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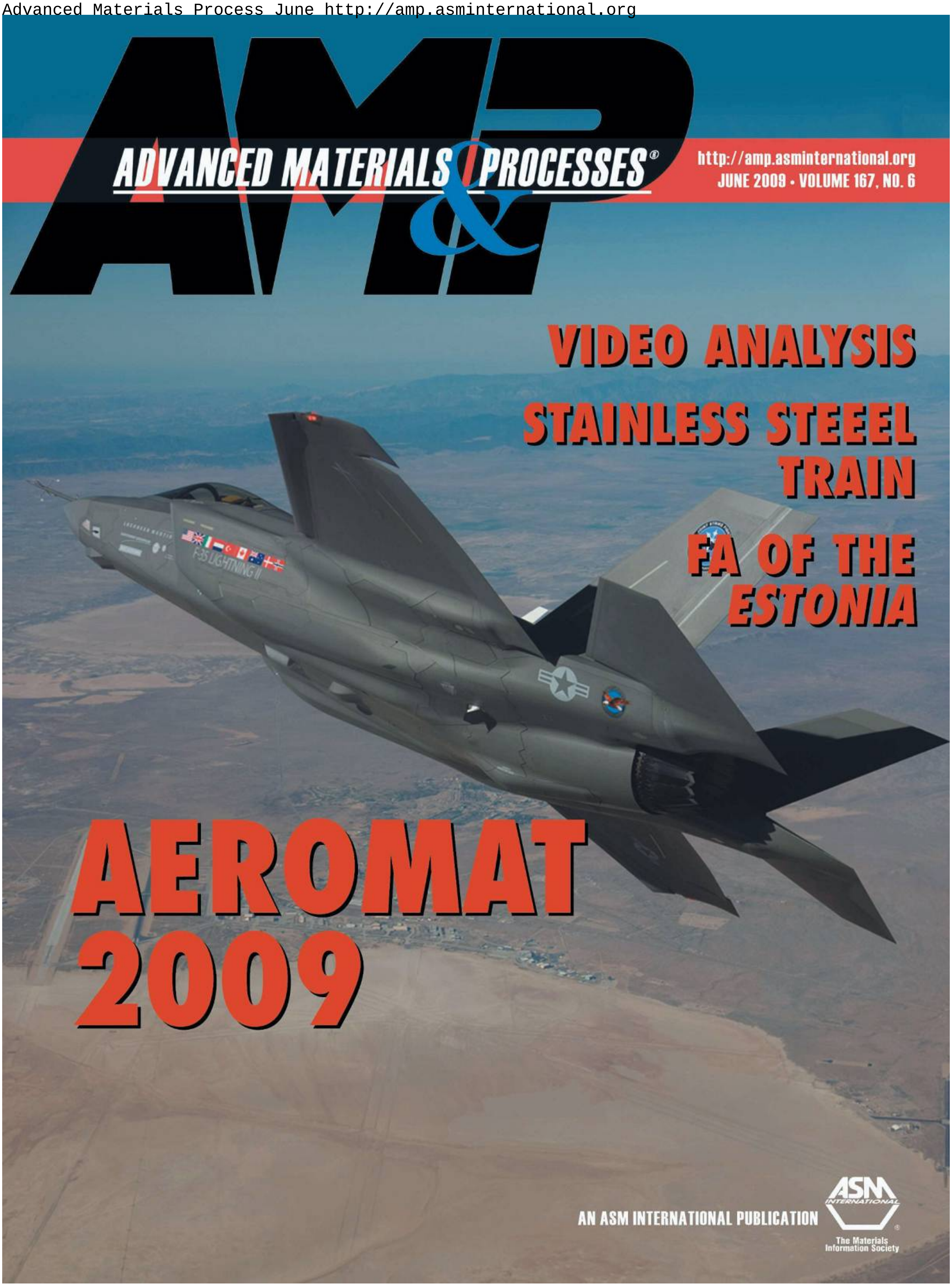

FAILURE ANALYSIS OF THE ESTONIA

Metallurgical analysis of samples from the ferry Estonia demonstrates that it is much more likely than not that an explosion caused the characteristic signatures visible in these samples retrieved from the sunken vessel.

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This is a photo of the ferry Estonia. Two samples were retrieved from a damaged area near the starboard forward bulkhead in a series of dives in the year 2000, six years after the ship sank. They are from the ship structure that would have been engaged with the bow visor, the portion of the ship that withstood the force of waves at the bow of the vessel. The visor is shown in the up position. At the time of Mr. Bemis's expedition to the ship, the bow visor was not present with the rest of the wreck.

