by H.P. Leighly, Jr., B.L. Bramfitt, and S.J. Lawrence

RMS Titanic: A Metallurgical Problem

On 14 April 1912, at 11:40 p.m., Greenland Time, the Royal Mail Ship Titanic on its maiden voyage was proceeding westward at 21.5 knots (40 km/h) when the lookouts on the foremast sighted a massive iceberg estimated to have weighed between 150,000 to 300,000 tons at a distance of 500 m ahead. Immediately, the ship's engines were reversed and the ship was turned to port (left) in an attempt to avoid the iceberg. In about 40 seconds, the ship struck the iceberg below the waterline on its starboard (right) side near the bow. The iceberg raked the hull of the ship for 100 m, destroying the integrity of the six forward watertight compartments. Within 2 h 40 min the RMS Titanic sank.

Metallurgical examination and chemical analysis of the steel taken from the Titanic revealed important clues that allow an understanding of the severity of the damage inflicted on the hull. Although the steel was probably as good as was available at the time the ship was constructed, it was very inferior when compared with modern steel. The notch toughness showed a very low value (4 joules) for the steel at the water temperature (-2 °C) in the North Atlantic at the time of the accident.

One evening in early 1907, Lord William James Pirrie, managing director and controlling chairman, Harland and Wolff, Shipbuilders, Belfast, Northern Ireland, entertained at dinner J. Bruce Ismay, chairman, Oceanic Steam Navigation Company. This latter company was better known as the White Star Line, named after the company pennant, a white star on a red field. The White Star Line was owned by the International Mercantile Marine Company, which was controlled by J.P. Morgan. After their meal, the two men planned the future of the White Star Line.

At that time, the chief competitor to the White Star Line was the Cunard Steamship Company, which had the two largest and fastest passenger ships in the world, the RMS Lusitania and the RMS Mauretania, each having a gross tonnage of 31,000 tons with a maximum speed of 26 knots (50 km/h). It was decided that the White Star Line should establish a three-ship weekly steamship service for passengers and mail between Southampton, England, and New York.

Harland and Wolff agreed to build three ships for the White Star Line, each having a gross tonnage of 46,000 tons; the RMS Olympic, the RMS Titanic, and the RMS Gigantic. (The name of the third ship was changed to the RMS Britannic after the RMS Titanic tragedy.) These ships were to be built on a cost-plus fixed-fee contract.

The White Star Line did not intend to compete in speed with the RMS Lusitania and the RMS Mauretania (23 knots vs. 26 knots)(45 km/h vs. 50 km/h), but rather to have more elegant accommodations and facilities than the Cunard ships. In order to build such large ships, Harland and Wolff would have to rebuild their shipyard replacing three smaller ways with two larger ones and install new gantry cranes having greater load carrying capacity.

The keel of the RMS Olympic was laid on 16 December 1908, with the ship being launched on 20 October 1910. The keel for the RMS Titanic was laid on 31 March 1909, followed by its launching on 31 May 1911. The RMS Titanic was fitted out and ready for sea trials in early April 1912. There had been a delay in the completion of the RMS Titanic because the RMS Olympic, on its fifth voyage, and the British cruiser HMS Hawke collided in the Solent off Southampton harbor on 20 September 1911.[1] The RMS Olympic was damaged on the starboard side 25 m forward of the stern.

The main damage was a gaping hole through the hull plates. After emergency repairs were made in Southampton, it proceeded to Belfast for permanent repairs at the shipyard of Harland and Wolff. Shipyard workers normally assigned to work on the RMS Titanic were diverted to the RMS Olympic in order to return it to service with as little delay as possible.

After two days of sea trials in the Irish Sea, the RMS Titanic tied up at Ocean Dock in Southampton on 4 April 1912. The days before the scheduled departure day, 10 April, were used to allow the workmen from the shipyard to complete the outfitting of the ship, to permit the loading of provisions on board for the voyage, to secure an adequate supply of coal because of a miners strike, and to conclude the hiring of the hotel staff and the ship's crew.

The iceberg raked the hull of the Titanic for 100 m, cracking hull plates and popping rivets, thus destroying the integrity of the first six of 16 watertight compartments formed by the transverse bulkheads.

The Voyage

Shortly before noon on Wednesday, 10 April, the lines holding the RMS Titanic to Ocean Dock were cast off and the RMS Titanic started down the Southampton Water into the Solent, then into the English Channel. As the RMS Titanic passed a neighboring dock where the SS New York was moored, a surge of water from the RMS Titanic caused the SS New York to break its cables so that it drifted toward the RMS Titanic. Skilled seamanship and the intervention by tug boats prevented the ships from making contact with each other.

Cherbourg was the first port of call. The RMS Titanic arrived in the port during the evening of the first day. Because the RMS Titanic was too long for the dock, the passengers and mail were transferred from the dock to the ship by the two White Star Line tenders, the SS Nomadic and the SS Traffic. Many of the first class passengers came on board at Cherbourg after having spent the winter in the South of France, on the Greek Isles, or in Egypt.

