The Development of M48 High-strength Bolt Steel for Wind Turbine Machine

SHOU-CHI LIN, JUI-FAN TU and HONG-RONG LIN

Iron and Steel Research & Development Department
China Steel Corporation

Wind turbine bolts have become the new promising product of the fastener industry in Taiwan, a major fastener exporter in the world for decades. The rigid strength, toughness and hardenability requirements of the wind turbine bolt steels are really challenging work for a steel company. Mass effect caused insufficient hardness and strength in M42 bolts and above with SCM440. M48 bolts would be a new product for our customers to develop in 2011, provided that the new steel is designed in time. New steel for M48 bolts, with careful alloy design and inclusion control, have been developed and well-received by our fastener customers. The specific heat-treatment parameters of the new steel, inclusive of temper embrittlement and quench sensibility, have been examined in this study. The tensile mechanism of a high strength material, especially the reduction of area, was also studied in this project.

Keywords: Wind turbine bolt, Alloy design, Hardenability, Inclusion control

1. INTRODUCTION

The use of wind power, a form of renewable energy, is soaring in the 21st century. World wind generation capacity has doubled about every three years between 2000 and 2006. The World Wind Energy Association forecast that, by 2010, over 200 GW of capacity will have been installed worldwide, predicting another impressive 30% yearly growth rate from 2006 to 2010.

A wind turbine is a rotary device that extracts energy from the wind. Horizontal-axis wind turbines, the most popular ones, generally consist of a foundation, tower, nacelle and blades. With the vast growth world-wide in the construction of wind farms in recent years, wind turbine bolts have become a new promising product for the Taiwan fastener industry, one of the leading fastener export countries in the world. Wind turbine bolts for nacelles and blades, like all bolts for aerospace use, have higher standards than other bolts as shown in Fig.1. The rigid strength, toughness and hardenability requirements of the wind turbine bolt steels are challenging work for a steel manufacturing company [1-2].

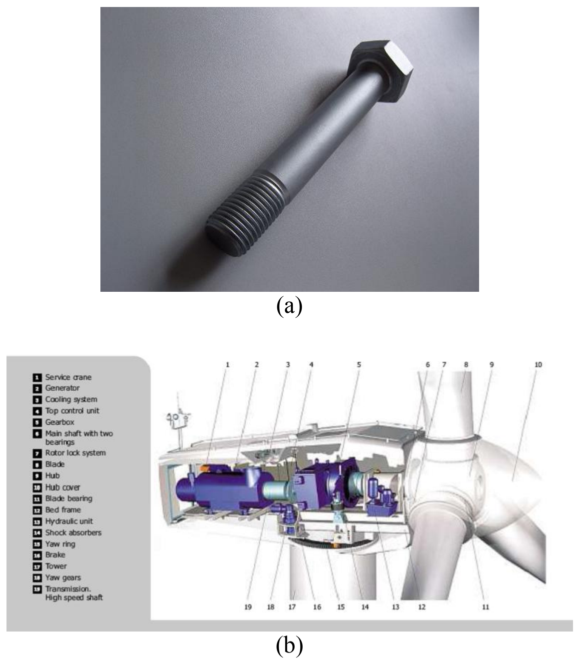


Fig.1. (a) Wind turbine bolts and (b) Nacelle and blades.

Screws and bolts are made from a wide range of materials, with steel being perhaps the most common, in many varieties. ISO 898.1 specification is the primary specification used in wind turbine bolt production. Some other specific requirements may be negotiated between buyers and suppliers. Tables 1 and 2 show the requirements of material, chemical composition, and mechanical and physical properties in ISO 898.1 Steel bolts usually have a hexagonal head with an ISO strength rating (called the property class) stamped on the head. The property classes most often used are 5.8,

Table 1 Material and chemical composition in ISO 898.1

Property class	Material and heat treatment	Chemical composition limits (cast analysis, %)				Tempering temperature °C min.
		C	P	S	B	
10.9	Alloy steel quenched and tempered	0.20/ 0.55	0.025 max.	0.025 max.	0.003 max.	425.
12.9	Alloy steel quenched and tempered	0.30/ 0.55	0.025 max.	0.025 max.	0.003 max.	425.