The ferry Estonia sank on the night of September 28, 1994, as it sailed across the Baltic Sea from the Estonian capital Tallinn to Stockholm in Sweden during a storm. All but 137 of the 989 passengers and crew on board perished. Most of the victims were Swedish. An official report into the disaster said the ferry sank because a flaw in the design allowed heavy waves to knock the ferry's bow door open and flood the car deck.

The ferry M/V *Estonia* sank in September 1994 with the loss of 852 lives. The investigation and official report of the reasons for that sinking were prepared by an official agency in 1997. Outside of the findings of that body, limited technical information and direct evidence have been released regarding this particularly tragic event. A thorough forensic exploration of the wreck has never been conducted or reported, though possible scenarios have been studied based on design data. This lack of information is surprising, given that the wreckage is only about 200 feet below the surface.

An aura of controversy and mystery still clings to this tragedy. Multiple theories about the cause have also been fueled by numerous questions about the credibility of the official investigation, which the Estonian, Finnish, and Swedish authorities published in 1997. Theirs is the only official report, but not everyone has accepted its conclusions, including the builders and designers of the ship.

The only official exploration of the wreck was the series of dives sponsored by the government authorities in 1997. However, George Bemis conducted another series of dives in August 2000. During those dives, two samples of metal were cut from a critical structural portion of the bow of the ferry M/V *Estonia*. Each sample consisted of a solid piece approximately 100 square centimeters. This article summarizes a series of various metallurgical studies conducted on the two specimens.

The findings indicate that it is much more likely than not, that an explosion caused the appearance of characteristic signatures to be observed in these samples. However, the possibility of an explosion is not part of any official account of the sinking of the ship, and is not explained in any official documents.

The official report stated that the bow visor became detached from the ship, and the loss of the visor was part of the reason it sank. The visor is a movable structure at the bow. When in place, it serves as a bulwark absorbing the force of waves. When retracted, (as shown in the up position in the photo), it allows the deployment of the vehicle ramp from the ship to the dock. When Mr. Bemis learned of this report, he realized that it was of critical importance to capture and record the condition of the steel at the point where the visor broke away from the hull. Therefore, divers removed two pieces that were part of the fracture face of a damaged visor location.

These two samples have been the subject of at least four separate technical reports. This article includes a review of the prior investigative work on these samples, along with a report of additional verification examinations completed in 2007 by the authors.

Official report

The official report states the following with regard to the failure of the visor:

• Two heavy-duty actuators opened and closed the visor. When sea loads (i.e., high waves and high travel speed) started to open the visor, they also caused an upward load on the actuators, which resisted the opening movement. The leverage from the center of attack of the sea loads added to that of the actuators enabled a high pulling force to be transmitted to the actuators. The port side actuator was

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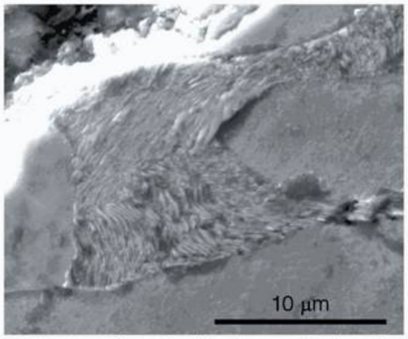

Fig. 1 — Deformed and broken pearlite lamellae, secondary electron image, sample F1. Note the presence of extremely fine lamellar pearlite. 10,000X

at this moment pulled out of the hull while only partly extended. This caused the locked-in hydraulic fluid to transmit the force to the lower attachment of the unit. Tests revealed signs of cold brittleness in this steel, even at room temperature. The actuator mounting platform has undergone a detailed investigation (described in a Supplement).

• The normal operating loads from the actuators appear to have been high enough to initiate fatigue cracking of the platform plating and the welds, in particular where some crack-promoting discontinuities may have existed. The port platform exhibited cracks around a large part of its periphery, generated by vertical loads from normal visor opening and closing.

• The seals in the starboard actuator failed, preventing the hydraulic fluid from transmitting the load. The piston rod of this actuator was therefore extended, and the actuator remained connected in the hull during the initial phase of the visor movement.

• If the official analyses were correct, the materials collected from the hull would exhibit physical evidence of failure consistent with these statements. In other words, evidence should indicate failure due to fatigue; brittle fracture; plate failure associated with and consistent with overloading of the structure; and weld failure associated with loads on the actuators.