The next morning, the RMS Titanic called at Queenstown (now Cobh), Ireland, where the two tenders, the SS America and the SS Ireland, brought aboard about 130 passengers, mostly immigrants in steerage class, and 1400 sacks of mail, much of which had been brought by train from London across southern England and by boat across the Irish Sea the night before.

After leaving Queenstown, the Titanic headed west on a great circle route toward "the corner," which is located in the Grand Banks of Newfoundland. At the corner, the direction would have been changed to a straight course line toward Sandy Hook, which is located 25 km south of Manhattan Island, New York. The Irish coast was left behind at dusk on Thursday, 11 April.

The next morning, Friday, 12 April, the weather was sunny but cold. Shortly after noon the French liner, SS La Touraine, sent advice by radio of ice in the shipping lanes. This was almost 60 hours before the RMS Titanic collided with the iceberg. In April, ice in the shipping lanes was not unusual; however, during the spring of 1912, the amount of ice in the North Atlantic was unusually large.

As the RMS Titanic continued westward on its course, more frequent and more urgent radio messages were received repeating the warning of ice ahead in the western North Atlantic. Twice Captain Edward Smith of the RMS Titanic ordered the ship to a more southerly course but he failed to reduce the speed. After the sinking of the RMS Titanic, it was determined on the basis of several reports that a very large icefield about 120 km long stretched on a northeast-southwest axis across the shipping lanes. It was estimated to be about 20 km wide.[2]

It was a moonless night on 14 April with no wind so the sea was dead calm. At 11:40 p.m., Greenland time, the lookouts in the crow's nest on the foremast spotted a huge iceberg, estimated to have weighed between 150,000 and 300,000 tons, about 500 m ahead. The bridge was alerted. The officer of the watch, First Officer William Murdoch, ordered the engines to be reversed and the ship be turned hard to port. Within 40 seconds, the RMS Titanic collided with the iceberg, the point of impact being on the starboard side, just behind the bow, about 3 m above the keel and 8 m below the water line. The iceberg raked the hull of the Titanic for 100 m, cracking hull plates and popping rivets, thus destroying the integrity of the first six of 16 watertight compartments formed by the transverse bulkheads. Captain Smith and Thomas Andrews, a managing director and chief designer for Harland and Wolff, together surveyed the ship. Their findings revealed that the ship could not survive long because it had been fatally damaged.

It was originally assumed that the collision developed a continuous crack 100 m long in the hull; however, Edward Wilding,[3] a design engineer for Harland and Wolff, calculated on the basis of the rate of flooding reported by survivors that openings in the hull totaling 1.115 m^2 had caused the RMS Titanic to sink. Recent computer calculations by Hackett and Bedford[4] using the same survivors' information, but allocating the damage to the first six individual compartments, is given in Table 1. Their calculated total area of openings in the hull is 1.171 m^2.

Captain Smith gave the order to abandon ship. It was difficult to persuade many of the passengers that the RMS Titanic was really sinking. In keeping with the British Board of Trade regulations of 1894, the RMS Titanic carried 16 lifeboats, the minimum allowable number. In addition, it carried four Engelhardt collapsible lifeboats. The total capacity of all these lifeboats was about 1100 persons, approximately half the number of people on board the ship. Very few of the lifeboats were loaded to their designed capacity before being lowered away, and only 706 persons were saved.

The fraction of those on board who were saved was greatest among the first class passengers, next were the second class passengers, and last were the steerage passengers, the crew, and the hotel staff. Because the voyage took place early in the sailing season, the RMS Titanic was not filled to capacity. It could have taken another 1000 passengers.

At 2:20 a.m., 15 April, the RMS Titanic sank below the surface of the North Atlantic. It went bow down at about a 35° angle. The stern section broke from the bow and drifted away to sink separately. The bow, being full of water, sank very quickly, burying itself 19 m into the mud on the bottom of the ocean. The stern sank more slowly. Both major pieces now sit in 3,700 m of water about 600 m apart with a debris field between them. Both sections are in the upright position.[3]

The Manufacturing of Steel Plate

To determine the possible contribution the hull steel made to the demise of the RMS Titanic, the following factors will be considered: the chemical composition, the microstructure, and the mechanical properties, mainly the notch toughness as determined by the Charpy Impact Test.

The steelmaking process can have an important effect on these factors. Steelmaking between the time of the construction of the RMS Titanic, 1909 to 1911, and current steelmaking practice are vastly different. It has been suggested that Harland and Wolff used less expensive and inferior steel; however, there was no incentive to use such steel – as pointed out previously, they had a cost-plus fixed-fee contract with the White Star Line to build the three ships of the RMS Olympic class.

