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Metal Removal via Slag Attack of the Steel from Building 7 of the World Trade Center—Some Observations

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Microstructural examination of a beam from Building 7 showed that temperatures higher than 940 °C were experienced in localized regions. Concurrent examination of the beam surfaces and surface layers showed evidence of extensive metal removal, and the analysis suggests that this removal occurred while the beam was exposed to the fire in the rubble pile after the building had collapsed.

Keywords: Building 7, microstructure, rubble pile, slag, sulfur, temperature

Introduction

The Worcester Polytechnic Institute Materials Science and Engineering faculty was asked by the Federal Emergency Management Agency (FEMA) forensic team to examine the microstructures of the steels from the World Trade Center disaster to determine the maximum exposure temperatures and to identify the mechanism for the extensive metal removal. These determinations were based on microstructural examination of portions of a beam.

Steel beam samples from Building 7 were collected during the FEMA forensic investigation after the September 11, 2001, attack. The Building 7 sample was identified by its location. The samples were collected by the FEMA forensic team from the "pile of rubble" that had been burning for many days. The samples had been exposed to the fires in the building while it remained standing as well as the fires in the rubble on the ground after the building collapsed. In this sample beam, extensive metal removal was observed with thickness decreases up to ½ in. and very localized regions of total metal loss. A photograph of the steel beam sample is presented in Fig. 1. A photograph of a metallurgical mount of a beam section is seen in Fig. 2.

Preliminary results from this investigation were presented in 2001[1] and the FEMA report,[2] and this case history updates those reports.

Fig. 1 *Severely eroded ½ in. wide flange beam from WTC 7. Nominal composition (%) of the A36 steel plate is 0.29C max, 0.80-1.2Mn, 0.04P, 0.05S, 0.15-0.3Si, bal Fe.*

Fig. 2 *Cross-sectional metallurgical mount*

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Microstructural Observations

Metallographic samples from the beam were prepared from several locations, including sections with total metal loss and thicker sections. The cross sections were mounted and polished using standard metallographic practice.

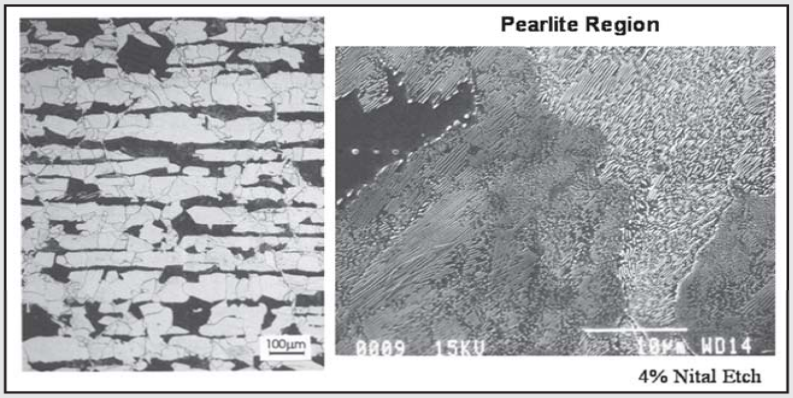

Fig. 3 *Microstructure of unaffected A36 steel. White—ferrite; dark—banded pearlite. Pearlite forms in bands due to manganese segregation and prior hot working. 4% nital etch*

Building 7 - A36 Steel

The microstructure of the steel from Building 7 is typical of a structural steel such as ASTM A36. The wide flange beam displayed a microstructure that consisted of a banded hot worked mixture of ferrite and pearlite (Fig. 3). The microstructures in these regions displayed no effects of excessive heat or metal loss.

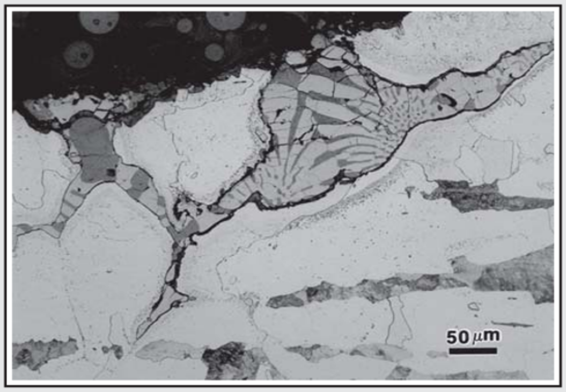

Fig. 4 *Optical micrograph of near-surface region showing iron oxide-iron sulfide eutectic structure, grain-boundary attack, and decarburization*

In the regions of the beam that exhibited extensive metal removal, an intergranular liquid slag attack was observed (Fig. 4). Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) identified the slag to be comprised of Fe, O, and S (Fig. 5). Chemical reactions including oxidation, sulfidation, and decarburization occurred, as well as the usually observed phase transformations in the steel.

