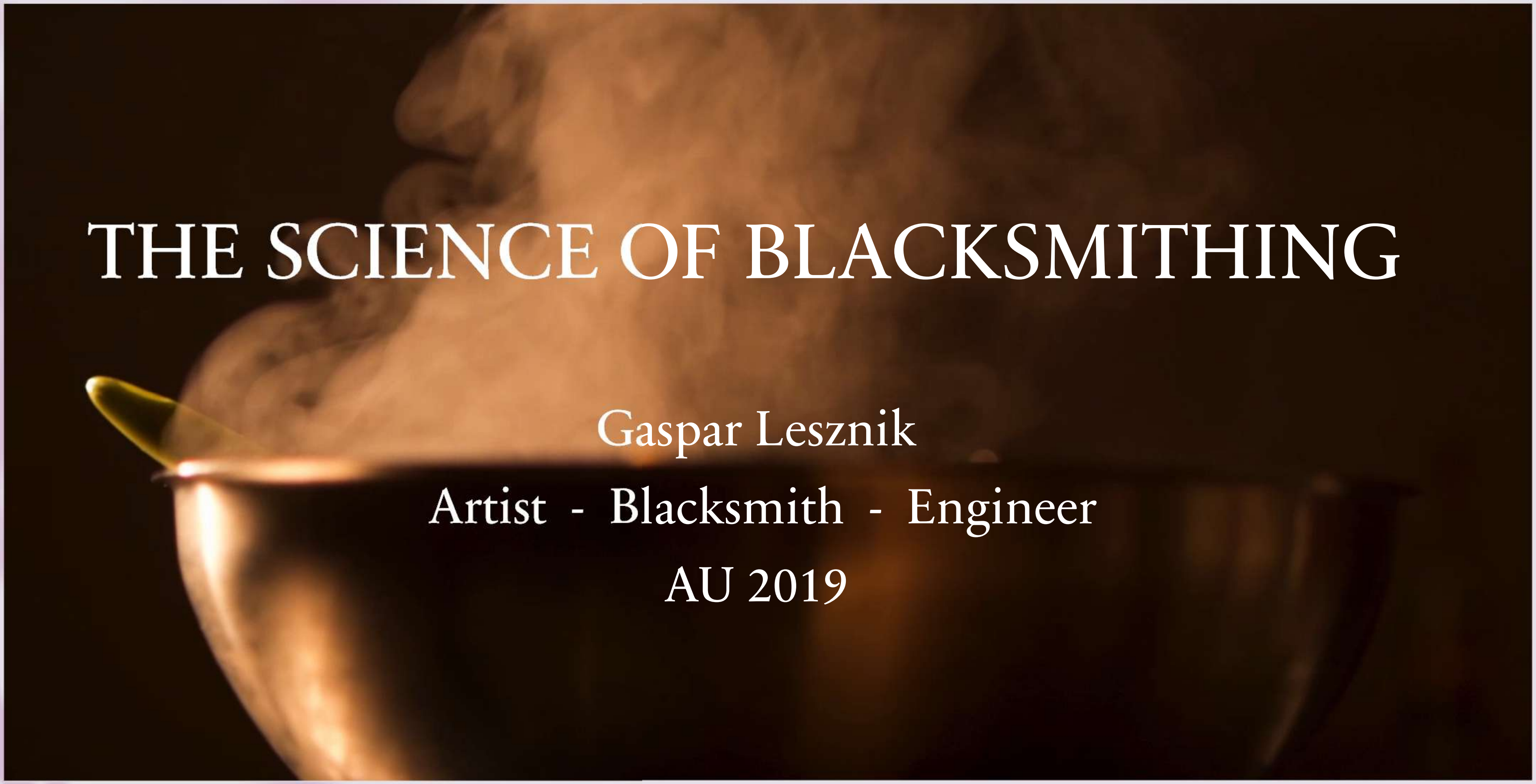

THE SCIENCE OF BLACKSMITHING

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AU 2019

Disclaimer

- I don’t shoe horses.
- Farriers shoe horses.
- All Farriers are Blacksmiths.
- Not all Blacksmiths are Farriers.