Ship Plate Manufactured for the RMS Titanic

It is believed that the main source of the steel plate used for the construction of the RMS Titanic was the steelworks of David Colville and Company located in the Borough of Dalzell in Motherwell, Scotland.[5] Evidence to support the supposition that the steel used in the Titanic was provided by David Colville and Company is a piece of channel beam with "Dalzell" embossed on it that was retrieved during the 1996 expedition. An earlier expedition (1991)[6] recovered another small piece of the hull of the RMS Titanic. The hull plate used in this study was recovered in August 1996 from the debris field located between the bow and stern sections on the bottom of the ocean.

According to Davis[7] about two-thirds of the steel produced in Britain in 1910 was made in acid-lined open hearth furnaces. Colville[5] installed a 50 ton acid-lined open hearth furnace in 1906. An acid-lined open hearth furnace utilized acid refractories such as silica, fireclay, and ganister as the lining for the furnace. An acid slag practice was employed. Because of the use of acid lining in the open hearth furnace and the acid slag practice, phosphorus and sulfur could not be removed during the steelmaking process. Low sulfur steel could be produced if a low sulfur pig iron was used, such as that smelted from low sulfur iron ore obtained from Sweden. This was a common source of iron ore used in Britain in the late 19th and early 20th century.[8,9] However, Swedish iron ore contained about 15% titanium dioxide, which requires more fuel and a higher blast furnace operating temperature because it is more difficult to reduce the ore to iron.

Colville continued to use cold pig iron and steel scrap to make steel in an acid-lined open hearth furnace until 1919.[5] From the composition of the steel used to construct the RMS Titanic given in Table 2, namely the high sulfur and high phosphorus content, it is apparent that it was made in an acid-lined furnace. The low nitrogen content precludes the possible use of a Bessemer converter in making this steel.

The open hearth furnace was tapped into a ladle after the steel was melted and refined. The low silicon and high oxygen content indicates that there may have been only limited deoxidation as the tapping occurred. The steel was teemed into ingot molds and allowed to solidify. The molds were stripped and the ingots were reheated in a soaking pit. They were rolled into 2.54 cm thick plates and allowed to air cool.

Modern Ship Plate Manufacturing Practice

To provide a comparison between the properties of the steel used in the RMS Titanic and modern steel, 1.25 cm hot-rolled plate manufactured by the Bethlehem-Lukens Plate Division of the Bethlehem Steel Corporation was obtained. The steel had been melted using steel scrap in an electric furnace. After melting and refining, the molten steel was tapped into a ladle. Through a porous plug in the bottom of the ladle, argon gas was bubbled through the molten steel to assist in mixing the alloy additions, such as carbon, manganese, and silicon, and to partially purge dissolved gases, such as hydrogen and oxygen. The silicon was added to provide deoxidation of the steel. Phosphorus and sulfur were reduced by the use of a special molten slag of basic composition placed on the top of the molten steel in the ladle. The gas removal was completed by placing the ladle in a chamber that can be evacuated that substantially lowered the oxygen and hydrogen content in the steel.

After these procedures were performed, the steel was continuously cast to produce a solid slab, which was cut to the desired lengths. During the casting, care was taken to shield the molten steel from contact with the atmosphere. A tundish located directly above the continuous casting mold trapped inclusions and slag that floated in the molten stream of steel. The slabs were heated to the desired rolling temperature to produce a plate 1.25 cm thick. *(continued on page 33)*

Table 1 Summary of damaged areas in the hull by compartments

Compartment	Computer Calculations (m^2)
Fore Peak	0.056
Cargo Hold 1	0.139
Cargo Hold 2	0.288
Cargo Hold 3	0.307
Boiler Room 6	0.260
Boiler Room 5	0.121
Total Area	1.171

The compartments are listed in order from the bow toward the stern.
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Table 2 Chemical analysis of the RMS Titanic and modern steel

Plate	C	Mn	P	S	Si	O	N	Mn:S
Titanic (1996)[a]	0.21	0.47	0.045	0.069	0.025	0.013	0.0035	7:1
Modern[b]	0.09	0.51	0.013	0.013	0.280	0.002	0.0089	39:1

(a) Analysis by Dale Brown and Associates of Laclede Steel Company
(b) Analysis by Bethlehem-Lukens Plate Division

RMS Titanic: A Metallurgical Problem *(continued from page 13)*

Testing Procedure

Materials

Two steel plates provided the material for the following experimental results:

1. A piece of the hull plate of the RMS Titanic 1.60 cm thick was recovered in August 1996 from the debris field at the bottom of the North Atlantic Ocean between the bow and stern sections of the ship. Bringham and Lafreniere[6] had calculated that the hull plate retrieved in 1991 from the RMS Titanic had been originally 2.54 cm thick prior to the sinking and that salt water corrosion had reduced its thickness to 1.60 cm during the intervening years between 1912 and 1996.