Table 2 Mechanical and physical properties of bolts, screws and studs in ISO 898.1

Property class	Tensile strength, MPa	Stress at 0.2% elong, MPa	Percentage elongation, %	Percentage reduction of area, %	Rockwell hardness, HRC	Impact strength, J, at -20°C
10.9	1040 min	940 min	9 min	48 min	32 - 39	27 min
12.9	1220 min	1100 min	8 min	44 min	39 - 44	---

8.8, 10.9, and 12.9. High-strength steel bolts have property classes of 8.8 or above, and wind turbine bolts have property classes of 10.9 or above. For the materials with property classes of 8.8 and above, there must be a sufficient hardenability to ensure a structure consisting of approximately 90% martensite in the core of the threaded sections for the fasteners in the "as-hardened" condition before tempering[3-6].

Wind turbine bolts have become the newest product of Taiwan fastener industry in this decade. SCM435 (AISI 4135) steel was the material for producing M24-M27 bolts, and SCM440 (AISI 4140) steel was for M30-M36 bolts. The nominal diameter of a metric bolt is the outer diameter of the thread, and M36 means that the nominal diameter of the bolt is 36mm. Our customers have consistently complained about the inhomogeneous mechanical properties of M42 bolt manufactured with SCM440 since 2009, and their complaints included unstable and insufficient hardness and strength reading. Mass effect caused this instability in the M42 bolts and above. The M48 bolt would be new product developed by our customers in 2011, and a new steel should be designed in time. Some quench cracking, and longitudinal cracks along the bolt body, have happened in production. The cause of this quench cracking, as requested by our customers, is examined in this study[7].

2. EXPERIMENTAL PROCEDURE

2.1 The Jominy end-quench test

The Jominy end-quench test is the standard method to determine hardenabilty. The cylindrical specimen is heated to the austenizing temperature. One end of the bar end is cooled by a water jet in the recirculating water tank. Since one end is quenched and the other end is at room temperature air, the cooling rate varies along the length of the bar. After cooling, the specimen is ground and the hardness values are measured along the length using the Rockwell hardness tester. The hardness data are plotted vs. length to generate hardenability curves as shown in Fig.2. The farther away from the quenched end that the hardness extends, the higher the hardenability.

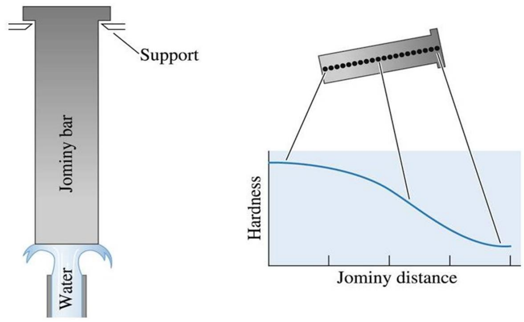


Fig. 2. The Jominy end-quench test.

The hardenability of ferrous alloys, such as steels, is a function of the carbon content and other alloying elements and the grain size of the austenite. The rate of cooling significantly affects the microstructure of steel. When a thick section of steel is quenched the cooling rate varies with the distance from the surface. Hardenability refers to the depth to which martensite is formed [8-9].

The new steel produced by China Steel (CSC) BC 4149, is a medium- carbon Cr-Mo alloy steel, designed for the M48 bolt, and has an adequate addition of hardening elements, such as carbon, chromium and molybnedem, to increase hardenability. The inclusion content and distribution, especially of phosphorus and sulfur, had a great influence on the ductility and impact energy and was therefore set to the minimum level of the mill. Table 3 shows the composition of CSC BC 4149. The Jominy end-quenched test-pieces were sampled from hot-forged steels to evaluate the hardenability of the steel.

Table 3 Chemical composition of BC 4149 (unit：wt %)

	C	Si	Mn	P	S	Cr	Mo	Al
BC 4149	0.49	0.24	0.77	0.014	0.008	1.00	0.19	0.023

2.2 Heat-treatment evaluation testing

The hardening of steel consists of heating the metal to a high temperature (austenitizing) for a specified time to complete transformation to austenite and diffusion of constituents and then cooling the metal in a quenching medium that produces the desired microstructure and as-quenched hardness. The quenching is necessary to suppress the normal breakdown of austenite into ferrite and cementite, and to cause a partial decomposition at such a low temperature to produce martensite.

To obtain this, steel requires a critical cooling velocity, which is greatly reduced by the presence of alloying elements, which therefore cause hardening with mild quenching (e.g. oil and hardening steels). This hardening treatment is most often followed by a lower temperature heating process (tempering) for stress relieving and finalizing the required microstructure to achieve the necessary physical properties. This sequence is illustrated in Fig.3.

