Corrosion - A Multi-scale Perspective

Corrosion is a pervasive phenomenon which when taken for granted, leads to many a disaster. The research group of Dr. Ilaksh Adlakha from the Department of Applied Mechanics aims to perform systematic multi-scale studies to capture the essential ideas of corrosion and come up with a predictive model for this phenomenon. This article encapsulates the core principles behind such studies.

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Every material reacts with its environment. If this interaction results in the destruction or deterioration of the material, it's called corrosion. Corrosion occurs everywhere, all the time. The most well-known example of corrosion is the rusting of iron. It happens in huge statues and also in our door hinges. Because of this ubiquity, the importance of understanding corrosion cannot be understated.

There have been many instances of catastrophic failures due to corrosion, including the collapse of buildings and bridges. If we ignore corrosion, we pay for it. There are many ways by which there's a recurring monetary cost due to corrosion. There's no easy way to estimate this exact amount because we must include both the costs needed for preventive measures like coatings and those for repairs of corroded parts. The estimate of the cost of corrosion is close to 5% of the country's gross domestic product! The cost of corrosion often exceeds the damages caused by floods, cyclones, and earthquakes all put together. The entire economy will drastically change if there's no corrosion. Though the cost of corrosion is inevitable, much can be done to reduce it! One good way to do this is by a proper selection of materials and sound design. Dr. Ilaksh Adlakha and his research group in the Department of Applied Mechanics at IIT Madras work on this problem.

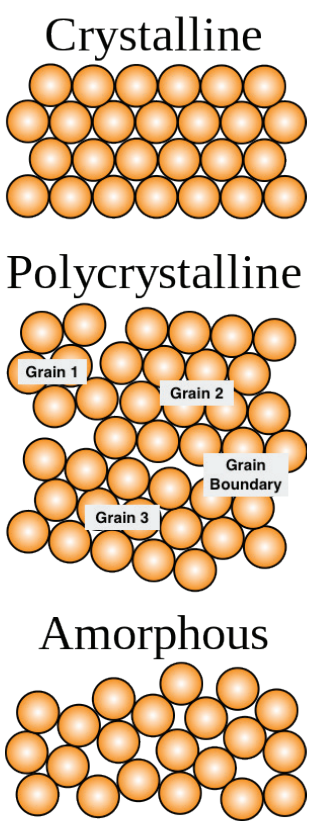

Fig 1: Arrangement of atoms in different types of materials. A polycrystalline material is made of different "grains".

When asked about why he chose to pursue this field, Dr. Adlakha says, "One of the motivations is to find out how to engineer the next generation of environmentally resistant structural alloys." In marine applications, there is constant exposure to the harsh environment of sea water. If we observe, in our kitchens at home, the salt is never stored in a stainless steel container while most of our other storage containers and utensils are made of shiny stainless steel. The reason for this is that the chloride ions present in common salt are capable of breaking through the protective layer in stainless steel to cause corrosion. At a large scale, underground pipelines, underwater appliances, and containers in contact with highly corrosive environments are severely prone to many kinds of corrosion. Hence, naval structures like aircraft carriers and the aircraft themselves require a robust selection of materials.

If we think about the many ways by which corrosion can happen, it's incredible that we have made any progress at all! But it's not all bleak if there is some way to judge whether a material can tolerate its environment. It is for this purpose that we need essential insights about the mechanisms of corrosion to provide useful inputs that help us to sieve through the possible materials and pick some for the required application.

There are multiple length scales associated with any material. When we look at an object with our naked eyes, we see its shape, dimensions, and the material it's made of. Materials are primarily of two types: crystalline and amorphous. Crystalline materials have a regular arrangement of atoms over long distances whereas amorphous materials don't. Most metals in everyday applications are crystalline. If we observe the same object a bit more closely, say with the help of an optical microscope, we will then find that most of the objects around us are not made of just one kind of arrangement of atoms. Instead, the atomic planes are oriented in different ways. Each material is therefore divided into many regions based on the orientation of the atomic planes. These regions are called grains, and the areas at the intersection of two or more of these grains are called the grain boundaries (Fig 1). If we go much deeper in our exploration, looking at the material magnified a billion times compared to the naked eye, we reach the scale of atoms. Depending on what property of the material we study, different length scales come into play.

