Connections and Pathways Evolving from a Metallurgical Education at Sheffield University

The 66th Hatfield Memorial Lecture

Sheffield University
December 11, 2018
Q: Can Steels be Superplastic?
A: Only with a lot of Carbon
Development of superplastic steels led to rediscovering ancient Damascus Steel secrets
Superplasticity was actually discovered in 1911
Persian scimitar is an example of a Damascus steel sword
Competitors for Worst Medieval Film

The Crusades
Directed by Cecil B. DeMille (1935):
King Richard: Henry Wilcoxon
Saladin: Ian Keith
Berengaria: Loretta Young
But: included the “veil cutting”

King Richard and the Crusades
Directed by David Butler (1954):
King Richard: Rex Harrison
Saladin: George Sanders
Berengaria: Virginia Mayo

Damascus steel in the movies about the Crusades
Duplicating Damascus steel which was produced until about the 18\textsuperscript{th} Century

\textbf{17\textsuperscript{th} Century}
Real Damascus pattern

\textbf{1980}
Simulating the Damascus pattern

\textbf{1989}
Stanford-developed Damascus blade
The Mystery of Damascus Steel Appears Solved

By WALTER SULLIVAN

Two metallurgists at Stanford University, seeking to produce a "superplastic" metal, appear to have stumbled on the secret of Damascus steel, the legendary material used by numerous warriors of the past, including the Crusaders. Its formula had been lost for generations.

Analyses of steel by Jeffrey Wadsworth and Oleg D. Sherby, in their search for a highly plastic form, revealed properties almost identical to those they then found in Damascus steel, though their own plastic steel had been produced through contemporary methods.

The remarkable characteristics of Damascus steel became known to Europe when the Crusaders reached the Middle East, beginning in the 11th century. They discovered that swords of this metal could split a feather in midair, yet retain their edge through many a battle with the Saracens. The swords were easily recognized by a characteristic wavy or "dama..." pattern on their blades.

The authors — perhaps from the time of Alexander the Great in the fourth century B.C. — the armormen who made swords, shields and armor from such steel were rigidly secretive regarding their method. With the advent of firearms, the secret was lost and never fully rediscovered, despite the efforts of men like P.P. Anosoff, the Russian metallurgist, who knew the steel as bulat.

In 1841 Anosoff declared: "Our warriors will soon be armed with bulat blades. Our agricultural workers will till the soil with bulat plow shares... Bulat will supersede all steel now employed for the manufacture of articles of special sharpness and endurance..." Yet his lifelong efforts to fulfill that dream were in vain.

Dr. Wadsworth and Dr. Sherby realized that they might be on the track of the method when a sword fancier, at one of their presentations, pointed out that Damascus steel, like their own product, was very rich in carbon. This led them to conduct comparative analyses of their steels and those of the ancient weapons.

Dr. Wadsworth, while still associated with Stanford, now works at the nearby Lockheed Palo Alto Research Laboratory. Dr. Sherby, a professor at Stanford, is an authority on deformable metals. When moderately heated, superplastic steel can be shaped into such complex forms as gears for an automobile, with minimal need for machining, leading to major economies in manufacture. Their research, Dr. Wadsworth said recently, has shown how to make steel even more amenable to shaping than the Damascus variety.

A basic requirement, as suspected by a number of early metallurgists, is a very high carbon content. Dr. Wadsworth and Dr. Sherby believe it has to be from 1 to 2 percent, compared to only a fraction of 1 percent in ordinary steel.

Another key element in Damascus blade production seems to have been forging and hammering at relatively low temperature — about 1,700 degrees Fahrenheit. After shaping, the blades were apparently reheated to about the same temperature, then rapidly cooled, as by quenching in a fluid.

The secrets of Damascus steel were shared by

Continued on Page 19

Typical damask pattern appears on a 16th-century Turkish sword. The New York Times / Josh Manning
Laminated metal composites can dramatically improve many properties.
Examples of welded Damascus steel gun barrels

Enlargement of a “Zenobe Gramme” Damascus barrel with the name worked into it.
UHCS and Damascus steels
Chronological Overview

- Superplasticity
- Ultrahigh carbon steels (UHCS) — Commercialization efforts
- UHCS-based laminated composites
- Damascus steels
- Welded Damascus steels
- Carbon dating
The steel sword was the preeminent hand weapon through a long period of history and many cultures.

