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An examination of different heat treatment effects to the fracture parameters of connecting rod made from C70S6 steel

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Abstract:

The main microstructure of the crackable C70S6 steel is pearlite (%90 of the structure is about pearlite). Changing the microstructure by various heat treatment applications such as hardening&quenching, annealing, tempering can be economic and technologic alternatives to the use of crackable C70S6 steel. In this study, the microstructure and the metallography of the crackable C70S6 steel is examined by various heat treatment applications. Besides this, some fracture experiments has been carried out for each heat treatment application. Finally, it has been seen that tempered martensite structure can be an important alternative to the pearlitic crackable C70S6 connecting rods.

Keywords: *tempered martensite, crackable connecting rod, heat treatment, metallographic examination, C70S6 steel*

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1. Introduction:

Connecting rods are widely used in variety of automobile engines. The function of the connecting rod is to transmit the thrust of the piston to the crankshaft and translate the transverse motion to rotational motion. It should be strong enough to remain rigid under loading, and also be light enough to reduce the inertia forces, which are produced when the rod and piston stop, change directions and start again at the end of each stroke [1].

The fracture splitting method is an innovative processing technique in the field of the automobile engine connecting rod (con-rod) manufacturing. Compared with traditional method, the technique has remarkable advantages. It can decrease manufacturing procedures, reduce equipment and tools investment and save energy. Hence the total production cost is greatly reduced. Furthermore, the technique can also improve product quality and bearing capability. It provides a high quality, high accuracy and low cost route for producing connecting rods (con/rods). The method has attracted extensive attention and has been used in some types of con/rods manufacturing. In recent years, with the rapid development of the automobile industry, the competition in the international automobile markets has become more severe. New market conditions demand manufacturers employ higher quality, greater efficiency and lower cost manufacturing technology to fabricate automobile parts so as to improve their competitive capability and meet the market requirements.[2]

Microalloyed high carbon steels (such as C70S6, SMA40 and FRACTIM) have been considered to be economic alternatives to powder metal and conventional steel, having been used as main crackable con-rod materials in recent years used in the fracture splitting method. Compared with powder metal and conventional steel, these microalloyed high carbon steels have remarkable advantages. One of the main advantages is that cost reduction can be achieved by changing the micro-structure of the con-rod. Sawing and machining processes of the rod and cap, in order to mate two faces can be eliminated, and is believed to reduce the production cost by 25%. Another advantage of this production method is that fracture-splitting connecting rods exhibit 30% higher fatigue strength and 13% less weight than conventional connecting rods, and can be splitted into two pieces (big body and cap) by fracturing with an instant impact load. Compared with powder metal and cast con-rods, it also has lower cost for the whole manufacturing process. Hence, it provides more advantageous production opportunities, and is prefered in manufacturing technology mostly.[3,4]

2. Materials and methods:

2.1. Aim of the study:

One of the fracture parameters optimizing methods is to change the metallography without tampering the chemical structure by heat treatment applications. No references about heat treatment effect to the microstructure on fracture parameters has been noticed in the literature. The fracture capability and effect of microstructure after heat treatment (esp. tempered martensite), optimizing the fracture parameters and comparing the conventional pearlitic C70S6 and tempered martensite C70S6 have been investigated in this study.

In this article it is aimed to observe the mechanical behaviour of the fracture and the properties of the microstructure after some kinds of heat treatment applications such as annealing, tempering, hardening. It is aimed to understand the effect of these heat treatment applications to the sudden (instant impact force) fracture. The metallography of the fracture surfaces have shown us some typical microstructures such as martensite, tempered martensite, ferrite, pearlite and mixture of them together.

The study consists of heat treatment applications, fracture tests, metallographic observation and the interpretation of these analysis. The hardness has been measured, the relation of the hardness and microstructure to the impact fracture load has been examined.

2.2. Previous studies in literature:

Although C70S6 is excellent in fracture-splitability thanks to its small deformation during splitting, it has a coarser structure than the ferrite/pearlite structure of the medium-carbon micro-alloyed steels currently used as con-rod steels. It is therefore low in yield ratio (yield strength/tensile strength) and cannot be applied to high-strength con-rods requiring high yield strength. Moreover, the inferior machinability of C70S6 owing to its pearlite structure has kept the steel from finding extensive utilization.[5]

Because of the problems above, new studies for optimizing the fracture parameters have been carrying out. Steels for fracture-split components have been developed in response to the foregoing needs. Changing the chemical structure by adding new materials as, Zr, Ca and Al. have been investigated by Manabu Kubota, Shinya Teramoto [6] and Ti adding via FEM method by J.W. Qiu , Y. Liu , Y.B. Liu , B. Liu , B. Wang , Earle Ryba, H.P. Tang [1] recently.