If we wish to study corrosion, it's not sufficient to stick to just one length scale. This multi-scale nature makes studying corrosion challenging, and it is a phenomenon that people have been looking at for over a hundred years but haven't yet understood fully. We know there is some amount of degradation of performance, but it remains to be fully understood how to break down the study of corrosion across different length scales.

Corrosion can be studied as a macro-scale phenomenon, where the material gets "eaten up" due to the chemical reactions. When examined at the microstructure level, the grains and grain boundaries play a role. The material can selectively deteriorate along the grain boundaries leading to the material zipping and opening up along the grain boundaries and causing failure. At the atomic scale, the hydrogen that can evolve as a part of the electrochemical reactions gets accumulated in specific regions, leaving behind areas that are susceptible to failure on the application of loads.

"As a part of my area of research, I have focussed on looking at the different scales in which this phenomenon happens", says Dr. Adlakha. "The hydrogen that accumulates starts degrading the mechanical performance, both by modifying how the material behaves under load and by changing the surface electrochemical reactions themselves after this application of load." Having worked on different scales, he is trying to link them into one consistent idea that can help predict, by some estimation, the contribution of each of these phenomena to mechanical degradation.

There are various techniques of study used at each scale. For instance, at the atomic level, we can imagine the atoms to be little balls or spheres. We can then use the same laws that Newton may or may not have come up with after the customary apple fell on him: Newton's laws of motion. These laws can be used to estimate how the atoms (spheres) move around just like how they can help in understanding the movement of macroscopic objects. We do this by solving for the velocities of the atoms from thousands of simultaneous equations (the exact number depends on the number of particles we want to model) using codes written for the purpose. Once the numbers are "crunched", we can simulate which regions the hydrogen atoms segregate to. Other techniques like phase-field modelling, crystal plasticity, and multiphysics simulations using tools like Comsol® are used to quantify plasticity (studying how the material permanently deforms under loads) and reaction kinetics during the electrochemical reaction. Once we have results from simulations at different scales, we need to look at the contribution of each of them to the big picture. This contribution changes from material to material.

It needs to be admitted that in our pursuits to isolate the study at each length scale, we have purposely ignored some aspects of the phenomena at other scales. But all of these are at play when corrosion happens in real life. This interplay of different phenomena is therefore only captured via experiments. Quantifiable parameters from experiments are crucial to thread together the scales by deciding on the weight to be given to each scale. "The overall idea is that, when you do a hierarchical study across many length scales, we can't carry all information from each length scale. We need to carefully choose which ones to", explains Dr. Adlakha. "We can feed everything into a predictive framework and see from experiments how far the results match. Along with my PhD students, I am trying to capture information from different scales and develop such a predictive model alongside experiments."

So, in the end, these studies aim to come up with a robust model across length scales, hierarchically, to ensure that we are in a position to predict when the failure occurs. Such a model will not only save money but also indirectly save time and needless to say life! This model can help understand corrosion better, thereby making it possible to either design new materials or pick existing ones with tailored properties to fit with the environment for different applications. The "MultiScale Mechanics" research group headed by Dr. Ilaksh Adlakha is driven to take us there.

Professor's Bio

Dr. Ilaksh Adlakha is an Assistant Professor in the Department of Applied Mechanics, IIT Madras. He obtained his PhD from Arizona State University in 2015. His research interests lie at the interface of solid mechanics and materials science with a special focus on the development of structure-property relationships across multiple length scales.

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Mythreyi is a fourth-year undergraduate student and is stoked about pursuing an interdisciplinary dual degree in Computational Engineering, which directly feeds her interests in Computational Materials Science. When not tinkering with digital tools that she stumbled upon by proactive serendipity, she can be found reading books and writing. She has elaborately created a blog in her head; she hopes it will "materialise" one day.