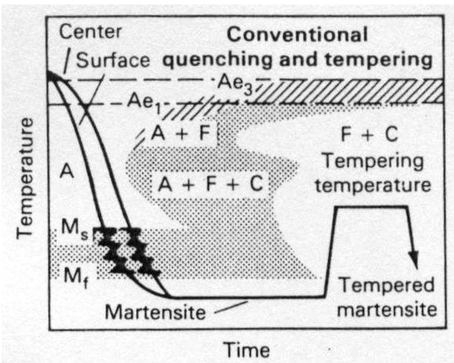


Fig.3. Quench and temper sequence.

The heat-treatment conditions for SCM 440 for our bolt customers was austentizing at 840°C and tempering at 540°C. Heat-treatment testing evaluation was carried out on the BC 4149 steel after austentizing at 840°C and tempering at 200-700°C. Several mechanical tests, and tensile, hardness and impact testing, were also performed on the heat-treated test-pieces.

The microstructure of tensile, hardness and impact test-pieces were observed under optical microscopes, SEM and TEM. Any fractured surface of the tensile and impact test-pieces were observed under SEM.

2.3 quench sensibility test

When steel is quenched the volume changes of austenite transformation occur very rapidly and unevenly throughout the specimen. Stresses are set up, which may cause the metal either to distort or to crack, if the ductility is insufficient for plastic flow to occur. Such cracks may occur some time after the quenching or in the early stages of tempering[10-11].

Quench cracks are liable to occur:

(a) due to excessive cooling rates during the quench (quench severity)
(b) non-uniform fluid flow or contamination of the quenchant
(c) non-uniform heating or cooling or localized overheating
(d) prior steel structure, and
(e) improper design of product

A quench sensibility test was performed to assess the quench sensibility of the steels. Hot-forged test-pieces, ψ50 and ψ60 BC 4149, were used to perform the test. Test-pieces after austentizing were quenched in an agitating 80°C oil and 20°C water mixture, the most popular quenching media, in ordinary and specific ways. A jet water quench, where water was pouring over one end of the test-piece, was tested. In another oil combined quench, 2 test-pieces were fixed together with wire and quenched in non-agitating oil tank after heating. Each test-piece was examined after the quenching to see if there was quench crack or not.

3. RESULTS AND DISCUSSION

3.1. The hardenability of the steels

The Jominy end-quench test is the standard method to determine hardenabilty. Jominy end-quenched test-pieces were sampled from hot-forged BC 4149 steel. The test results of SCM440 and BC 4149 are shown in Fig.4, which exhibits that BC 4149 had a better hardenabilty than SCM440. Each hardness reading for a different distance from the quenching end represented a specific cooling rate. At a certain cooling rate, for example at J7 (13mm or 7/16inch from the quenching end), the hardness of SCM440 was HRC50, and of BC 4149 it was HRC57. The farther away from the quenched end that the hardness extends, the higher the hardenability. For a hardness above HRC 50, the reading of SCM440 was at J7, and of BC 4149 at J10. With a substantial increase of hardenability, BC 4149 steel could meet the uniform microstructure requirements of M48 bolt, with over 90% martensite in the core of the threaded sections for the fasteners in the "as-hardened" condition before tempering.

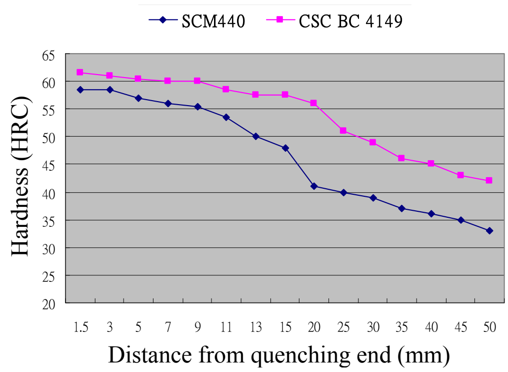


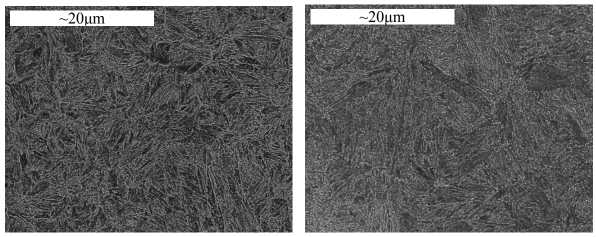
Fig.4. Jominy end-quench test result of SCM440 and BC 4149.