Topics

- Traditional Blacksmithing
- The Raw Material - Steel = Iron + Carbon
- Steel – the tough stuff
- Blacksmithing Equipment
- Forging
  - Temperatures and Physical State
  - Moving Metal - Physical and Mechanical
  - Heat Treatment
- Forge Welding

Traditional Blacksmithing

- A blacksmith makes tools and other objects out of metal by heating it and using force to bend, twist and otherwise shape the material.
- Before the Industrial Revolution (~1760 to 1840) the blacksmith was your local "factory" to make just about everything made of metal. Nails, chains, plows, pots, knives, chisels, hinges, latches, kitchen utensils, chains, etc.
- **Tools for all the Trades.**
- **Traditional** blacksmithing – how it has been done for thousands of years up until the industrial revolution (~1750 AD). *(my definition)*

The Raw Material: Steel = Iron + Carbon

- Iron (Fe) – *Latin: ferrum*
  - by mass is the most abundant element on earth, just ahead of oxygen, 32.1% and 30.1% respectively
  - Extracted from ores found on earths crust and surface
  - Melts at ~2,750°F where it is separated from other minerals present
  - Relatively soft and malleable, dense
- Carbon (C) – *Latin: carbo (coal)*
  - Abundant in nature in many forms: coal, diamond, burnt toast…..
  - A building block of life. Without carbon life as we know it would not exist.

Steel - the tough stuff

- Steel is a **solid solution** of iron and carbon. The carbon is dissolved in the iron. Iron is the solvent and carbon is the solute.
- In 2020 the world produced 1,878 million tons of steel.
- Infinitely recyclable.
- There are over 3,500 grades of steel broken down into 4 categories
  - Carbon steel (90% of all steel produced).
  - Alloy steel
  - Tool steel
  - Stainless steel

Steel – the tough stuff

- Carbon Steel = Fe (~99%) + C (~<1%)
  - Mild (Low Carbon) Steel: C = < 0.25%
    - Inexpensive, the most abundant steel used globally (~90%). It is used in everything that does not require superior strength or durability.
    - Can not be hardened. Can not hold a sharp edge.
    - Piping, fencing, ornamental, wide range of structural applications (bridges)….
  - Medium Carbon Steel: C = 0.25 – 0.55%
    - Can be hardened.
    - Railroad tracks, machinery parts, pressure vessels, cranks…..
  - High Carbon Steel: C = 0.55 – 0.99%
    - Maximum strength and hardness, low ductility.
    - Knives, chisels, punches, spring steel, cutters, ………

Steel – the tough stuff

- Alloy Steels
  - Contain one or more alloying elements (nickel, manganese, titanium, copper, silicon, chromium, molybdenum, cobalt, tungsten, vanadium, and aluminum) to obtain various steel properties for different applications.
  - Hardenability, corrosion resistance, strength, formability, weldability, or ductility can be improved.
  - More expensive than carbon steels. Widely available.
  - Thousands of variations.
- Tool Steels
  - A subset of alloy steels derived for material toughness, high hardness, abrasion resistance, heat resistance.
  - Machine tools, hammers, molds, dies, cutters…………
- Stainless Steels
  - Up to 20% chrome and 10% nickel. Corrosion resistant, sanitary, aesthetic…..

Steel – the tough stuff

- The carbon content determines the maximum *obtainable* hardness of the steel
- Heat treatment determines the *actual* hardness and flexibility
- How steel is heated and cooled will dictate whether the given steel will shatter, bend, or flex.
- Heat affects the growth and arrangement of the steel's crystalline structure
- *Wrought Iron*
    - *An iron alloy with <0.02% carbon and ~2% other impurities (slag)*
    - *Used throughout history but replaced by advanced steelmaking methods*
    - *No longer commercially available, last foundries shut down in the 1970's*

Four-digit AISI Alloy Numbering System

Note: Alloying elements are in weight percent, "xx" denotes carbon content.