The fracture parameters and microstructures have been examined by Z.Aksoy, Z.Özdemir and T.Özdemir in detail [3,4]. Relationship between fracture parameters and microstructure is also investigated by As Xianzhong. Zhang., Qingfeng. Chen., Qizhou. Cai., Guifeng. Zhou., Yuzhang. Xiong [7]. J.W. Qiu , Y. Liu , Y.B. Liu , B. Liu , B. Wang , Earle Ryba , H.P. Tang examined the effect of Ti addition using FEM analysis as microalloy to the powder forged con-rod steel [1]. Also Manabu Kubota, Shinya Teramoto [6] studies are also important about optimizing the fracture parameters.

Liming, Z. and his friends investigated the lazer effect to the starting notch and fracture parameters [8]. Deen, Z. and his friends investigated the lazer effect to the starting notch depth and Radius [9]. J.W. Qiu and his friends have used FEM to the Ti added connecting rod and simulated the results [1]. Fracture parameters and metallographic structure have been examined in detail by Z.Özdemir and his friends [5,6].

Roman C. and his friends examined the fracture surfaces of connecting rods [10].

Kou S.Q. and his friends composed the starting notch with laser and investigated the effect of this to the fracture parameters [11].

Iwazaki S. and his friends designed and created a machine to manufacture crackable connecting rods [12].

Guirgos S. tried a different kind of method. In this method, crackable connecting rod's stress in the fracture area increases in a controlled atmosphere by a stress-increasing device and as the stress increases, the sudden fracture occurs. [13].

Fatigue characteristics of C70S6 and SMA40 materials as a potential application in connecting rod for an Internal Combustion (IC) engine were investigated by Hye Sung Kim and his friends. An average fatigue life of 140,200 and 168,700 cycles and a fatigue limit of 432 and 437MPa were determined for C70S6 and SMA40 specimens, respectively. However, when tested under the fretting condition, the fatigue lifetime was decreased by 77.8% and 20% and the fatigue limit was reduced to 96 and 350MPa for C70S6 and SMA40 specimens, respectively. From the observations of fracture surfaces, it was confirmed that the fretting played a critical role in introducing many cracks at the initial stage of fatigue. It is clearly shown in this study that special attention should be given to the fatigue behavior of given materials under fretting condition to ensure reliable design and application of components in an automobile [14].

2.3. Structure of martensite and tempered martensite:

Martensite is formed when austenitized iron–carbon alloys are rapidly cooled (or quenched) to a relatively low temperature (in the vicinity of the ambient). Martensite is a nonequilibrium single-phase structure that results from a diffusionless transformation of austenite. It may be thought of as a transformation product that is competitive with pearlite and bainite. The martensitic transformation occurs when the quenching rate is rapid enough to prevent carbon diffusion. Any diffusion whatsoever will result in the formation of ferrite and cementite phases. Since the martensitic transformation does not involve diffusion, it occurs almost instantaneously; the martensite grains nucleate and grow at a very rapid rate—the velocity of sound within the austenite matrix. Thus the martensitic transformation rate, for all practical purposes, is time independent [15].

In the as-quenched state, martensite, in addition to being very hard, is so brittle that it cannot be used for most applications; also, any internal stresses that may have been introduced during quenching have a weakening effect. The ductility and toughness of martensite may be enhanced and these internal stresses relieved by a heat treatment known as *tempering.* Tempering is accomplished by heating a martensitic steel to a temperature below the eutectoid for a specified time period. Normally, tempering is carried out at temperatures between 250 and 650°C; internal stresses, however, may be relieved at temperatures as low as 200°C. This tempering heat treatment allows, by diffusional processes, the formation of **tempered martensite,** according to the reaction; martensite (BCT, single phase)→tempered martensite (α + Fe_3C phases) [15].

where the single-phase BCT (Body-centered tetragonal) martensite, which is supersaturated with carbon, transforms to the tempered martensite, composed of the stable ferrite and cementite phases, as indicated on the iron–iron carbide phase diagram. The microstructure of tempered martensite consists of extremely small and uniformly dispersed cementite particles embedded within a continuous ferrite matrix. Tempered martensite may be nearly as hard and strong as martensite, but with substantially enhanced ductility and toughness [15].

