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Short Communication

Where the Damascus Steel Meets Nanotechnology and Additive Manufacturing

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Abstract

Made few centuries ago, the technology behind Damascus steel and its fine ingredients remain still a mystery. The birth of modern metallurgy was catalysed by Damascus steel. It has a high strength in terms of yield stress and ultimate tensile strength. It can be identified by the unique surface texture due to combination of metals with different carbon percentages. Even though the appearance was reconstructed with reasonable physical properties, features such as existence of multiwalled carbon nanotubes make it unique compared to modern day replications.

Introduction

Damascus steel refers to the steel material used to make swards that Europeans have found in Damascus. According to scientists, the entire metallurgical scientific world in Europe was fascinated by Damascus Steel and laid the foundation for western metallurgical science. The name mainly given to the place where Europeans found it rather than the place where it was made, Damascus steel is a key turning point of the modern materials science. Smith [1] highlights the significant role of Damascus steel in the evolution modern metallurgy by attempting to unravel the mystery of Damascus steel. One easy way to distinguish Damascus steel from other types of steels is the typical pattern called Damascus pattern or Damascene pattern which resemble flowing water that can be seen to the naked eye. The advanced microstructure and metallurgical composition of the steel is evident from the visual appearance of the surface of the blade itself. The Damascus swards which were originated in the Middle East and Asia were far superior to the European steels at that time. They have demonstrated a far superior strength and a sharp cutting edge. It is believed that the raw material to produce Damascus steels were originated from ancient India and Sri Lanka. This was known in the west as Wootz steel. It is believed that the process of making Wootz would have taken from 6 hours to 6 days and the finest metal was made in Sri Lanka using monsoon wind. Unfortunately, the real process used to make Damascus steel and its raw materials during the 16 to 18th century is now a mystery.

Microstructure and Physical Properties

It is commonly agreed that the microstructure of a Damascus steel blade consists of wavy arrays of light-coloured cementite particles in a dark steel matrix. It has a yield strength of 750 MPa and UTS of 1030 MPa with a high carbon percentage in the range of 0.59 to 1.87. Such a high carbon percentage was present as the metal is made in a sealed crucible [2]. At room temperature, pure iron is having a Body Centered Cubic structure. Small pieces of the metal were mixed with charcoal in a sealed clay crucible and heated to a high temperature around 1,200 C. At this temperature the metal is solid with a Face Centered Cubic structure. This crystal structure is making an interstitial with carbon impurity, by diffusing carbon to Iron. The process form Austenite structure. The addition of carbon lowered the melting point of the metal. When carbon content increases in the surface, the surface begins to melt. The completion of the melting process can be identified by shaking the crucible. The melting process can take from six hours to few days depending on the temperature. After melting, the crucible is allowed to cool slowly. It is believed that the ancient Wootz were made in two different carbon percentages. For a mixture of Iron and Carbon, the eutectoid composition is 0.8 weight % of carbon at 725 °C. If an austenite composition with less than 0.8% (proeutectoid) is cooled slowly, it will result in soft perlite and ferrite. If it contained more than 0.8% the result will be hard perlite and cementite.

Chemical Composition and Role of Impurities

Verhoeven et al. [3] and Peterson et al. [4] have analysed an original Damascus steel sample for 81 elements and have confirmed that the main impurities were Ni, Cu, Zn, Au, and Pb and no other element was present above the 0.01% (100 ppm) level. Further Verhoeven et al. [2] have suggested that the band formation in Damascus steels from micro segregation of low levels of carbide forming elements such as V, Mo, Cr, Mn and Nb. The process is effective with Vanadium and Molybdenum. Research has shown that Vanadium concentrations as small as 40 ppm is effective in producing clustered particles.

Role of Carbon Nanotubes

Damascus steels exhibit very high yield stress and UTS. Many scientists attempted to describe the ultra-high strength capability of Damascus steels. Kochmann et al. [5] have gone into the nano scale to investigate samples of genuine Damascus steel. Upon observation through electron microscopy, they have found high density of nanowires outside the cementite particles in samples taken from different places. Carbon nanotubes were oriented parallel to each other with a spacing of about 50 nm. Some of them were straight and some of them were curved. Carbon nanotubes are generally classified as single wall, double wall, and multiwall. The presence of nanowires is supposed to act as crack arresters and obstacles for dislocations. This could enhance the fracture toughness and overall mechanical properties of Damascus steels and one of the secrets behind extraordinary properties of Damascus steel. Kochmann et al. [5] have concluded their research with a question for us to answer as: "how does the composition of wootz and/or the processing of Damascus blades lead to the formation of those nanowires and what are the consequences for their exceptional properties?". Nevertheless, in a separate encounter, Kokarneswaran et al. [6] have observed carbon nanotubes in ancient pottery found in India dating back to the sixth century BC. What is interesting about the discovery is that they have had bundles of single-walled carbon nanotubes, multi-walled carbon nanotubes and sheets like structures as the inner coating of the pottery.

Composites are generally made of a matrix and fiber where, fiber being brittle and strong and the matrix being ductile. Composites demonstrate superior strength and low specific weight. The same analogy can be used to explain the superior properties of Damascus steel. Pearlite itself is a microscopic scale composite, which is a combination of ferrite and cementite. Here, the strength is provided by the hard layer made of cementite. The soft layer made of ferrite, was subjected to strain hardening thus allowing the material to absorb energy without fracture. Even though there have been many speculations on naturally occurring carbon nanotubes, MacKenzie et al. [7] dispute them with valid reasons. If so, a question arises as to how carbon nanotubes were formed in Damascus steels?

Alignment with Laser Sintering

Damascus steel is considered a layered combination of steel. This is evident from the fact that Damascus swards had varying carbon content across the sward and its visual appearance. The layers were fused together by heating the layers to a high temperature and subsequent application of pressure, probably by means of hammering. Scientists believe that this process was done many times to the same piece of metal to get the required properties. For example, if a blacksmith started with just four layers and prepared new four layers from the finished steel and repeated the same four times, the number of layers will be 44 = 256. Still steels with carbon nanotube composite production are at laboratory scale. Powder metallurgy is a common and effective way of producing Carbon Nanotube reinforced metal composites. The author's opinion is that still most of work is done in Aluminium based Carbon Nanotube composites. The Results of experiments show a drastic improvement of yield strength.

Selective laser melting is a kind of additive manufacturing where a laser beam is used to melt a metallic powder layer in a sequential manner controlled by a computer to give a final desired shape after solidification. It was mentioned that Damascus swords are made of layered combination of steel. Although the two processes are not similar, an analogy can be drawn regarding layered combination of Damascus swards and additive layer manufacturing. Recently Gu et al. [8] have reported producing Carbon Nanotubes (CNTs) reinforced aluminium matrix nanocomposites by means of laser additive manufacturing. They have been able to determine the optimal processing parameters in terms of laser power and scan speed. They have observed tailored microstructures and excellent mechanical properties.

Conclusion

The existence of layered structure is very important for Damascus swards. Ancient metallurgists who have supplied raw materials knew how to make hard Wootz and soft Wootz by changing the carbon content. The hard section was made of cementite and the soft section was made of ferrite. The existence of Carbon nanotubes was not known to humankind until 1991. Even with the modern technological development there can be many more nano and micro scale particles yet to be discovered. Then the scientists will be able to fully describe the real mechanisms that were underlying behind the superior strength of Damascus Steels and fully resolve the mystery.

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