10xx	Basic plain carbon steels
11xx	Plain carbon steel with high sulfur & low phosphorous (resulferized)
12xx	Plain carbon steel with high sulfur & high phosphorous
13xx	1.75 manganese
23xx	3.50 nickel (series deleted in 1959)
25xx	5.00 nickel (series deleted in 1959)
31xx	1.25 nickel & 0.60 chromium (series deleted in 1964)
33xx	3.50 nickel & 1.50 chromium (series deleted in 1964)
40xx	0.20 – 0.25 molybdenum
41xx	0.50 – 0.95 chromium & 0.12 – 0.30 molybdenum
43xx	1.83 nickel, 0.50 – 0.80 chromium & 0.25 molybdenum
44xx	0.53 molybdenum
46xx	0.85 or 1.83 nickel & 0.23 molybdenum
47xx	1.05 nickel, 0.45 chromium & 0.20 – 0.35 molybdenum
48xx	3.50 nickel, & 0.25 molybdenum
50xx	0.40 chromium
51xx	0.80 – 1.00 chromium
5xxx	1.04 carbon & 1.03 or 1.45 chromium
61xx	0.60 or 0.95 chromium & 0.13 – 0.15 vanadium
86xx	0.55 nickel, 0.50 chromium & 0.20 molybdenum
87xx	0.55 nickel, 0.50 chromium & 0.25 molybdenum
88xx	0.55 nickel, 0.50 chromium & 0.35 molybdenum
92xx	2.00 silicon

Steel – the tough stuff

- Junkyard Steels (my choice)
  - Used and abused and discarded steel of an unknown grade (and quality)
  - Widely available and cheap, often free
  - Infinite possibilities
  - Tool steel: Automobile springs (coil and leaf); axles, bed frames, saw blades, farm machinery, sucker rod, garage door springs…..
  - Carbon steel: Wrecking bars, fences, machinery parts and housings…..

Testing Junkyard Steel for Carbon

- Consider original use
- Spark test
  - Low or no carbon steels have dull sparks
  - Medium and high carbon steels are bright and explosive sparks

Blacksmith Equipment - the Forge

- Hearth or forge to heat metal.
  - Target high temperature from 1,700° to 2,300°F.
  - Usually constructed of cast iron, steel, brick and mortar
  - Must have forced air (oxygen). Blower, fan, bellows…..
- Fuel
  - Coal (clean bituminous is best). Widely available. Efficient and inexpensive.
  - Wood, charcoal can be used but very inefficient.
  - Propane
- Delivery of air (oxygen) is essential for a hot fire