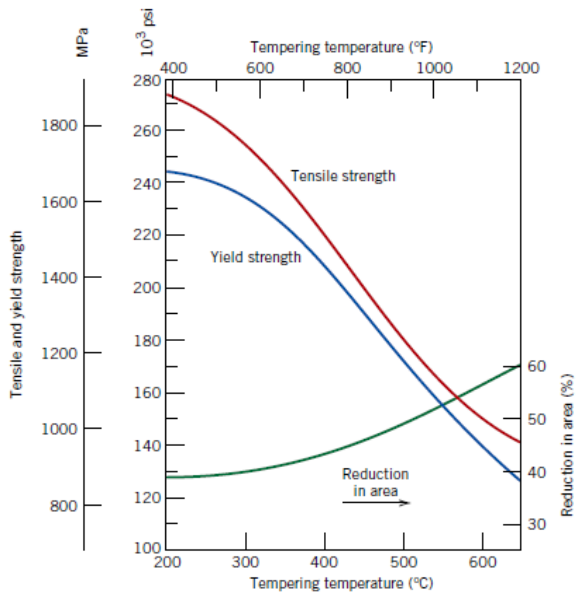

Fig.1. Tensile and yield strengths and ductility (%RA) (at room temperature) versus tempering temperature for an oil-quenched alloy steel (type 4340).(Adapted from figure furnished courtesy Republic Steel Corporation.) [15]

2.4. Heat treatment applications and examination in optical microscopy:

The examination consists of heat treatment applications (hardening, annealing and tempering), fracture experiments, metallographic observation and the interpretation of these analysis. The hardness has been measured, the relation of the hardness and microstructure has been examined. Fractured specimens' optical photos were carefully examined at the Nikon MA 100 Metal Microscopy (Fig. 2).

The heat treatment and quenching applications are applied seperately to C70S6 con-rod crackable steels. The details are below.

Fig. 2. Optical microscopy

Table 1. Chemical composition of fracture splitting C70S6 steel used in heat treatment applications (%) [3,4]

Designation %	C	Si	Mn	P	S	Cr	V	Ni	Fe
C70S6	0.692	0.182	0.507	0.02	0.064	0.114	0.042	0,060	Remain

2.4.1. Hardening and quenching:

2.4.1.1. Hardening and quenching in water (martensite)

The C70S6 con-rod is subjected to a thermal treatment consisting of austenitisations at 800°C/45 min. followed by water quenching.

Fig. 3. Crackable con-rod C70S6 heated to the 800°C and held in furnace 45 min., then quenched in water

The microstructure of the steel is investigated via the optical photos below (Fig.4-5). The microstructure being mostly fine martensite with ferrite particles can be seen appearently. The Hardness is measured as 352 HB.

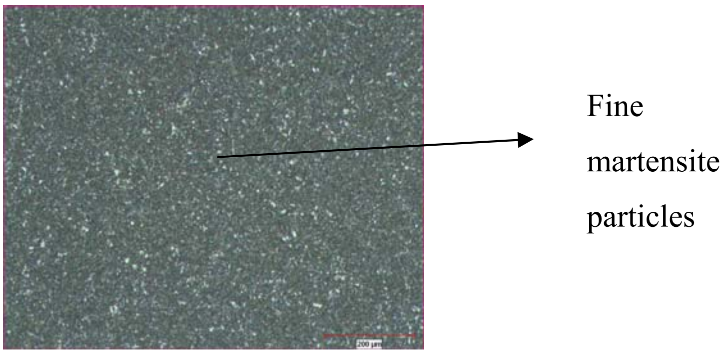

Fig. 4. Optical microstructure (X 100)