2. A plate 1.25 cm thick was produced in December 1998 at the Bethlehem-Lukens Plate Division of Bethlehem Steel Corporation according to the American Bureau of Shipping (ABS) grade A and the American Society for Testing and Materials (ASTM) A 131 grade A specifications.

Tensile Tests

Tensile tests were conducted according to the ASTM E 8 standard test. Duplicate specimens were prepared from both plates in the longitudinal direction.

Notch Toughness Tests

Standard V-notch Charpy test specimens were machined from the central thickness for both plates in the rolling direction and in the transverse direction according to ASTM E 23. The Charpy test was developed during the early 1900s.[10] Although the test had been developed before the construction of the RMS Titanic, it had not been standardized. The ASTM established their first Provisional Standard for the Charpy Impact Test in 1933.

Light and Scanning Electron Microscopy

Optical metallographic examination of the microstructure was conducted to determine the volume percentage of pearlite, acicular ferrite, the grain size, and the volume percentage of inclusions.

Scanning electron microscopy (SEM) was used to examine the fracture surfaces of the Charpy specimens tested at various temperatures. With this instrument, one can determine the mode of fracture as a function of test temperature, i.e. to identify fracture in the upper and lower shelves and in the transition regions of the absorbed energy vs. temperature curve. Energy dispersion spectroscopy (EDS) was used to obtain chemical analysis of the nonmetallic inclusions lying on the fracture surface. For more detailed chemical analysis of selected inclusions, electron probe microanalysis (EPMA) using wavelength dispersion spectroscopy (WDS) was employed.

Table 3 Tensile properties of the RMS Titanic and modern plates

Plate	Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation	Reduction in Area
Titanic (1996)[a]	193 (28 ksi)	417 (61 ksi)	29.0%	57.1%
Modern[b]	338 (49 ksi)	441 (64 ksi)	27.0%	66.0%

(a) Tested by K. Felkins[12] using a 25.4 mm (1 in.) gage length specimen.
(b) Tested by Bethlehem-Lukens Plate Division using a 200 mm (8 in.) gage length specimen.

Results and Discussion

Chemical Analysis

The chemical composition of the hull plate recovered from the wreck site of the RMS Titanic in 1996, as well as the composition of the modern steel manufactured in 1998, are given in Table 2. Basically the RMS Titanic plate is a plain carbon steel (0.21% C) with higher than normal sulfur and phosphorus content. The Mn:S ratio for the steel recovered in 1996 is 7:1. The modern steel is lower in carbon, oxygen, sulfur, and phosphorus, all elements that are capable of reducing the notch toughness of steel, and has a very respectable Mn:S ratio, 39:1. The RMS Titanic steel would not have met ASTM or ABS chemistry requirements due to the excesses of sulfur and phosphorus and deficiency in manganese.

Tensile Properties

As previously pointed out, the first ASTM Provisional Standard for Charpy Impact Testing was established in 1933. Before that time, the only mechanical properties for evaluating steel were the measurement of the yield strength, the ultimate tensile strength, and the percent elongation on a 200 mm gage length. For the steel to be used in the RMS Titanic, Harland and Wolff required a design tensile strength of 34 to 45 ksi (234 to 310 MPa). [11] The tensile strength for the steel recovered in 1996 would have met their requirement, as given in Table 3. The modern steel plate also would have met the requirements of ASTM and ABS.

Notch Toughness

The Charpy impact test results for specimens oriented in the longitudinal and transverse directions for both the RMS Titanic steel and the modern hull plate are plotted in

Fig. 1.[13] Not surprisingly the modern steel shows very superior results. As a point of reference, it should be noted that the sea water temperature at the time of the collision was –2 °C (29 °F). The impact energy for the RMS Titanic steel at this temperature was 4 joules (3 ft-lbs.) in both the longitudinal and the transverse directions. The ductile-brittle transition temperature for the impact energy vs. temperature curve for specimens taken from the RMS Titanic and oriented in the longitudinal direction was 30 °C. Those specimens oriented in the transverse direction had a transition temperature of 42 °C.

For the modern steel, the impact energy at –2 °C for the longitudinal direction is 325 joules (240 ft-lbs.) and in the transverse direction the impact energy is 100 joules (73 ft-lbs.). The ductile-brittle transition temperature for the modern steel is –42 °C in both the longitudinal and transverse direction.

The low notch toughness of the RMS Titanic steel of 4 joules (3 ft-lbs.) at the temperature of the sea water (–2 °C) at the time of the collision with the iceberg means that the steel would have been prone to brittle fracture. Certainly brittle fracture of the steel hull plate contributed to the sinking of the ship. The low manganese:sulfur ratio of 7:1 for the 1996 RMS Titanic steel will allow the formation of iron sulfide or mixed iron-manganese sulfides in preference to the formation of manganese sulfides. Iron sulfides tend to be less plastic and more brittle than manganese sulfides. In order to have only manganese sulfide present, the Mn:S ratio must be at least 20:1. The modern steel used in this study has a Mn:S ratio of 39:1, hence yielding a high notch toughness and the low ductile-brittle transition temperature.

