Changes in steel can be heard

The knock-on effect of flipping crystal lattices
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Cracks in welds are a major problem in the steel processing industry. One of the causes is a change in the microstructure that occurs if steel cools too rapidly during the welding process. Researcher Stefan van Bohemen of the Applied Sciences faculty at TU Delft demonstrates how this change is accompanied by the production of high-frequency mechanical vibrations, in other words, acoustic emission. The production of sound, however slight, turns out to be a good indicator for tracing faults in welds. In the second half of his research term, van Bohemen will focus on mapping these changes in steel. This is essential in order to be able to determine the optimum conditions not only during the welding process, but also during the production of unique, new steel types such as TRIP steel, which appears to be destined as the new material for the automotive industry. As the research is considered to be of practical relevance it is supported by Dutch industry through the Netherlands Institute of Metals Research (NIMR).

Steel is one of the most widely used materials today, and it is employed for an endless variety of structural purposes, from buildings to ships, from lift systems to nuclear power stations to oil and gas pipelines – each and every one of these employs steel, held together by high-grade welds. Making a good weld still takes skill and lots of experience. A welder cannot tell whether his work is a success or not until it has been checked, for example by means of X-rays, or even by cutting up samples of welded material for testing under a microscope. The latter in particular is an expensive type of quality control since it destroys the end product. There is a real need for techniques that enable the welding process to be monitored in real time in order to provide a permanent means of checking the quality of the work, and if necessary, adjust the welding process. There are some alternatives to destructive techniques for detecting the presence of cracks, for example, X-ray inspection. Other methods include penetrating contrast liquid (for surface cracks only), magnetic testing using iron powder, Eddy currents, and an ultrasonic method that uses a transducer to transmit sound waves and receive the reflection (see Delft Outlook 94.1).

However, these methods are not considered to be suitable for observing the forming and growth of cracks. A promising technique that can be used for this purpose is acoustic emission. ‘When a welding fault is formed, this generates sound waves inside the material that can be detected several metres away,’ Research student Stefan van Bohemen explains. ‘This enables us to use the equipment at a safe distance not only to detect welding faults, but also to

A test weld on hardenable steel (42CrMo4) with a high carbon content shows a cold crack resulting from the brittle microstructure and excessively rapid cooling (in the air).

The cold crack occurred in martensite, which is formed during rapid cooling of a weld. The crack does not form until the steel reaches room temperature, at which point the stresses in the weld become too high as a result of the different rates at which the different microstructures contract. Martensite was named after the German metallurgist, Adolf Martens (1850-1914) who first observed this structure.

A weld may appear perfect on the outside, but this says nothing about its quality. Initially, small cracks will not travel all the way to the surface, which is why all major steel structures are tested using X-rays or ultrasonics.
find out where they are and how big they are. The on-line remote measuring capability is what makes this technique so extremely useful.’

Orchestra
The idea of acoustic emission is far from new. When a method had to be found to check the steel doors of the Oosterschelde barrier, in the late nineteen-eighties, the engineers at tno and tu delft thought of the idea of using sensitive equipment to ‘eavesdrop’ on the internal changes taking place within the steel, such as the corrosion process and micro cracks. However, the pounding waves of the sea and stamping feet of visitors generated so much noise that acoustic emission was considered too unreliable, and so it was put on the back burner. Even so, Prof. Dr. Gert den Ouden of the Welding Technology research group, who has now retired, never lost his faith in the application of the idea. ‘The problem was the use of acoustic emission always yielded some sort of result. It was a bit like listening to an orchestra without being able to pinpoint a flute and a double bass as separate sources of sound’, Den Ouden explains. ‘Over the last couple of years, the measuring equipment has been improved to the point where composite sounds can be unravelled. So now we can tell what’s playing.’ Den Ouden also contributed to the idea of using acoustic emission measurements to detect welding faults.

Piezoelectric
The appearance of a welding fault or a micro crack can only be detected by acoustic means if the process progresses in abrupt stages. Each step generates a tiny shock wave that releases sufficient energy to start the surrounding material vibrating. The vibration is inaudible to the human ear, because the frequency of the sound generated by a welding fault lies between 50 kilohertz and 1 megahertz, whereas the range of human hearing stretches roughly from 20 hertz to 20 kilohertz. To detect these vibrations, Van Bohemen uses a special sensor containing a piezoelectric crystal a few millimetres in size. To improve the chances of detecting the vibration, the sensor is attached to the steel surface with a contact medium (vacuum grease). The vibrations induce deformations in the crystal, which create a changing voltage across the crystal. The resulting sound wave signal is amplified and fed to a computer for analysis.