Analysis of Bemis samples

The Bemis expedition recovered two samples from the damaged area near the starboard forward bulkhead above the B Deck level. The steel in the M/V *Estonia* was manufactured in Germany to the St 37-2, DIN specification.

• **The Material Testing Laboratory of the State of Brandenburg** examined in detail one of the samples using a number of different specimens extracted from one of these samples. Those researchers reported that they observed severely deformed and broken pearlite lamellae at several locations (Fig. 1). Such severe deformation of the pearlite lamellae in areas adjacent to a rapidly traveling fracture surface is indicative of a very high strain rate, a potential characteristic of a possible detonation.

• **The Institute for Material Testing and Technology – Clausthal-Zellerfeld** examined one of the large samples. Since they were restricted by not being allowed to section that sample any further, their investigations were conducted using X-ray radiation. These investigations showed a zone of about 100 microns in width caused by very high deformation rates. In the Clausthal-Zellerfeld report, Professor Dr. V. Neubert concluded that they found evidence of adiabatic shear bands near the fracture surface due to the presence of martensite.

• **The Southwest Research Institute (SwRI)** also evaluated the steel. The SwRI documents did not report the presence of severely deformed and broken pearlite lamellae. However, it is not known if that analysis was part of the examination that was undertaken in those studies. SwRI did find deformation twinning (i.e., Neumann bands) and minimal pre-fracture necking in the deformed regions near the fracture surface. These are characteristics of extremely high strain rate conditions for a failure that occurred under ambient conditions. SwRI concluded that an explosion was far more likely than a mechanical loading event, to have produced the observed microstructural features.

• **The current investigation by ESI.** Examination in this current investigation did verify the severe deformation and broken nature of some pearlite colonies near the fracture surfaces. Figure 2 shows a typical area of severely deformed and broken pearlite lamellae somewhat distant from the fracture surface. Figure 3 shows the metallographic microstructure of the St 37-2 steel in this current investigation. The microstructure consists of slightly banded lamellar pearlite in a matrix of fine-grained ferrite with elongated manganese sulfide inclusions. The grain size was determined to be slightly greater than ASTM No. 8. In several areas, the lamellar structure of the pearlite has been clearly distressed. The Brandenburg report observed the same thing, as documented in their scanning electron microscope (SEM) images.

The Southwest Research Institute letter report,

Fig. 2 — Metallographic cross section sample F1. 100X 2% Nital etch.

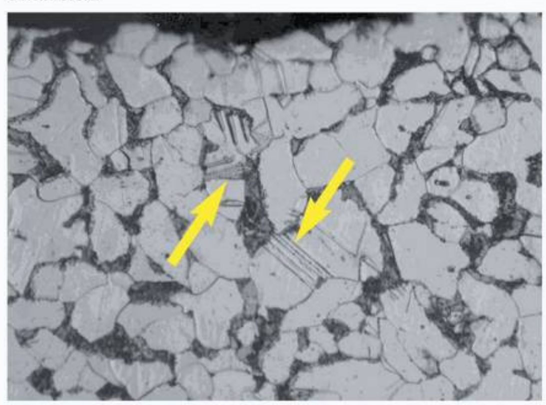

Fig. 3 — Sample F1 microstructure showing Neumann bands (yellow arrows) close to the fracture surface. Magnification 500X. 2% Nital etch.

the Brandenburg report, and the results of this current examination did reveal and document the presence of deformation twins or mechanical twins (i.e., Neumann bands) within the microstructure of the steel specimens. Figures 4 and 5 show the presence of Neumann bands (yellow arrows) within the sample at a location that is somewhat removed from (i.e., not at but close to) the fracture surface. This twinning was identified as Neumann bands, which in ferritic steels are caused by highly localized deformation associated with very fast brittle fracture or by very dynamic, high-energy-event stresses.

Corroded surfaces

No evidence of secondary cracking was observed in this current study, or the SwRI documents, or the Brandenburg report. However, these fracture surfaces were severely corroded, affecting the plate for some distance in from the original fractured surfaces. The length of post-incident time that the steel had spent at the bottom of the Baltic Sea (six years) led to this severe corrosion, therefore it is not surprising that these details would not be observed. Additionally, the distinctive adiabatic shear bands, typically adjacent to the fracture surface locations, would also have been obliterated as a result of these corrosion processes.

The presence of these shear bands would have conclusively established these failures as resulting from an extremely high energy impact event, such as an explosion. Since the surfaces had been so severely corroded, the absence of adiabatic shear bands does not rule out a failure mechanism caused by such a very high energy event.