3.2. Heat-treatment evaluation

The heat-treatment testing evaluation for BC 4149 was arranged to be austentizing at 840°C and tempering between 520-620°C. Evaluation results of the mechanical properties are shown in Tables 4 and 5. As the tempering temperature went higher, the strength (YS, TS, hardness) went down and ductily (Percentage elongation and reduction of area) went up. For 10.9 bolts, the target hardness reading should be HRC 35-37, as a lower hardness would result in insufficient strength, and a higher hardness would result in insufficient ductility.

The austenizing temperature is 840°C for hypo-eutectoid BC 4149 steel, which is the same as for SCM440. Adequate tempering conditions for BC 4149 should be 580-600°C after quenching. All the mechanical requirements, strength, elongation and impact energy, could be met by an adequate heat-treating operation.

Figure 5 shows the SEM microstructure of BC 4149, tempered at 500°C and 600°C, was over 90% tempered martensite. Precipitated carbide was more obviously observed on the 600°C test-pieces. TEM observation of the 600°C test-pieces are shown in Fig.6, with 10-60nm carbides precipitated along the grain-boundaries and within the grains under the higher tempering temperature. Some recrystalization may have occurred, as some new grains without dislocation inside are noticeable.



(a) (b)

Fig.5. SEM microstructure of BC 4149 (a) 500°C and (b) 600°C .

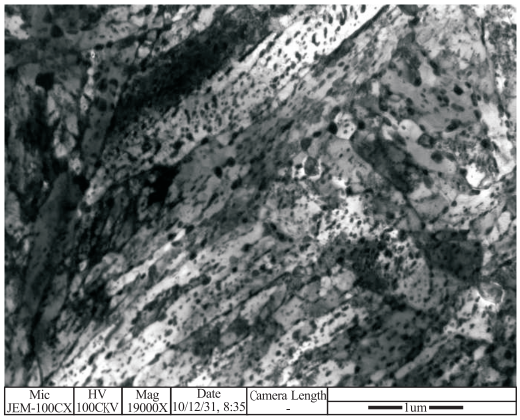


Fig.6. TEM microstructure of BC 4149, tempered at 600°C.

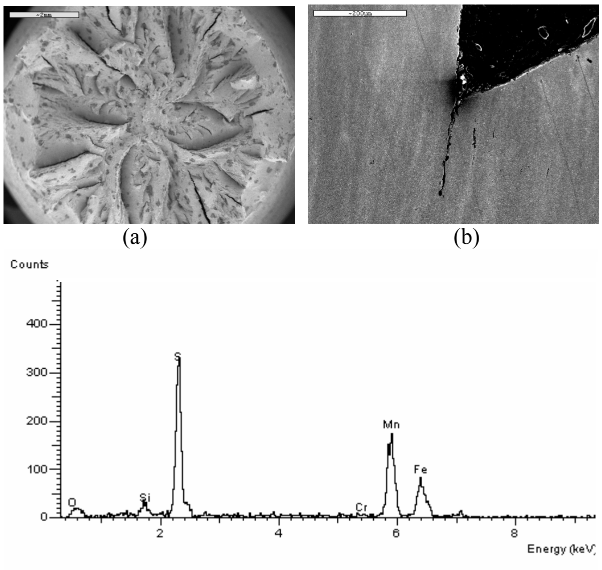
Any fractured surface of the tensile test-pieces was examined under SEM. There were cracks initiating area in the center, with 1-3mm in diameter, the crack then propagated outward and resulted in fracture, as shown in Fig.7(a). Minor cracks also followed the inclusions in the steel in cross-section observation of the fractured surface. The inclusions were identified as MnS by EDS.

Table 4 Tempered hardness of BC 4149 (in HRC)

	200°C	300°C	400°C	500°C	600°C	700°C
BC 4149	57	52	49	43	35	26

Table 5 Mechanical properties of BC 4149

	Y.S. (MPa)	T.S. (MPa)	E.L. (%)	R.A. (%)	Impact(J) -40°C
ISO 898.1	940 ↑	1040 ↑	9 ↑	48 ↑	27 J ↑
BC 4149-580°C	1020	1140	18.5	54.45	41.9
BC 4149-600°C	980	1099	18.12	54.95	58.8



(a) (b) (c)

Fig.7. SEM (a)Fractured surface of BC 4149, (b)Minor cracks along the inclusion, and (c)MnS.

3.3. Results of quench sensibility test

After general water or oil quenching procedures, no quench cracks were observed. In jet water quench, where water was pouring over one end of the test-piece, circular end cracks appeared on the quenching end of both steels. Theses circular quench cracks were due to excessive cooling rates during the jet quench and are exhibited in Fig.8(a).