Phase transformations
One of the phenomena Van Bohemen started to investigate two years ago was the occurrence of cold cracks in welds. As the name implies, these cracks are formed after the weld has cooled down. The speed at which the steel cools during the welding process plays a crucial part in this, since it determines the internal structure of the steel and consequently, the quality of the weld. At temperatures above 730°C, steel atoms are arranged according to a crystal lattice form known as austenite. As steel slowly cools, austenite changes into ferrite, which has a different lattice structure. A transition like this, from one type of lattice to another, is
referred to as a phase transformation. The resulting ferrite is the most well-known form of steel: easy to work and reasonably strong. If the steel is very rapidly cooled however, the austenite changes into martensite. Although the lattice structure of martensite closely resembles that of ferrite, as a result of the rapid cooling process carbon is trapped in the iron lattice, creating internal stresses. This makes martensite very hard as well as brittle, so it is easily fractured. In this respect it resembles cast iron, but martensite contains approximately 0.4 to 2 percent carbon by weight, whereas the cast iron we all know contains 2 to 5 percent carbon by weight.

Knock-on effect
The phase transformations during cooling occur in two different ways. The change of austenite into ferrite takes place as part of a gradual process in which the atoms can move across relatively large distances. In comparison, the change into martensite is a more abrupt process, in which the atoms move together within a very short time span of about 1 microsecond across a relatively small distance (i.e. less than the atomic distance). As a result of this collective movement of iron atoms, the austenite lattice flips into the martensite configuration in one go. The flipping process is a bit like the knock-on effect that topples a row of dominoes. Once a single martensite disc has been formed, the rest follows, causing the lattice structure of martensite to be created in a series of abrupt reshuffles. The series of collective atom movements creates sound waves. Van Bohemen has demonstrated that the acoustic emission measured in this way can indeed be attributed to the creation of martensite.

Hydrogen gas
The forming of cold cracks, so it has been discovered, is affected by two materials, hydrogen gas and martensite. If either of the two is missing, the risks of cracks forming are nil. Hydrogen gas is created when water, oil, and/or grease decompose as a result of the welding process. Preventing the decomposition of these materials is practically impossible. The creation of martensite can be avoided, however, by strict control of the welding conditions, e.g. by preheating the steel so the weld cools less rapidly, or by adjusting the welding speed and current.

Once trapped inside the material after the steel has cooled, the hydrogen gas can no longer escape easily, unless it can diffuse, for example, to an internal boundary where two different metal lattices meet. A boundary between ferrite and martensite tends to attract the hydrogen, as it were. Any other remaining hydrogen nearby also diffuses to the boundary, increasing the internal pressure. At a certain point, the tension in the steel reaches a critical stage, causing a microscopic crack to increase abruptly in length. Therefore, the important thing is to be able to monitor constantly how much martensite is being formed. Van Bohemen has already managed to ascertain the existence of a proportional relationship between the average amplitude of the acoustic signal and the quantity of martensite.
formed during the welding process. To do so, he has had to fit the sensor to a wave-guide to protect it from overheating. The temperature of the steel near a weld can reach 1500 °C, whereas the sensor can only operate to 100°C.

Bainite
His acoustic emission tests have also enabled Van Bohemen to find a solution to another piece of the puzzle, i.e. the forming of bainite, another microstructure of steel, a process that has formerly been shrouded in mystery. Bainite is a steel phase that lies somewhere between ferrite and martensite. It is formed if austenite is cooled slightly faster than is needed to form ferrite, but not so fast that it will transform into martensite. The properties of bainite, strength and ductility, also place it between ferrite and martensite. Van Bohemen has been able to measure sound waves during the forming of bainite, which points to the collective movement of iron atoms during cooling. ‘On the other hand,’ says Dr. Ir. Jilt Sietsma of the Microstructural Control of Metals research group, ‘some researchers have reported finding iron carbide (Fe3C) in the bainite. The presence of carbide is characteristic of a diffusion driven mechanism which occurs when ferrite is formed, so this would indicate an individual movement of iron atoms during cooling. If steel cools slowly enough, any carbon it contains will have time to escape from the iron lattice and bind iron atoms into carbide segments. During the martensite formation process, the steel cools so rapidly that carbon becomes trapped inside the lattice and cannot form carbide. Van Bohemen’s method will prove invaluable for further research into the mechanism of bainite formation.

TRIP steel
The forming of martensite is more than an annoyance that occurs during welding. In a new type of steel, TRIP steel, in which TRIP is short for Transformation Induced Plasticity, the forming of martensite is used to advantage. This steel type combines the hardness and strength of martensite with the ductility of ferrite. Sietsma: ‘The special thing about TRIP steel is that it contains stable austenite even at room temperature, while austenite cannot normally exist at such temperatures.’