It has been suggested that the sinking of the RMS Titanic was due exclusively to the fracture of the rivets holding the hull plates together. The rivets were made from wrought iron. This implies that fracture of the plates would not have occurred as the iceberg raked the hull for 100 m. There were examples of fracture with no ductile behavior observed on the edges of the plates recovered during the 1996 expedition. Because the bow of the ship had plunged so deeply into the mud at the bottom of the ocean (19 m), it will never be possible to examine the nature and extent of the damage to the hull caused by the collision with the iceberg.

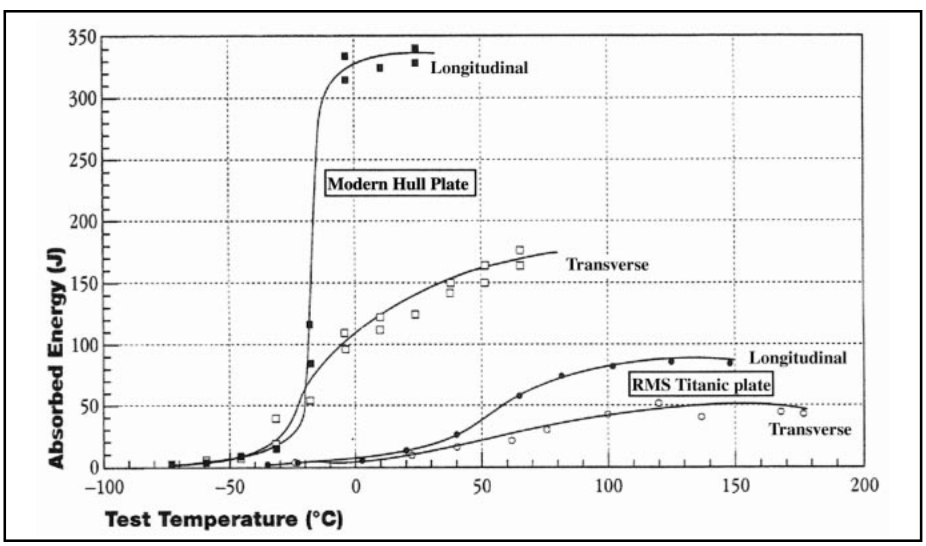

Fig. 1 Longitudinal and transverse toughness of the 1996 RMS Titanic plate compared with that of modern steel plate. Reproduced with permission of the Iron & Steelmaker.[13]

Optical Microscopy

The RMS Titanic plate from the 1996 expedition was prepared metallographically to reveal the microstructure on the longitudinal and transverse directions, as shown in Fig. 2. The longitudinal section shows pearlite and acicular ferrite. Because the direction of rolling is parallel to the horizontal orientation of Fig. 2b, one observes banding of the pearlite colonies, and elongation of the sulfide particles and silicate particles. The microstructure is fairly typical of a 0.21% C steel. The percentage of pearlite is about 15% of the microstructure. The acicular ferrite, about 5%, is the result of air cooling of a steel having a large austenite grain size through the Ac_3 temperature. The average grain size is 22.7 μm (ASTM 7.6). The transverse section shows very little or no banding.

The microstructure of the modern steel plate is shown in Fig. 3, both longitudinal and transverse sections. There is no evidence of banding in either of the sections. For comparison, the same magnifications are used in Fig. 2 and 3. The microstructure consists of ferrite and a small amount of pearlite, 8.5%, which is expected because the carbon content is 0.09% in this steel. The grain size of the modern steel is 20 μm (ASTM 7.9), somewhat smaller than the RMS Titanic steel.

Analysis of the Non-metallic Inclusions

Optical microscopic examination of

a well polished but unetched RMS Titanic steel specimen revealed the non-metallic inclusions. Figure 4 shows a typical worst field view (ASTM E 45) of inclusions at 500×, for the transverse plane. The dark gray inclusions are silicates, whereas the light gray inclusions are sulfides. The elongated and rounded particles of a large silicate and several sulfides are shown in Fig. 5. The composition of the sulfide particles determines its plasticity. Manganese sulfide particles are more plastic than iron sulfides. The presence of iron in the manganese sulfide reduces the plasticity of the particles.

Because the RMS Titanic steel has a Mn:S ratio of 7:1, the MnS particles will have a varying amount of iron replacing manganese. The silicate particles (slag) are the result of their entrapment in the molten steel during teeming into an ingot mold. By modern standards, the RMS Titanic steel is "dirty steel." It would not be acceptable by current standards. The RMS Titanic steel (1996) has 0.396 vol.% sulfides and 0.133 vol.% silicates, as compared with modern steel having 0.021 vol.% sulfides and 0.014 vol.% oxides and mixed oxides and sulfides. From these data, it is apparent that the modern steel is much cleaner than the RMS Titanic steel.