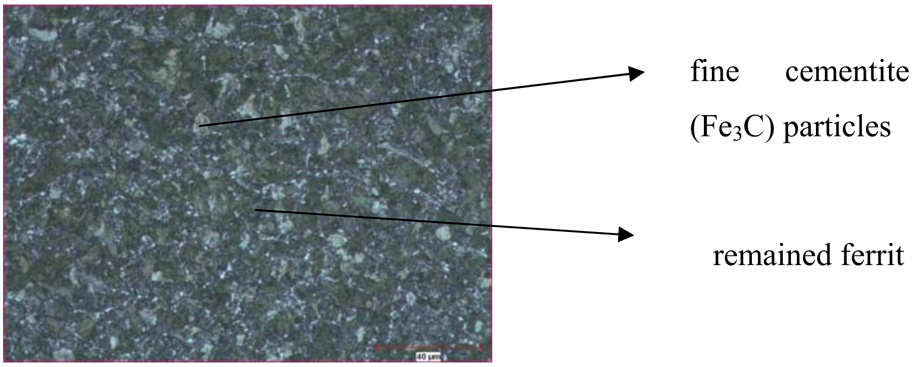

Fig. 5. Optical microstructure (X 500)

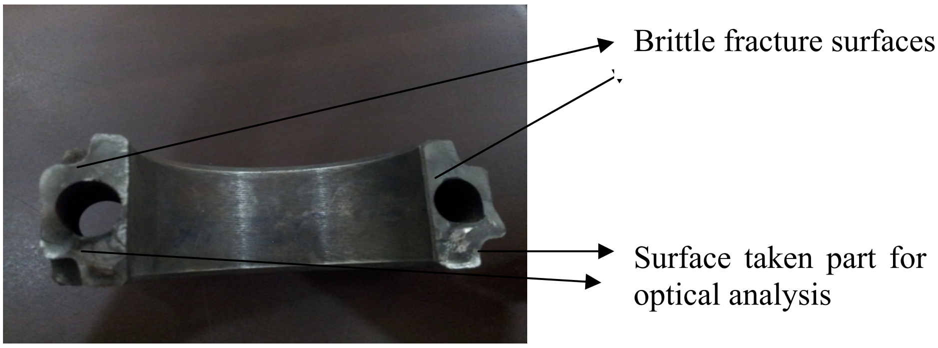

Fig. 6. The photo of C70S6 con-rod after fracture test applied

After the fracture experiment, a brittle fracture is obtained. The structure is harder (352 HB.) than conventional C70S6 crackable con-rod's hardness (280 HB.).

2.4.1.2. Hardening and quenching in %10 NaCl solution (martensite)

The C70S6 con-rod is heated to the 800°C, it is held in furnace for 45 min. Then it is quenched in %10 NaCl water.

Fig. 7. Crackable con-rod C70S6 heated to the 800°C and held in furnace 45 min., then quenched in % 10 NaCl water

Fig. 8. The photo of C70S6 con-rod after fracture test applied

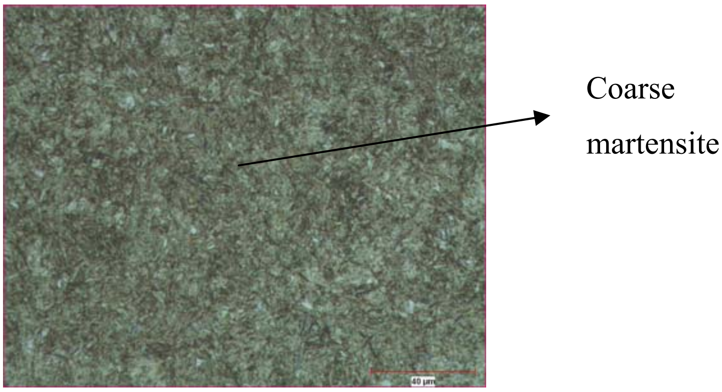

Fig. 9. Optical microstructure (X 500)

A martensite microstructure could be seen in Fig. 9. After the fracture experiment, a brittle fracture could be obtained, but the fracture did not begin from the starting notches but throughout the whole part of the con-rod head section side wall. That is because the structure's being very hard and brittle (612 HB).

2.4.2. Annealing, quenching and tempering:

2.4.2.1. Annealing and slow cooling (pearlitic and ferritic microstructure)

The C70S6 con-rod is heated to the 800°C, then it is quenched in still air.

