing provides 10% increase of fatigue resistance in comparison with the level registered on the quenched and tempered matrix without subsequent thermochemical processing. Further increase of the performance brought by nitrocarburizing on the fatigue

resistance level could be reached, if after the thermochemical processing, the superficial zones of maximum about 5 μm where micro-cracks can occur will be removed by polishing.

     3. The selection of proper steel matrix of 42CrMo4 steel before sub-critical thermochemical processing has to be correlated with the component exploiting demands hence with the resistance characteristics concerned.

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