- **Turkish blade, Alacahöyük, Anatolia, ~2500 BCE**
- **Persian scimitar, 17th century or later**
- **Indonesian kris, 19th century**
- **Merovingian blade, 650–700 CE, Finland**
- **O-Kanehira, Japan, ~1000 CE**
- **Chinese pattern-welded blade, 17th century CE**
Modern simulations of folding using UHCS and Fe-3%Si
## Possible property improvements in laminated materials

<table>
<thead>
<tr>
<th>Laminated artifact</th>
<th>Limited material</th>
<th>Processing to make bulk material</th>
<th>Tensile strength</th>
<th>Improved toughness</th>
<th>Improved damping</th>
<th>Attractiveness quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gizeh iron plate</td>
<td>✓</td>
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<td>✓</td>
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<td>Achilles’ shield</td>
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<td>Chinese refinings</td>
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<td>Merovingian</td>
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<td>Japanese sword</td>
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<td>European gun barrels</td>
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<td>Shear/double-shear</td>
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<td>Chinese pattern welded</td>
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<td>✓</td>
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<td>Persian dagger</td>
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<td>✓</td>
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<td>FSU materials</td>
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<td>Modern knives</td>
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<td>✓</td>
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<tr>
<td>Modern chisels</td>
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<td>✓</td>
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</tbody>
</table>
In modern times, the Ukrainians are using laminated composite designs for engineering applications.
Three puzzles in Materials Science

<table>
<thead>
<tr>
<th>Puzzle Description</th>
<th>Status</th>
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<tbody>
<tr>
<td>The knives of Frank Richtig</td>
<td>Solved</td>
</tr>
<tr>
<td>The iron plate found in the Pyramid of Gizeh</td>
<td>Could be solved</td>
</tr>
<tr>
<td>Pancake rocks and zebra rocks</td>
<td>Unsolved</td>
</tr>
</tbody>
</table>
Frank Richtig’s knives and his secret process
Frank Richtig’s secret died with him

[Richtig] told me that he had found no one worthy of being told or taught his knifemaking, and until he did, nobody was going to get his “secret.”

During his declining years, no one came forward, and when he passed away in the early 1970s, so did the tempering process.

A man is entitled to some secrets, and that’s mine.

Frank J. Richtig

Glen Lambert
Comparison of Austempered and Q&T steels

Austempered 52100 steel

Quench and tempered 52100 steel

Stress (MPa)

0 500 1000 1500 2000

0.05 0.10 0.15 0.20

Strain

0 0.05 0.10 0.15 0.20

Strain
Conclusions about Richtig’s secret

- Steel is 1090 or 1095
- Quenching was from just above the $A_1$
- Probably an austempering process, at about $300–400^\circ C$, MP of Lead, $327^\circ C$
- Hardness is $R_c = 40–55$

The austempering process is generally recognized to have been introduced by Bain and Davenport in the 1930s.

Since the Richtig knives were famous by this time, Richtig discovered the process first.
In 1837, a steel laminate claimed to date to 2650 B.C. was found in the Great Pyramid in Giza.

"The age of this plate is important... if it can be shown to be the same age as the pyramid, then it is one of the most ancient pieces of iron yet discovered."

El Gayer and Jones, JHMIS, 23, (2), 1960, 75-83
The cross section of Giza laminate revealed

Examination concluded that “these laminates have been inexpertly welded together by hammering. The various layers differ from each other in their:

· grain sizes
· carbon contents
· nature of their non-metallic inclusions
· thicknesses.”
Carbon content vs age summarizing all AMS radiocarbon dating data
“We feel that it could be premature to date the Giza iron at this stage, when future advances in technology will almost certainly provide superior reliability and accuracy so that any resulting date would have a better chance of being accepted as valid.”

“We are anxious to avoid a situation in which the dating might be dismissed as unreliable owing to contamination of one kind or another . . . with . . . destruction of a significant part of the object.”

“To have the best chance of achieving this might mean waiting for some years, perhaps decades, whilst the dating technology available to us improves.”
The mechanism for formation of these rocks is unknown.

Layered mudstone and limestone with a layer of spacing of about 8 cm
Is there a correspondence between pearlite formation in steels and the Pancake Rock layers?
Can the Pancake Rocks growth rate be predicted by extrapolation of the pearlite growth rate?

\[ v = \lambda t_\lambda \]
\[ t_\lambda = \frac{\lambda^2}{D_{\text{eff}}} \]

Accumulation of shells and mud
Compaction and solid-state transformation
Multilayers of limestone and mudstone
Rocks exposed by Kaikoura Orogony
Advances in structural materials have changed the balance of power.