Fig. 10. Crackable con-rod C70S6 heated to the 800°C and quenched in still air

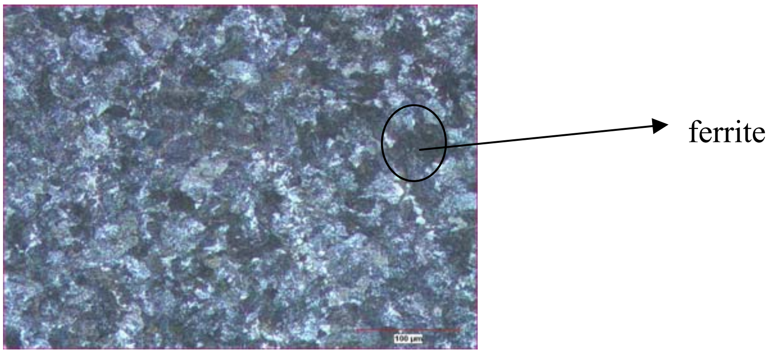

Fig. 11. Optical microstructure (X 200)

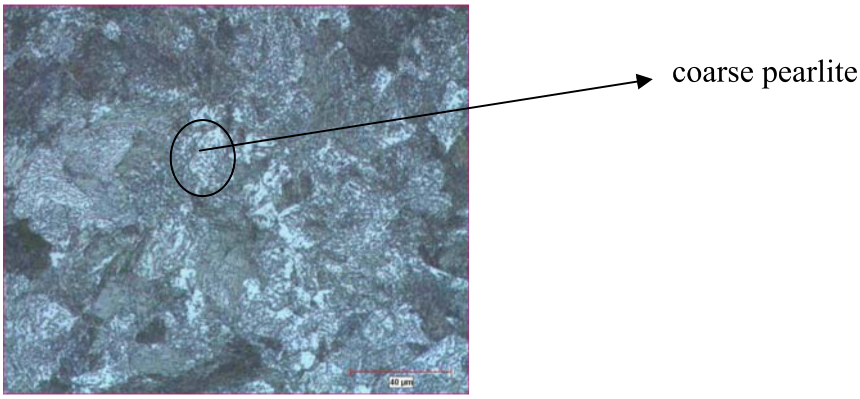

Fig. 12. Optical microstructure (X 500)

The microstructure is mostly lamellar and spheroid coarse pearlite and could be seen remain ferrite. It is very soft and not brittle (190 HB.) The structure is very soft and readily lends itself to deformation. The fracture test has been tried to apply, but it failed because of the soft structure, distortions and crushing have been observed.

2.4.2.2. Quenching and tempering (tempered martensite)

The C70S6 con-rod is heated was subjected to a thermal treatment consisting of austenitisations at 780°C/45 min. followed by water quenching, and tempered at 450°C/30 min. then taken to the still air.

Fig. 13. Crackable con-rod C70S6 heated to the 780°C and held in furnace

45 min., then quenched in water, tempered at 450°C for 30 minutes

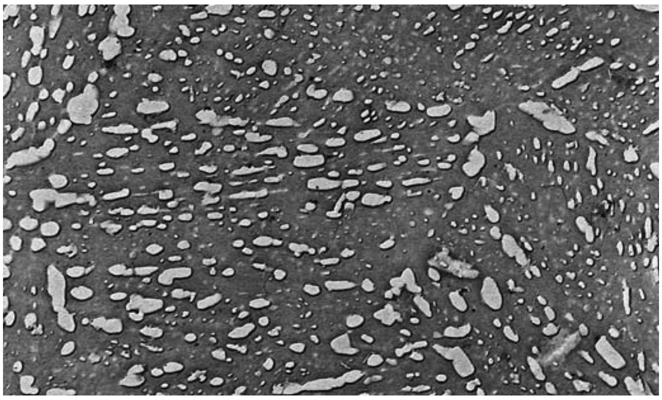

Fig. 14. Electron micrograph of tempered martensite. Tempering was carried out at 594◦C (1100◦F). The small particles are the cementite phase; the matrix phase is α-ferrite. 9300×. (Copyright 1971 by United States Steel Corporation.) [15]