Sietsma’s group is collaborating with Corus of IJmuiden to discover the conditions required to manufacture TRIP steel. The addition of silicon and aluminium prevents carbide from being formed as the austenite cools. This results in the forming of regions containing ferrite or bainite in which the carbon has been expelled, and spots containing austenite in which the carbon has collected. This can add up to a carbon content of up to 0.2 percent by weight.

‘This level of carbon interferes with the austenite to such an extent that the latter cannot be transformed of its own accord. It needs a little push in the right direction, by applying for example mechanical stress. This causes the austenite to flip into martensite in one go, another microscale knock-on effect. In this way, the
hard martensite is not formed until we want it, which is when the cooled steel is given its final shape, for instance pressed car body parts. Acoustic emission is the perfect technique for detecting these phase transformations, and it is ideal for monitoring the production process’, says Sietsma.

Change of course
Acoustic emission may seem the perfect instrument to monitor the changes in microstructure that occur in steel as it cools during the production process, but for the time being it remains an impractical method, because it requires direct contact between the sensor and the hot steel.

‘Even so, we can use laboratory tests with controlled conditions to find what the cooling rate must be in order to obtain the desired phase transition. How many buckets of water Corus needs to pour onto the steel plates as they whiz past is for them to find calculate’, Sietsma says.
The first results obtained by Van Bohemen and the many possibilities the technique offers for monitoring phase transformations have brought about a change of course in his research. From finding welding faults, he has switched to studying martensite formation.

‘We are currently one of only a few research groups worldwide investigating martensite formation in this way. What we have discovered is so unique and promising that we must now push on to find out in more detail what acoustic emission can reveal about the way martensite is formed’, says Van Bohemen.

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The needle-like microstructure of bainite (dark) that was formed at cooling rates in between the cooling rates of martensite and ferrite. Bainite, which occurs practically always in combination with martensite (white), possesses only moderate strength, but the combination of the two microstructures results in high-strength malleable steel.

Schematic diagram of the test setup Van Bohemen used to detect welding faults by means of acoustic emission (AE). As a steel plate is welded, sound waves (50 kHz – 1 MHz) are produced that can be detected with a sensor and converted into an electric voltage. Analysis of this signal can show whether the welding process is going according to plan.
The acoustic emission signal (RMS) as a function of time during the welding of hardenable steel (42CrMo4) at four different currents. The signal level increases with the current.

Sections of welds corresponding with the four plots in the previous figure. These sections were used to calculate the quantity of martensite that was formed during the welding process per unit of time.

Cutaway drawing of a sensor as used to detect AE waves. The device contains a piezoelectric element (crystal). The AE waves in a steel plate generate minute displacements at the surface of the material. As a result of these, the crystal in the sensor is slightly deformed, generating a voltage across the crystal.
The piezoelectric principle

The acoustic emission signal (RMS) plotted as a function of the welding time, with a welding current of 75 A. (1) Baseline signal with noise. (2) As the welding arc is formed, the signal rises slightly. (3 & 4) After a few seconds of welding, the signal level rises as martensite is formed (the flipping process that generates sound). (5) The welding process has stopped, and a spike clearly indicates that more material is being transformed per unit of time.

Section through a weld, showing a clear transition in the microstructure. The entire weld section is martensitic, but the structure of martensite in the weld metal (the part that was melted) is coarser than that in the heat-affected zone.
Graph plotting the power of the acoustic emission signal (RMS2) against the volume of martensite being formed per unit of time. The data points resulted from 15 measurements, four of which are shown in the two previous figures. The resulting linear correlation between the two quantities is very useful for further research, i.e. into martensitic transformations by means of acoustic emission.

Different sizes of spot welds (using different currents) on a test piece to track the transformation of the microstructure in the material. Spot welding allows the transformation to be measured practically undisturbed by noise from the welding process.
The welding simulator used during tests to measure the acoustic emission as martensite was being formed in a specimen rod. By sending a very high current through the specimen rod, its centre heats up to temperatures near the melting point (1400°C). This phenomenon whereby electrical resistance causes an object to heat up is known as the Joule effect. The acoustic emission signal being produced during the cooling process can be read from the monitor on the left. Inset: the glowing test rod during the austenisation process (> 730°C).

In view of the high temperatures that occur during this test, Van Bohemen fitted a wave-guide between the specimen rod and the sensor. The narrow end of the conical wave-guide was welded to the test rod. The wide end was fitted to the sensor, with a vacuum grease seal.

A possible application field for TRIP steel is the automotive industry. As a side panel is cold-pressed from TRIP steel, the crystal lattices flip over to form hard martensite structures to reinforce the shaped parts of the structure.
The acoustic emission signal plotted against the temperature of a specimen rod as it cooled in the welding simulator. As the plot shows, during cooling bainite is formed first, followed by martensite.