(a) (b)

Fig.8. (a)Circular quench cracks, and (b)A longitudinal quench crack.

In the oil combined quench, the combined test-pieces were heated and then quenched in a non-agitating oil tank. A longitudinal crack appeared on one side of BC 4149 ψ60 test-piece as shown in Fig. 8(b), while no crack appeared on the ψ50 test-piece. The combined test-pieces had an uneven cooling; the cooling rate of the contact side was so slow and of the non-contact side was fast. The difference of the cooling rate induced a longitudinal stress field and a quench crack appeared. The type of quench crack in the customer's plant was longitudinal quench cracks on the bolts. Poor racking of the parts prior to the quench or non-uniform fluid flow around the part in the oil quench tank should be the cause of the quench crack.

3.4. Manufacture of bolts at customer's plant

The BC 4149 steel was vacuum-melted, ingot cast hot forged, spheroidizing annealed and machined to the dimensions for a customer trial. Sample steels BC 4149 were sent to our customer for M48 bolt manufacturing. Head forging, thread rolling, heat-treating practices were smoothly conducted. Tables 6 and 7 list the mechanical and physical properties of the bolts. The hardness distribution of the cross section after quenching had a very uniform result. Strength, elongation, and impact energy were good, but the percentage reduction of area was below the 48% requirement. The testing temperature for the impact test was -40°C, stricter than the -20°C by specification.

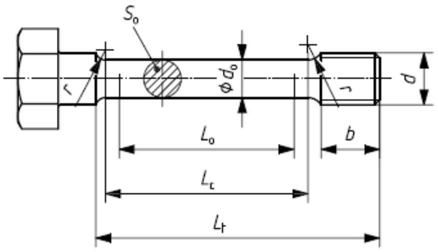
The types of tensile test-pieces used could lead to the difference of reduction of area readings between the laboratory and plant. According to the ISO 898.1 specification, a machined test-piece should be tested for large bolts as shown in Fig.9. For the M48 bolt, a machined test-piece with 36mmψ was tested. A 20 mmψmachined test-piece was used to perform tensile test for large bolts in the plant because of the capacity of the old 50-ton universal testing machine. Besides, the laboratory test-pieces sampled from the 30mm bar after forging, with higher reduction ratio, had better readings than the test-pieces of bolts from the 55mm bar.

Table 6 Tempered hardness of BC 4149 on the M48 bolts (in HRC)

	As-quenched	Center	1/4 D	1/2 D
BC 4149-M48	58.5	37.2	36.3	36.2

Table 7 Mechanical properties of BC 4149 on the M48 bolts

	Y.S. (MPa)	T.S. (MPa)	E.L. (%)	R.A. (%)	Impact(J) -40℃
ISO 898.1	940 ↑	1040 ↑	9 ↑	48 ↑	27 J ↑
BC 4149-M48	1048	1145	12.9	44.2	30.7
M48 2nd test	1023	1124	14.8	52.2	45.7



(a)

Key

- d nominal thread diameter
- d_o diameter of machined test piece (d_o<$d_{3\ min}$ but, whenever possible, $d_o \geq$ 3mm.)
- b thread length ($b \geq d$)
- L_o original gauge length of machined test piece
  - －for determination of elongation: $L_o = 5d_o$ or $(5,65\sqrt{S_O})$
  - －for determination of reduction of area: $L_O \geq 3d_O$
- L_c length of straight portion of machined test piece $(L_o + d_o)$
- L_t total length of machined test piece $(Lc+2r+b)$
- S_o cross-sectional area of machined test piece before tensile test
- r fillet radius (r ≥4 mm)

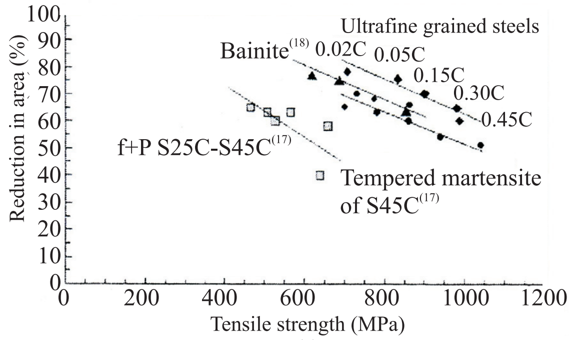
(b)

Fig.9. (a)A machined test-piece in ISO 898.1 specification, and (b)A machined test-piece from stud.