As the temperature increases, several microstructural changes[3] normally occur within the steel. Two important intermediate temperature transformation reactions that occur soften the steel. These are the pearlite spheroidization reaction at temperatures below the A1 temperature, and the conversion from ferrite and pearlite to austenite at temperatures above the A1 temperature and above the A3 temperature, followed by transformation back to pearlite and ferrite on cooling. Typical examples of these transformations are presented in Fig. 6 and 7, within the pearlite banded regions near the bottom of Fig. 4. In Fig. 6, the Fe_3C in the pearlite had started to spheroidize. Also, some pearlite bands have areas where a re-austenitization had occurred and new finer-grained regions of pearlite and ferrite formed on cooling (Fig. 7). These observations indicate that the steel in this region had experienced temperatures in the range of 550 to 850 °C.

An example of a typical near-surface microstructure is shown in Fig. 8. This microstructure shows the scale and slag reaction effects at the top of the micrograph and the normal metallurgical reactions that occurred in this steel on heating and cooling toward the bottom. As the temperature increased, some changes in the microstructure of the steel occurred as a result of heating and cooling. However, as higher temperatures occurred, microstructural as well as chemistry changes occurred due to the reactions with the environment. The interaction of heat in a corrosive fire environment resulted in exposing the steel to sulfidation, oxidation, and reductions in thickness.

Using EDS with SEM, it was determined that the slag contained iron, oxygen, and sulfur (Fig. 5). The reaction of this slag with the steel resulted in several metallurgical effects. First, the surface of the steel was decarburized in this environment (Fig. 8). Second, the slag preferentially attacked the grain