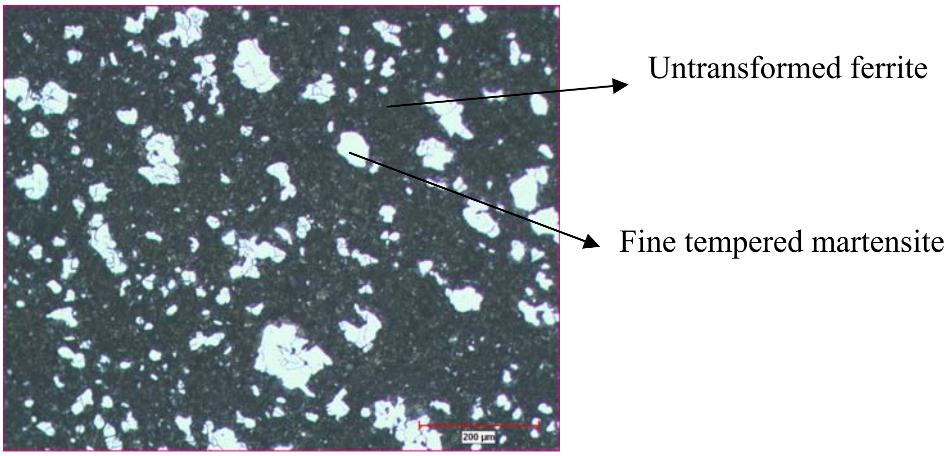

Fig. 15. Optical microstructure (X 200)

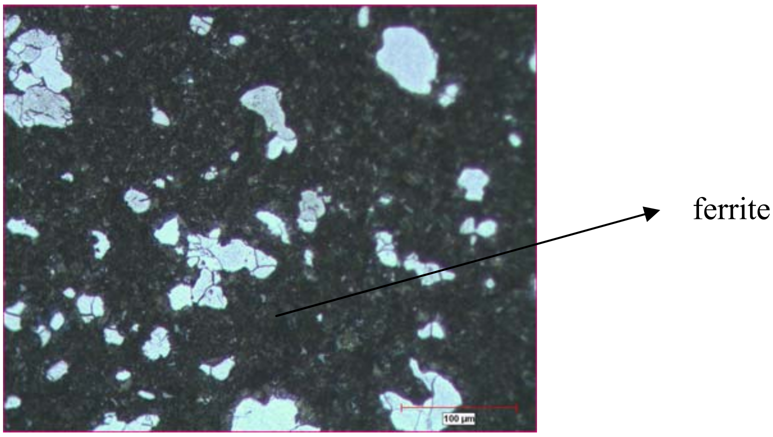

Fig. 16. Optical microstructure (X 100)

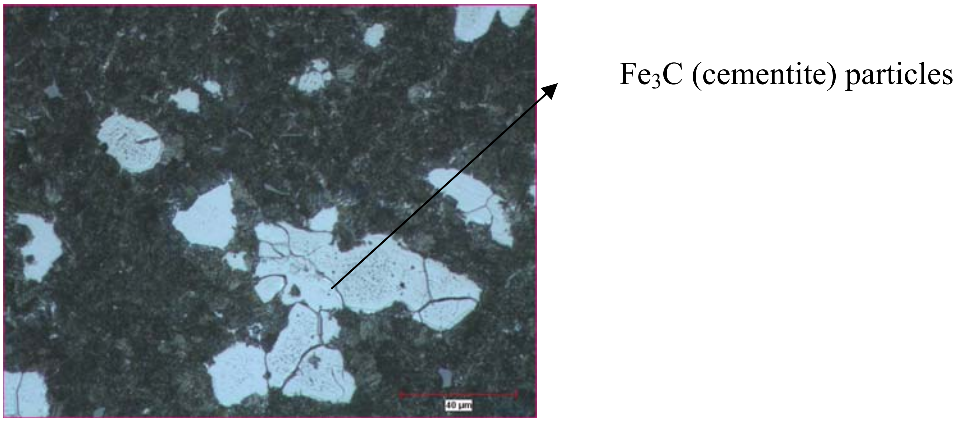

Fig. 17. Optical microstructure (X 500)

The microstructure of the steel is investigated in the optical photos (Fig.15-17). It can be seen appearently that the microstructure is mostly tempered martensite with untransformed ferrite. The hardness is measured as 306 HB. The microstructure is fine tempered martensite. After the fracture test, a brittle fracture is obtained. The structure is almost same as (306 HB.) conventional pearlitic C70S6 crackable con-rod with a hardness degree of 280 – 310 HB.

2.5. Fracture tests:

The testing apparatus for evaluating fracture-splitability consisted of a split die and a 100 ton hydrolic press. The fracture has been started from starting notches (Fig. 18.). The split die had the shape of a cylinder formed on a rectangular steel member. A wedge hole was machined in the mating faces of the two semicylinders. In the fracture-split test, the test piece was clamped in the split die, a wedge was inserted, and the assembly was placed on the hydrolic pressure. In these examples, fracture-splitting was conducted by 100 ton hydrolic press 150 mm. with an impact load.