The BC 4149 steel was accepted by our customer after the first test. A 2nd test was then arranged to be carried out. For the 2nd bolt test, the 36mm ψmachined test-pieces were tested on a 200-ton universal testing machine, and all the properties met the mechanical requirements, with an acceptable 52% RA.

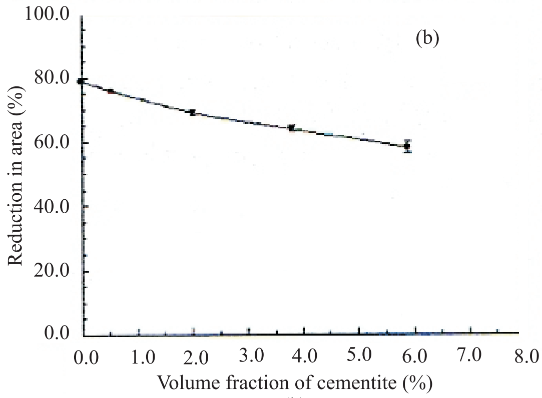
3.5. Reduction of area test

It was reported that the percentage reduction of area was directly related to the microstructure. Different microstructures, such as those of ferrite and pearlite, ferrite and cementite, bainite, and martensite, had a certain value range of percentage reduction of area in tensile result. From the database of the National Institute of Material Science in Japan, the value of the percentage reduction of area of ferrite and pearlite lay between 45-70%, bainite between 62-82%, tempered martensite between 50-65%, and ultrafine-grain steel between 45-70%. For a ferrite and cementite microstructure, the percentage reduction of area reading went lower as the volume of cementite increased. As shown in Fig.10, when the volume of cementite increased from 0.1 to 6% , the percentage reduction of area reading fell from 80 to 60 % [12-13].



(a)

Relationship between reduction in area (RA) and tensile Strength of ferrite + perlite steel (■)(9), bainite steel(Δ)(10) tempered martensite (●)(9), and ultrafine-grained steel (♦).



(b)

Fig.10. (a)Percentage reduction of area with different microstructures, and (b)Reduction of area under different volume of 2nd phase.

Due to the incident in the customer's bolt plant, a reduction of area test was performed to realize the tensile mechanism. Test-pieces of BC 4149 were pulled at several different stages to monitor the progress of the tensile test. Compared with the reduction of area, the elongation readings were much easier to control in a universal tester. From a stress strain curve for BC 4149, load reached its maximum value at around 7% strain, then, necking began. Test-pieces with differing elongation targets of 10, 12, 14, 16, 17, and 18%, were tested and then the loading was stopped and the test-pieces released for further investigation. The reduction of area readings linearly increased with elongation readings between 10-18% elongations. The 18% test-piece was broken at once on the machine upon load-release.

All elongation-RA test-pieces were examined by

X-ray Radiographic inspection, to see if any flaw had developed during the different tensile elongation stages. Radiographic inspection is a nondestructive testing technique used to evaluate objects and components for signs of flaws which could interfere with their function. It is accomplished with the use of radiographs, images generated by bombarding the object under inspection with radiation. X-ray and gamma ray radiographic inspection are the two most common forms of this inspection technique. China Steel has our own nondestructive inspection facilities for in-house inspections. No flaw was observed in any of the elongation-RA test-pieces, not even in the 17% El test-piece, as shown in Fig.11 (14) .

The basic steps of ductile fracture, void formation, void coalescence (also known as crack formation), crack propagation, and failure, often result in a cup-and-cone shaped failure surface. For a high-strength material, there are three steps in a fracture process: crack initiation, crack propagation and final fracture. The bolt material BC 4149, with 18% elongation and good toughness, had a very long crack initiation step while crack propagation and fracture followed and developed soon after crack initiation.

(a) (b)

Fig.11. (a) Test-pieces with different elongation %, and (b) Metallurgical sample of 17% testpiece.

4. CONCLUSIONS

The new steel, BC 4149, with adequate hardening elements and inclusion control, could meet the heat treatment requirements of the M48 bolt. The hardness distribution of the cross section after quenching had a very uniform and steady result, and ensured a 90% martensite microstructure requirement. Austenizing temperature is 840°C for both steels. The tempering conditions for BC 4149 are 580-600°C after quenching. All the mechanical requirements, strength elongation and impact energy, could be met by a proper heat-treatment operation. M48 bolt samples, using the actual production line of the customer, were made in this project. Satisfactory trial results were achieved and the first order will ship to customers this April for M48 wind-turbine bolts.

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