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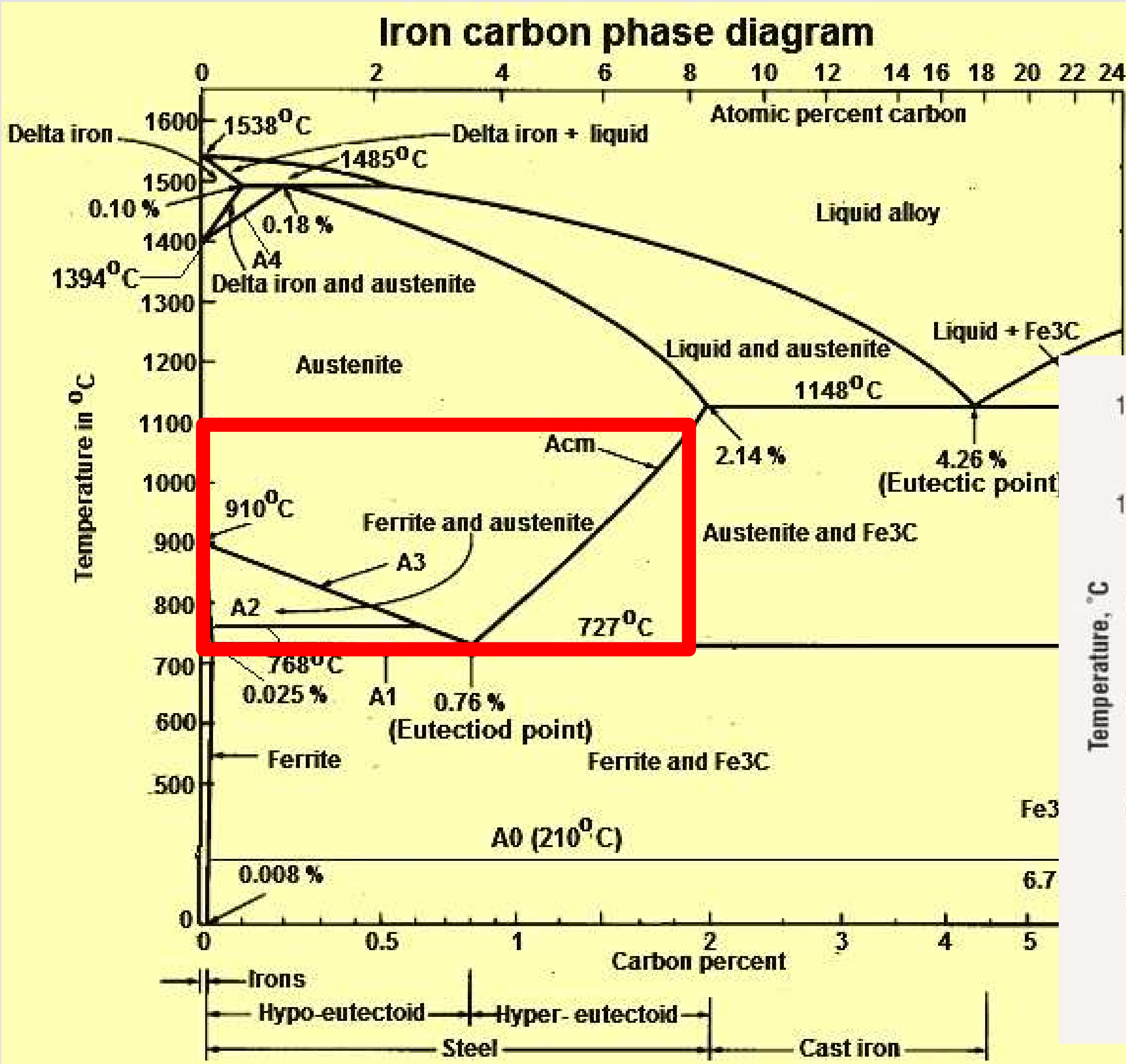
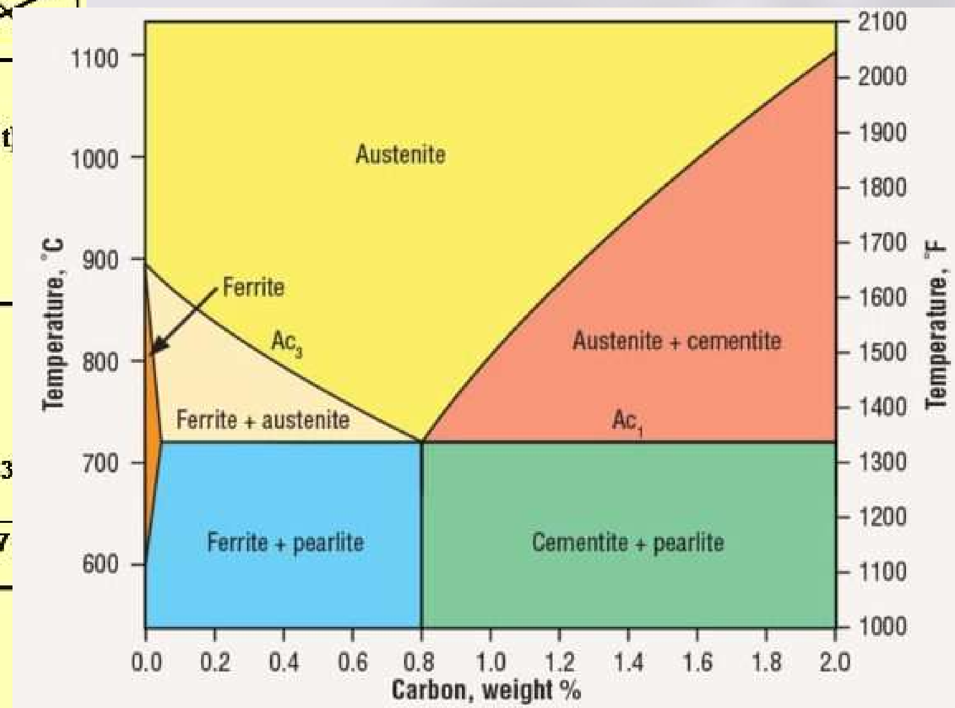
Blacksmith Equipment – the Anvil