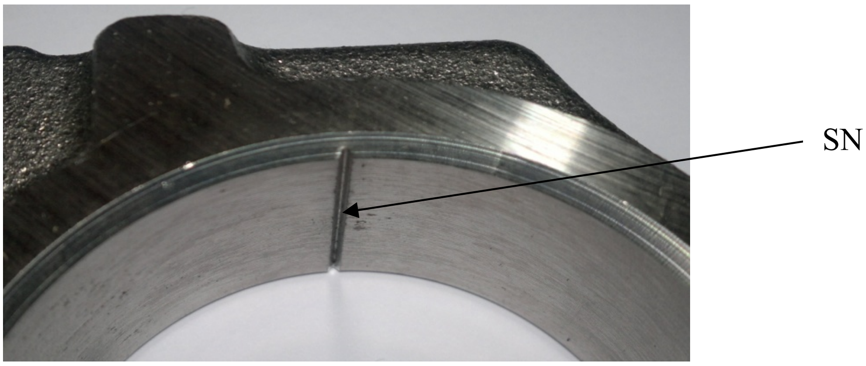

Fig. 18. Starting-Notch (SN) of crackable con-rod C70S6

Fig. 19. Tempered martensite fractured surface after fracture test (a perfect brittle fracture)

The fracture tests have been executed for each heat treatment application separately. The following results have been obtained:

1. The tempered martensite is separated into two pieces from the starting notches. An excellent fracture from starting notches has been obtained.

2. The martensite structure obtained by %10 NaCl water quenching is too brittle and hard (612 HB.) so as to get a perfect fracture from the starting notches. So no technological usage is predicted for this crackable con-rod.

3. The martensite structure obtained by water quenching is brittle and hard (352 HB.) Almost an excellent fracture from the starting notches has been obtained. But the use of crackable con-rods should be considered carefully. Because the microstructure is hard for fracture splitting.

3. Results and discussion:

The following results are obtained:

a. An excellent fracture has been obtained due to the tempered martensite. The hardness is 306 HB. This is suitable for fracture parameters.
b. Because of water quenched martensite microstructure is too hard and brittle (612 HB.), the fracture started not only from starting notchs but almost the whole part of con-rod. This is not an acceptable situation for parameters of crackable C70S6 con-rod.
c. %10 NaCl water quenched martensite microstructure is hard and brittle (352 HB.). The fracture started from starting notchs. This could be an acceptable situation for parameters of crackable C70S6 con-rod. The usability of this microstructure in crackable con-rods should be investigated carefully
d. Pearlitic and ferritic microstructure is too mild (195 HB.) to be fractured by an impact load. So this microstructure is not applicable for crackable C70S6 con-rod usage.
e. The pearlite and ferrite structure is too soft (190 HB.) to get a perfect brittle fracture.

As a result; and according to the optical and SEM photos, it has been appraised that tempered martensite microstructure in C70S6 could be an important alternative to conventional % 90 pearlite C70S6 con-rod steel. It has been splitted into two pieces by an impact load successfully without deformation. Hardness value is measured as 306 HB. In this study we have observed the changes of parameters by some kind of heat treatment applications. It has also been appraised that appropriate fracture parameters of hardness and toughness could be obtained esp.obtaining tempered martensite. The impact fracture test is carried out and it has been seen that the crack starts from SN and it is a one peace and brittle fracture. That is a desired effect for crackable parameters.

Fine Fe_3C particles (Fig.17) increase hardness in tempered martensite and untransformed ferrite particles increase toughness. The optimum hardness value for crackable C70S6 con-rods is 280-310 HB.[5]. The hardness of tempered martensite is measured as 306 HB. This is an important result. The technological use of tempered martensite in crackable con-rods should be investigated according to the results above. The con-rods as in working conditions need strength and toughness. It is evaluated that tempered martensite is applicable in crackable con-rods.

4. Conclusions:

The following conclusions can be drawn from this study:

1. The tempered martensite could be an economic alternative to the fracture splitting process, but water quenched martensite is not suitable for fracture splitting process because its microstructure is too hard and brittle.
2. Pearlitic and ferritic microstructure is too mild, so it could not be a better alternative to the fracture splitting process.
3. Changing the chemical structure by adding different alloys and austempering to get lower or upper bainite and evaluation SEM metallography could be a future study to optimize the fracture parameters.
4. Fracture tests of the C70S6 bainitic microstructure could be studied, this could be another research area.
5. Fatigue and impact test could be carried out of the tempered martensite and ferritic microstructure.

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