Hardness of the specimens was studied in this current investigation and also in the Brandenburg report. Though different techniques were used (Vickers by Brandenberg and Knoop in the ESI study), we were unable to find the level of microhardness increases near the fracture surfaces of the magnitude reported in the Brandenburg report, where microhardness values, $HV_{0.05}$, of 450 to 550 were typically encountered. The only exception was in those areas of the samples in the heat affected zone (HAZ) where the samples had been thermally cut for removal. It is certainly possible that the $HV_{0.05}$ technique used in the Brandenburg report would have been more sensitive than the HK_{50} examination used by ESI.

The Clausthal-Zellerfeld study

In the Clausthal-Zellerfeld study, researchers examined for the presence of a body-centered tetragonal, martensitic microstructure on one of the Brandenburg specimens, via X-ray diffraction analysis. The metallographic microstructure was shown in the Brandenburg report to be predominantly a slightly banded lamellar pearlite in a matrix of fine grained ferrite, with interspersed manganese sulfide inclusions.

Prof. Dr. V. Neubert reported evidence of adiabatic shear bands near the fracture surface, caused by the presence of martensite. He added that adiabatic shear resulted in heating of the shear band

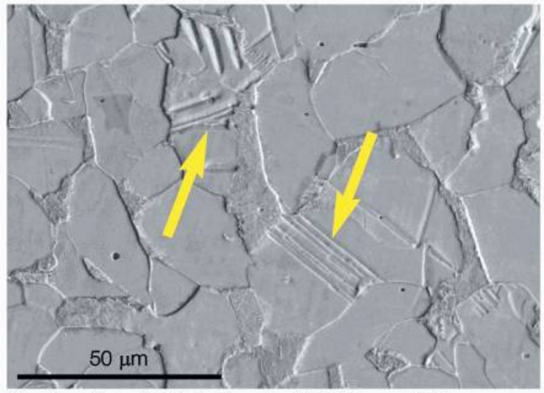

Fig. 4 — Sample F1, backscatter SEM image of Neumann bands shown in Fig. 3, magnification 2000X.

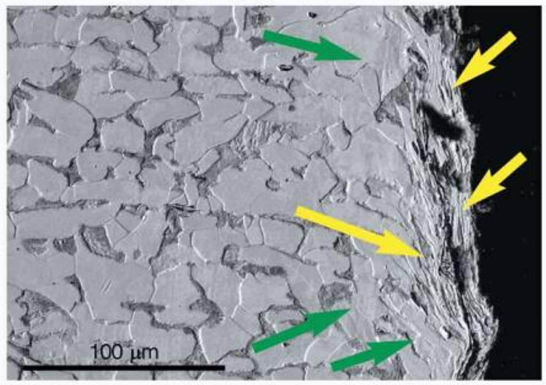

Fig. 5 — Potential severe plastic flow zone and wavy structure (yellow arrows) in a micro area of Specimen F1. Also shown are wavy slip lines (green arrows) within the grains close to the fracture surface. Backscatter electron image, magnification 1000X.

Three items were found in the examination of the documented reports and the artifacts that are consistent with an allegation of an explosive detonation.

areas to 1290 to 1330°F during rapid shear failure deformation. The report further concluded that actual strain rates of between 1000 to 100,000 in./in./sec were developed in these shear bands, and that this could only be the result of deformation produced by a detonation or a projectile.

The Clausthal-Zellerfeld study established the presence of martensite by the widening of the X-ray diffraction peaks of the (110) planes, slight peak shifts with regard to the X-ray diffraction angle, and the absence of minor peaks, depending on location of the examination. The current authors note that the widening of the X-ray diffraction peaks and peak shifting can also be caused by the hardness increases as a result of plastic deformation and work hardening. We recommend that this seminal examination be verified by additional testing and a more complete analysis, in which compensation for increased hardness in the areas analyzed is undertaken.

The composite photomicrograph shown in Prof. Neubert's report details the fracture surface of that specimen, showing considerable plastic deformation at a significant distance away from the fracture surface. Adiabatic shear bands are normally quite narrow and close to the fracture surface, and as such would typically be lost to the post-incident corrosion of these fracture surfaces.

The Clausthal-Zellerfeld study also stated that a significant decrease in the grain size was found in the areas where martensite is reported. Prof.

Neubert attributes this to the martensite transformation as triggered by the adiabatic shear heating.

Both the Clausthal-Zellerfeld and SwRI reports allude to the presence of adiabatic shear heating as a result of shock or impact loading. However, neither these reports nor the ESI study could provide direct metallographic evidence of the presence of such shear bands associated with the fracture surfaces.