The characteristic X-rays emitted by the large silicate particle shown in Fig. 5 are mapped in order to identify the elements present. The resulting images are shown in Fig. 6. The dominant and most uniformly distributed element present is silicon, which is to be expected. Manganese is nearly uniformly distributed, while the oxygen and silicon have a similar density. This indicates that they co-exist as manganese silicate present in copious amounts in the slag inclusion. The sulfur is confined to small regions on the slag inclusion, which appear as "droplets" on the slag particle shown in Fig. 5. The silicon and oxygen have parallel concentrations while the sulfur concentration is complementary to the silicon and oxygen concentration, i.e. where there is a high concentration of silicon and oxygen, there is little or no sulfur and vice versa. The small amount of titanium in the slag offers confirmation to the idea suggested above that titanium bearing low sulfur iron ore from Sweden was probably used to make the RMS Titanic steel in order to minimize the sulfur in the steel produced in an acid open hearth furnace. [8,9]

Figure 7 is a back scattered electron image (BEI) of the slag particle shown

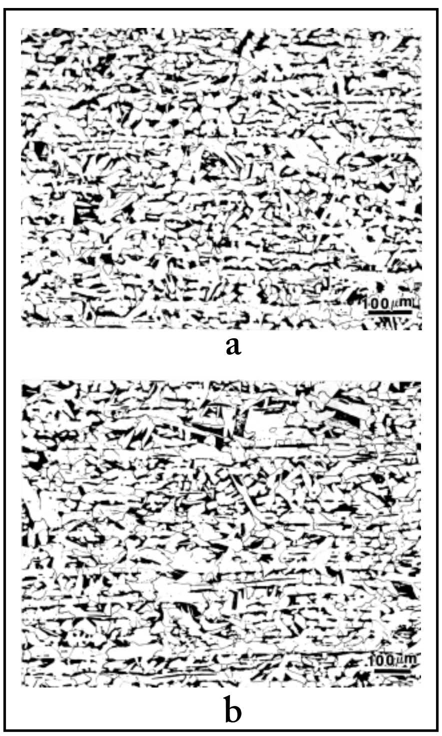

Fig. 2 The general microstructure of the (a) longitudinal and (b) transverse planes of the RMS Titanic plate. (4% picral + 2% nital etch — 100×)

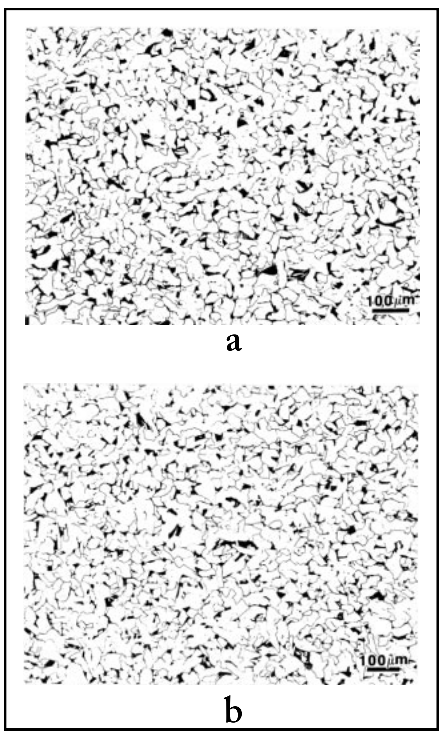

Fig. 3 The general microstructure of the (a) longitudinal and (b) transverse planes of the modern steel plate. (4% picral + 2% nital etch — 100×)

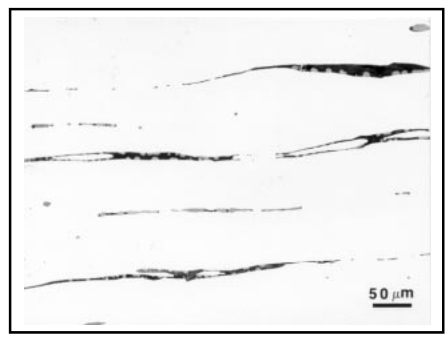

Fig. 4 Typical worst yield view of inclusions at magnification of the RMS Titanic steel plate in the transverse plane. (Unetched — 500×)