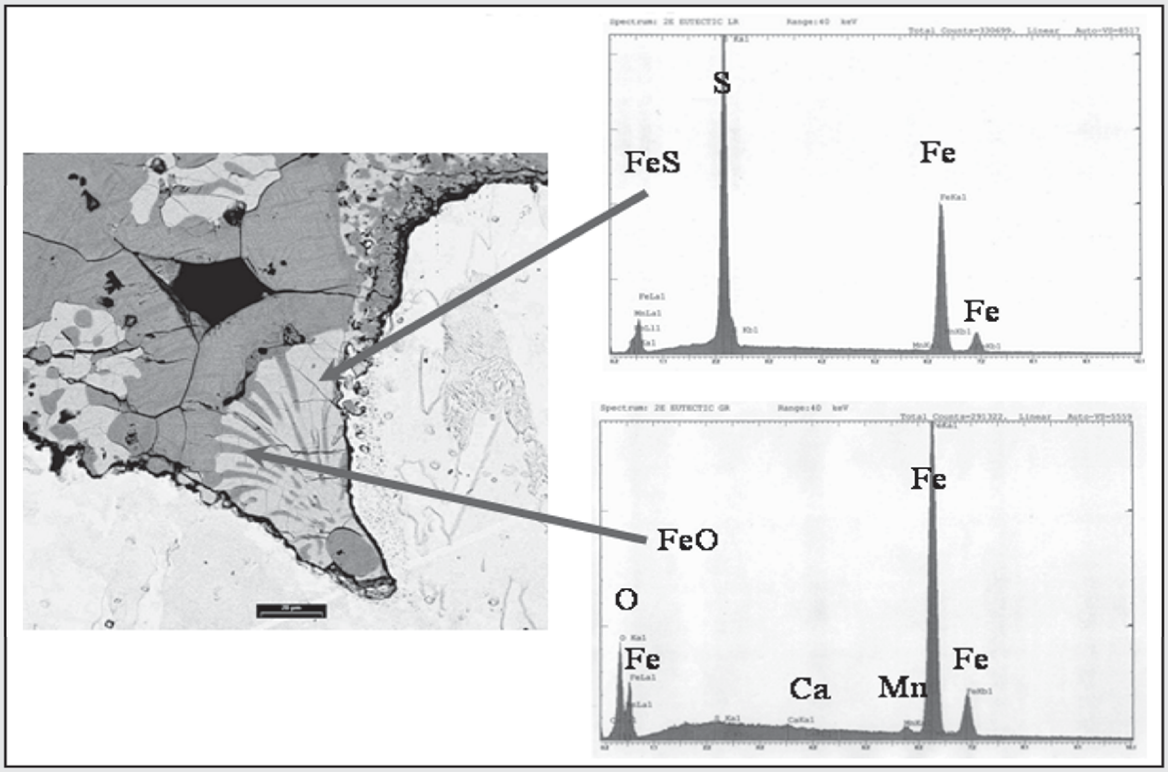

Fig. 5 *Energy dispersive X-ray spectroscopy (EDS) analysis of eutectic region*

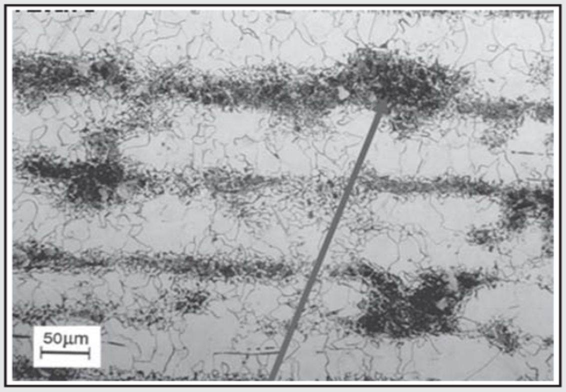

Fig. 6 *Typical microstructural changes that occur when A36 steel is heated to the vicinity of the eutectoid reaction ~727 °C (1340 °F), held for a short time, and cooled to ambient temperature. Arrow indicates partial carbide spheroidization.*

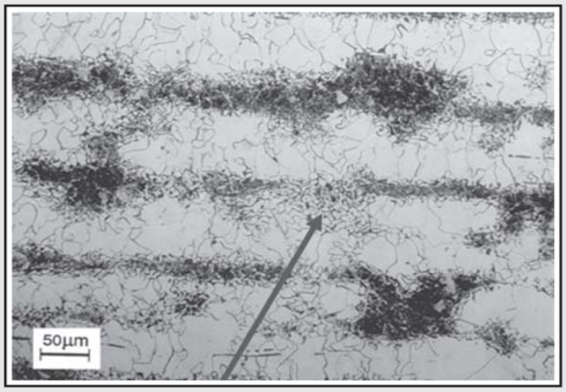

Fig. 7 *Typical microstructural changes that occur when A36 steel is heated to above the eutectoid temperature ~727 °C (1340 °F) and cooled to ambient temperature. Arrow indicates a typical region where conversion to an austenite matrix (on heating) occurred followed by a retransformation to a ferrite matrix on cooling.*

boundaries (Fig. 9). This grain-boundary attack and metal dissolution was the cause of the severe metal removal in some sections of the beam.

The microstructure of the slag at room temperature displayed a eutectic structure with one phase rich in iron and oxygen and the other rich in iron and sulfur. Assuming these phases are FeO and FeS, their phase diagram[4] is a simple eutectic with the eutectic composition of approximately 55 mol.% FeS at 940 °C. The microstructure of the slag is composed of primary FeO and the eutectic structure (Fig. 4, 5, and 9).

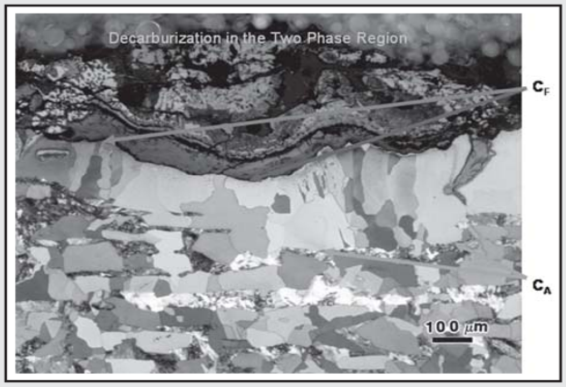

Fig. 8 *Decarburization in the two-phase region. Courtesy of George Vander Voort*

Discussion

Based on these metallurgical observations, can the temperature, time, and environment that this beam was exposed to be determined?

The microstructural changes in the steel must have occurred at temperatures between 550 and 850 °C. These changes would require times on the order of hours.