The post-failure corrosion of the fracture surfaces would most probably have seriously altered or obliterated any evidence of these shear bands near the fracture surfaces. For this reason, it is somewhat surprising that the X-ray diffraction work could find evidence of adiabatic shear bands. Additionally, any grain refinement in such regions close to the fracture surfaces should also be investigated. Should either martensite or grain refinement be present close to the fracture surfaces, the probability that these plate fractures were caused by an extremely high energy rate event would be a virtual certainty.

The Brandenburg report and the SwRI documents as well as the ESI study provide evidence regarding wavy slip planes and general shear bands within the microstructure. The current authors also found such features where it appears that the fracture surface was subject to impact during a high energy event. This is shown in Fig. 5.

Evidence for explosion

Three items were found in the examination of the documented reports and the artifacts that are consistent with an allegation of an explosive detonation.

- First, there are several areas where the lamellar pearlite colonies were revealed to be distorted and broken up. This was found in the Brandenburg report and verified by this investigation with both of the specimens as shown in Fig. 1. This disruption of the pearlite lamellae is consistent with high strain rate deformation of the metal, such as by explosion.
- Second, Neumann bands, or mechanical twinning in the ferrite phase of the metallurgical structure, were found at some distance from the actual fracture line. These features are also sometimes referred to as "impact twinning" or "deformation twinning." It is important that these Neumann bands were found at some distance away from the fracture surfaces, since two different operating mechanisms are involved. The one near the fracture surfaces would be adiabatic shear if high energy impact loading were involved. The one further away would be high strain-rate twinning resulting in the formation of Neumann bands. The locations distant from the fracture lines are not consistent with shot peening effects.
- Third, the presence of wavy slip bands and localized severe shear bands within individual ferrite grains indicates the existence of very high mechanical strains at exceedingly high deformation strain rates (i.e., a high energy event). In addition to the evidence found by and presented in Fig. 5 of this report, both the Brandenburg report and the SwRI

documents provide further evidence regarding wavy slip planes and general local severe shear bands within the examined sample microstructures.

Study conclusions

- The process that causes adiabatic shear generates considerable heat in a very narrow shear band region, which enables massive shear deformations at a very low stress and at a very fast rate. It is important to note that adiabatic shear and Neumann band formation mechanisms are not at all compatible with one another, and that they should be separated by some distance from each other. In this case, the Neumann bands were found some distance away from the fracture surfaces, and any adiabatic shear bands, if they were not obliterated by post-incident corrosion, should be found in close proximity to the fracture surfaces.
- Two other items reported by others could not be confirmed in the scope of the current examination, and also may have been lost due to corrosion. First, the Clausthal-Zellerfeld study claimed the presence of martensite in one of the specimens (i.e., as created from an adiabatic shear band). Second, Prof. Dr. V. Neubert, in the Clausthal-Zellerfeld study, also claimed the presence of significant grain refinement as created by the martensite transformation due to the formation of an adiabatic shear band.
- The macroscopic view of the fracture surfaces on both samples removed from the *M/V Estonia* at the starboard forward bulkhead area above the B deck location revealed an angled fracture surface at approximately 45 degrees, with very little evidence of necking. The considerable amount of plastic deformation associated with the fracture surfaces indicates that the failure occurred as a result of a shearing mechanism, and that the failure was ductile in nature and not the result of a fast-running brittle failure.
- No evidence of brittle fracture or evidence consistent with a fatigue cracking was found in any study. The purported causes of metal fractures in the official report were not consistent with any of these metallurgical findings. The analysis of the visor failure in the official report does not provide or propose a failure mechanism that explains these metallurgical findings.
- Both metal samples display features adjacent to the fracture surfaces that resulted from a high strain rate event at ambient temperature. This event was more likely than not the result of very rapid deformation of the metal as part of an explosion. The only other events that could produce these types of features are deformation of the steel at cryogenic temperatures, or a fast-moving, brittle crack propagated through the materials. Cryogenic temperatures are impossible during the accident sequence on this ship, and no fractographic brittle failure mechanism was found.
- The metallurgical features observed in this study, combined with the conditions of the metal in situ at the time of the sample removal, are simply not consistent with brittle fracture mechanism leading to plate failures associated with and consistent with overloading of the structure, weld failure associated with loads on the actuators, or fatigue. The author's view of a high-energy event fracture mechanism is consistent with the features found in very rapid strain rate deformations leading to ductile failure, typically encountered in an explosion.

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