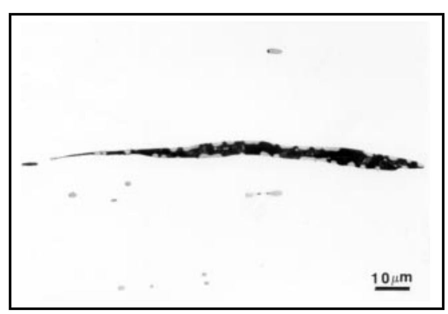

Fig. 5 View of a large silicate inclusion (dark gray) and smaller sulfides (light gray) of the RMS Titanic plate in the tranverse plane. (Unetched — 100×. Reproduced with permission of the Iron & Steelmaker.[13]*)*

in Fig. 5. (Note that Fig. 5 and 7 are mirror images of the slag particle.) The arrows 1, 2, and 3 point to constituents analyzed by wavelength dispersive spectroscopy (WDS). The dark appearing matrix (arrow 1) is basically manganese silicate with a small amount of titanium and no iron. The titanium is dissolved in the manganese silicate. Arrow 2 points to a dark gray particle that appears to be a mixture of manganese silicate, MnS, FeS, and titanium. The presence of sulfide in the silicate slag suggests that the sulfide, at high temperatures, is soluble in the slag but it becomes immiscible at lower temperatures. The rounded particles, arrow 3, are essentially MnS containing a small concentration of iron. This would be the product of the rejection of the sulfide from the silicate caused by declining temperatures.

The Fracture Surfaces

SEM photomicrographs were taken of the fracture surfaces of several broken Charpy specimens made from the plate from the RMS Titanic recovered in 1996. Those in Fig. 8a are from longitudinal Charpy specimens fractured at temperatures on the upper and lower shelves, respectively. Those in Fig. 8b are similar specimens in the transverse direction. The specimen broken in the upper shelf temperature range shows ductile fracture with inclusions in the voids created during fracture. The Charpy specimens broken in the temperature range of the lower shelf show cleavage fracture typical of low temperature failure of steel.

Figure 9 is the fracture surface of a transverse Charpy specimen. The inclusion labeled B protrudes from the surface. The EDS spectrum for particle A is substantially MnS with a smaller amount of FeS while particle B is a nearly equal mixture of Fe and Mn sulfide. This means that the A particle is more plastic than particle B. This could account for the protrusion of particle B in that being less plastic, it could have fractured as the specimen fractured.

Conclusions

It is quite apparent from the test results and the metallography that the steel obtained in 1996 from the site of the RMS Titanic was inferior in mechanical properties to steel commercially available today. A significant factor is that the last eight decades have shown a marked improvement in steelmaking.

The slag content of the RMS Titanic steel is absent in the modern steel and the volume fraction of both sulfides and silicates is greater than in the modern steel. The lack of clean-

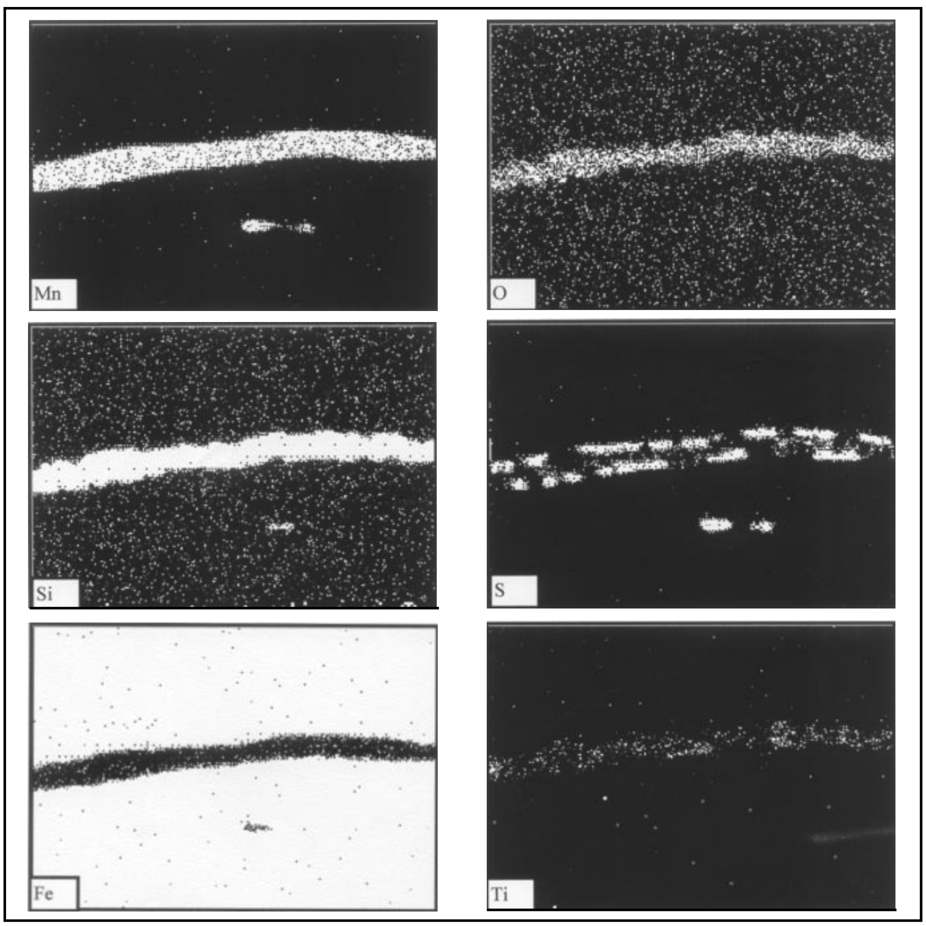

Fig. 6 X-ray maps showing the elements contained in the large silicate inclusion in Fig. 5. The maps are of the same field shown in the BEI of Fig. 7. Reproduced with permission of the Iron & Steelmaker.[13]