- Anvil (the soul of the smithy)
  - Acts as a mold, platform and third hand to shape the metal
  - Accepts various tooling for cutting, twisting, holding, etc.
  - Must have mass
  - Traditional anvils are expensive (~$7 - $9 per pound)
  - Any heavy metal block can work to degree
- Accessories
  - Vice, quench bucket(s), hammers, tongs, hand tools

Forging and Temperature

- Forging is the act of shaping metal with kinetic energy (tools and muscle)
- Heating steel to above it's critical temperature (~1,350°F) changes the crystalline structure of steel making it malleable. A plastic state called austenite. Non-magnetic.
- Forging is typically done between 1,650°F to 1,975°F
- As temperature drops the steel begins to harden and stresses develop. Forging at too low a temperature can crack or break the steel.
- Heating the steel above 2,000°F can reduced the carbon content if held too long. Above 2,300°F (dazzling white) the steel will begin to spark and burn.


Iron carbon phase diagram
Atomic percent carbon
Delta iron
1538°C
Delta iron + liquid
1485°C
0.10 %
0.18 %
A4
1394°C
Delta iron and austenite
Liquid alloy
Austenite
Liquid and austenite
Liquid + Fe3C
1148°C
Acm
2.14 %
4.26 %
(Eutectic point)
910°C
Ferrite and austenite
Austenite and Fe3C
A3
A2
727°C
768°C
0.025 %
A1
0.76 %
(Eutectiod point)
Ferrite
Ferrite and Fe3C
A0 (210°C)
0.008 %
Temperature in °C
Carbon percent
Irons
Hypo-eutectoid
Hyper- eutectoid
Steel
Cast iron