<table>
<thead>
<tr>
<th>Time</th>
<th>Example</th>
<th>Materials advance</th>
</tr>
</thead>
<tbody>
<tr>
<td>50,000 BCE</td>
<td>Cro-Magnons overwhelm the Neanderthal</td>
<td>Shaping of stone and bone (ceramics later)</td>
</tr>
<tr>
<td>6000–1800 BCE</td>
<td>Rise of city-states with armies in Asia, Mesopotamia, Europe</td>
<td>Copper and bronze</td>
</tr>
<tr>
<td>1500 BCE (?)</td>
<td>Kingdoms and empires in Asia, Near East, Southern Europe</td>
<td>Iron and steel</td>
</tr>
<tr>
<td>1300–1800 CE</td>
<td>European wars and colonial expansion</td>
<td>Gunpowder and firearms</td>
</tr>
<tr>
<td>1850 CE</td>
<td>Modern warfare</td>
<td>Mass production of iron and steel</td>
</tr>
<tr>
<td>1945 CE</td>
<td>Nuclear weapons</td>
<td>Graphite, uranium, plutonium</td>
</tr>
<tr>
<td>1956–2000 CE</td>
<td>Submarine-launched ballistic missiles</td>
<td>Molybdenum, tantalum, niobium, tungsten</td>
</tr>
<tr>
<td>2000 CE</td>
<td>Network-centric warfare</td>
<td>Silicon; electronic and photonic materials</td>
</tr>
</tbody>
</table>
Winning the Cold War: Refractory metals development
New tools led to improvements in understanding the processing

Role of C and O on Mo fracture stress (Kumar and Eyre, 1980)

In situ Auger electron spectroscopy study of Mo grain boundaries (Wadsworth et al., 1984)
Using lasers to deliver solutions to issues of national critical importance.
1929

Battelle Founded
1940s
Xerography

1965
First Major Lab Contract
1970s–80s

Universal Product Code, Compact Disk, Cruise Control
Battelle’s current strategy
1990s
Lab Management Leader

2000s
Further Growth and International Expansion

1929
1940s-1960s
1970s-1980s
1990s–2000s
Today

INL
Idaho National Laboratory

NBACC

BROOKHAVEN
National Laboratory

OAK RIDGE
National Laboratory

NREL
National Renewable Energy Laboratory

Lawrence Livermore
National Laboratory

UK National Nuclear Laboratory

Republic of Georgia
Developing some of the world’s largest and most powerful scientific instruments

Spallation Neutron Source
Summit

World’s fastest computer in 2018

Former fastest computer 2012-2014

Former fastest computer 2009-2010
Building world-leading capabilities for x-ray imaging and high-resolution energy analysis

NSLS-II
Advanced Synchrotron
Solving complex and interlocking national security challenges
Battelle DroneDefender™

Safe, directed-energy countermeasure that instantaneously disrupts undesirable drone activity.

2 DEFENSES
- Remote control disruption
- GPS disruption

Immediate response to immediate threats

- Demonstrated range: >400m
- Cold start time: <0 1 seconds
- Operating time: Up to 1 hr. continuous

Low cost • Lightweight • Minimal training

This is a prototype.
Can you spot the armored vehicle?

Neither can the enemy.
Proliferation of nuclear technology
Should the energy crisis be viewed as an opportunity?
Shortages of vital energy resources have driven innovation in the past.

Bronze to iron, ~1500 BCE
- Shortages of tin led to development of smelting
- Price of iron fell by a factor of 80,000 over 1200 years

Charcoal to coke, 1700 CE
- Wood shortages drove use of coal
- Invention of coke smelting advanced the mass production of iron and brass
- Casting methods enabled economical production of steam engines

Fossil fuel to sustainable energy, 2050 CE?

Stephen Sass
Leading the development of 3D Printing
Developing treatments for the Ebola epidemic
Targeting reanimation of paralyzed limbs through a neural bridging system

Cortical Implant

Re-encoding Algorithms

Neural Signal Decoding

High Definition Neuromuscular Stimulation Cuff

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Advising global leaders about R&D, technology and educational challenges
Some leading scientists who advance R&D and education

- William Shockley, Nobel Prize
- Edward Teller, Physicist
- James Watson, Nobel Prize
- Raghunath Anant Mashelkar, Chemical Engineer
- Lowell Wood, Most prolific US inventor
- Robert Laughlin, Nobel Prize
- Glenn Seaborg, Nobel Prize
- Carl Wieman, Nobel Prize
- Sir Richard Roberts, Nobel Prize
- Harold Kroto, Nobel Prize
Battelle – partnering to transform education