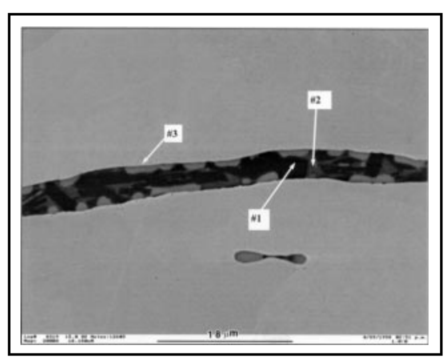

Fig. 7 The back scattered image (BEI) of the large silicate particle in Fig. 5. The arrows, 1, 2, and 3, point to constituents analyzed by WDS. Reproduced with permission of the Iron & Steelmaker.[13]

liness of the steel had a deleterious effect on the mechanical properties, particularly the notch toughness as dem onstrated by Charpy Impact Tests.

These factors were contributing causes of the rapid sinking of the Titanic. Omitted in this study have been design faults and poor seamanship, which were basic to the loss of the RMS Titanic.

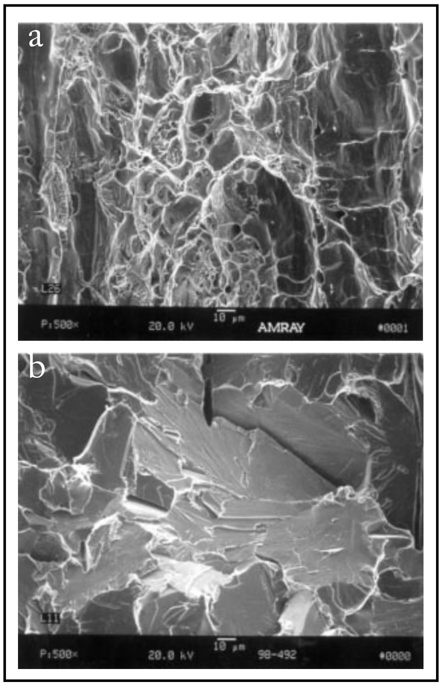

Fig. 8a SEM micrographs showing fracture surfaces of longitudinal Charpy specimens from the RMS Titanic plate tested at (a) 120 °C and (b) –32 °C. Reproduced with permission of the Iron & Steelmaker.[13]

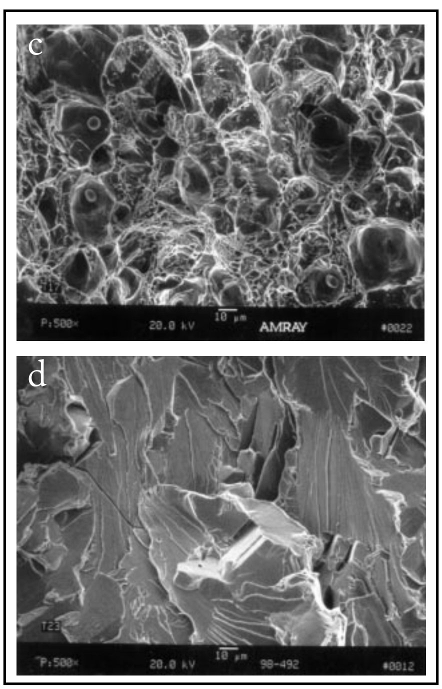

Fig. 8b SEM micrograph showing fracture surfaces of transverse Charpy specimens from the RMS Titanic plate tested at (c) 148 °C and (d) –34 °C. Reproduced with permission of the Iron & Steelmaker.[13]

Acknowledgments

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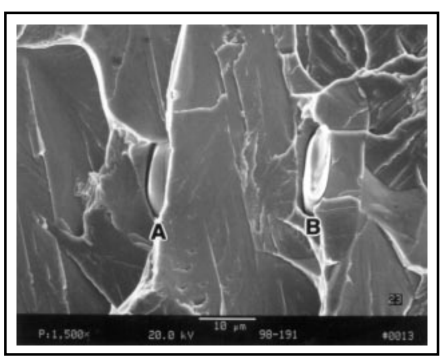

Fig. 9 The SEM micrograph shows sulfide inclusions A and B in the fracture surface of the transverse Charpy specimen from the RMS Titanic plate tested at –34 °C. Reproduced with permission of the Iron & Steelmaker.[13]

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