The microstructure of the slag with the eutectic structure and the primary FeO indicates temperatures in this region above 940 °C and maybe up to 1100 °C, as indicated by the phase diagram.[4]

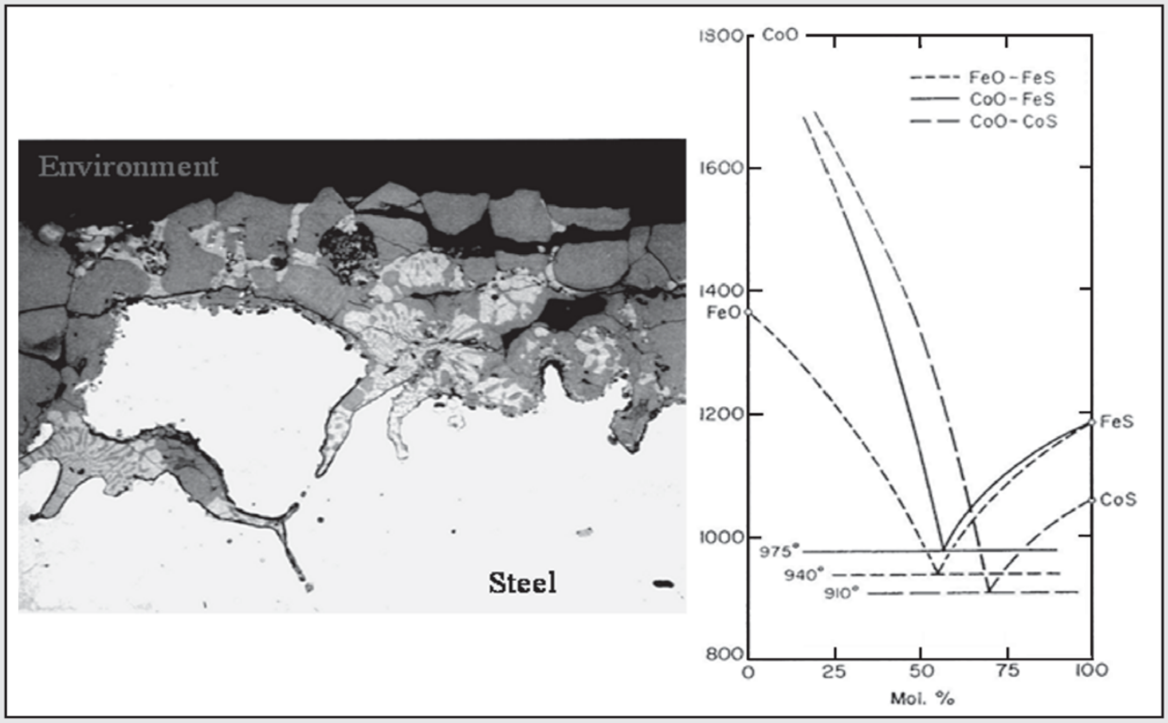

Fig. 9 *Optical micrograph of near-surface region showing iron oxide–iron sulfide eutectic structure, grain boundary attack, and decarburization and the FeO–FeS phase diagram. Source: Ref 4*

The metal removal rates from A36 steel by this liquid slag are not known and may be highly dependent on impurity content as well as oxygen and sulfur partial pressures in the atmosphere of the fire. However, preliminary experiments[5] at 1100 °C with mixtures of FeS and FeO placed on the steel surface and heated in air indicated that the reaction was not fast and dissolved little metal in 24 h. This observation indicates that the liquid slag attack probably took place during the prolonged exposure to the fire in the rubble.

Another frequently asked question concerns the source of the sulfur. Some of the sulfur may have come from the fuel on the airplanes or the fuel that was stored in Building 7. However, this source would have been short-lived in the fires. Sulfuric acid in acid rain or SO_2 or SO_3 in the atmosphere could also contribute sulfur to the slag. A more probable source of sulfur is the materials in the building, such as gypsum (hydrated calcium sulfate) board or other construction materials.

Conclusions

The maximum temperatures in the beam from Building 7 varied with position along the beam, and the maximum local temperatures were above 940 °C. The extensive metal removal from the beam occurred by the reaction between a liquid iron oxide and iron sulfide slag and the steel. The oxides and sulfides formed by a reaction between the steel and the environment in the fire at high temperatures. The metal removal most probably occurred in the fire in the rubble after the building collapsed rather than during the fire while the building was standing.

The source of the sulfur was most probably the materials of construction in the building (e.g., gypsum board) rather than the sulfuric acid in acid rain or the jet fuel.

Acknowledgments

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