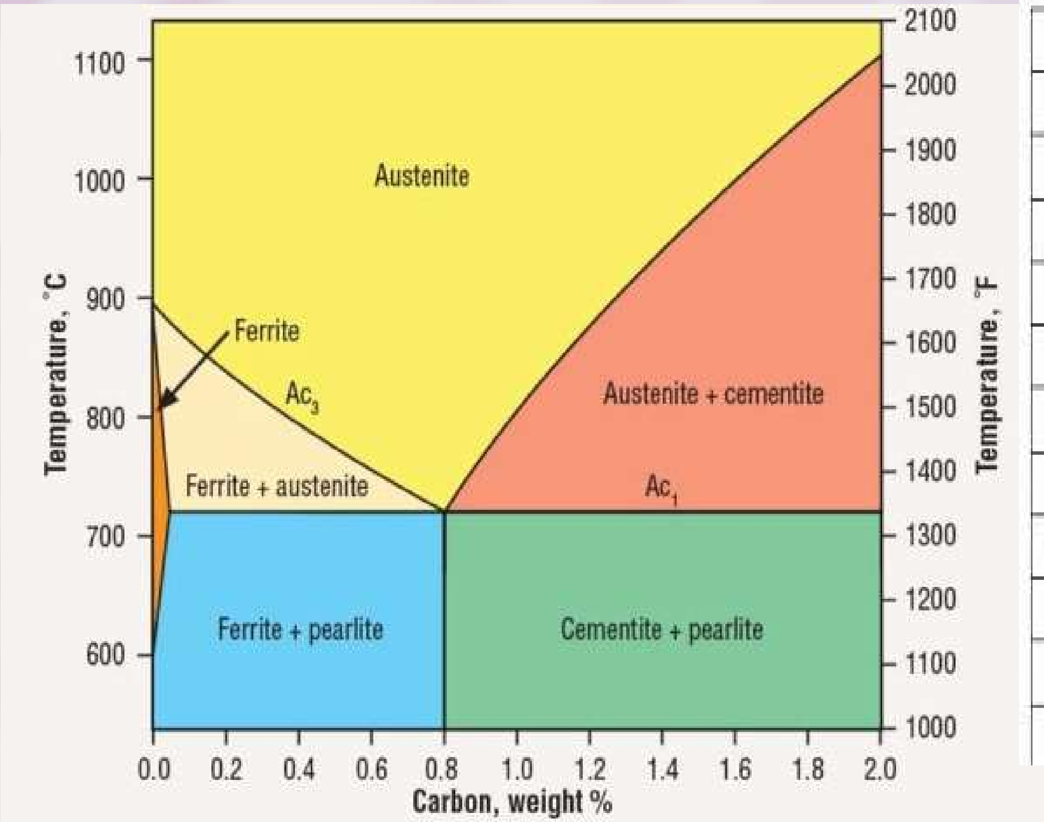

Austenite
Ferrite
Ac3
Austenite + cementite
Ferrite + austenite
Ac1
Ferrite + pearlite
Cementite + pearlite
Temperature, °C
Temperature, °F
Carbon, weight %

Forging - Moving Metal

- Forging is fast.
  - Temperatures drop quickly. Be ready. Strike while the iron is hot.
  - The greater the mass the longer it stays hot.
  - But also radiates more heat making it more difficult to work
- Moving metal by forging is physical and mechanical
  - Hammers have different profiles to achieve different results
  - Possibilities are nearly endless

Forging - Color of Heat

- Blacksmith shops are dark for a reason
  - Peaceful
  - Adds to the mystery. Almost mystical.
- *Temperature is determined by color of the steel.*
  - Inexact but close enough
  - Everyone's eyes are different
  - Experience teaches



Fahrenheit	The Color of the Steel
2000°	Bright Yellow
1900°	Dark Yellow
1800°	Orange Yellow
1700°	Orange
1600°	Orange Red
1500°	Bright Red
1400°	Red
1300°	Medium Red
1200°	Dull Red
1100°	Slight Red
1000°	Very Slightly Red, Mostly Grey

Forge Welding

Forging

Heat Treatment

- Forging is violent
  - High temperatures
  - Hammering, twisting, bending….
  - The object being made takes on numerous stresses which must be relieved to avoid fracture.
  - At the same we want to create a hard, ductile tool that will withstand hard use.   A chisel for example.
- The process to relieve the stresses and develop a finished tool is called Heat Treatment

Heat Treatment - Annealing

- To relive all the stresses the object must be *annealed* or *normalized* to a relaxed molecular state.
- The tool is slowly heated to above the critical temperature (non-magnetic) then allowed to cool very slowly (in a dying fire, still air, insulated enclosure).
- This may be done 2 or 3 times to ensure the tool is fully annealed.
- A metal nirvana.
- Good time to do any necessary filing or grinding.

Heat Treatment - Hardening

- After annealing the tool is free of stresses but is too soft to do any work and must be hardened.
- Next step is to heat it up again above the critical temperature and the cool rapidly.   Quenching.
- Different steels require different quench baths.   Brine, water, oil, air. The rapid cooling is violent and must be done properly to avoid cracks and failure.
- Following quenching the tool is now ‘glass hard’.   A file will skim across it without scratching.
- Very hard and very brittle. If dropped it may shatter.
- The crystals created (martensite) from rapid cooling are unstable.

Heat Treating – Tempering

- Full hardening leaves the tool too brittle for use. It is hard but not tough. The hardness must be relieved in a controlled way.
- Tempering reduces hardness (stress) and increases ductility.
- The tool is slowly brought to a low heat which changes some of the hard crystals (martensite) to more ductile ferrite and cementite.
- Temperatures range from 400^{o}F to 800^{oF}
- It is a slow process and requires patience.

Tempering

- Steel is brought to a bright polish.
- Heat is slowly applied
- Color of the steel changes
- The darker the softer, more ductile
- By controlling heat distribution areas of hardness and ductility are also controlled.

Fahrenheit	The Color of the Steel
2000°	Bright Yellow
1900°	Dark Yellow
1800°	Orange Yellow
1700°	Orange
1600°	Orange Red
1500°	Bright Red
1400°	Red
1300°	Medium Red
1200°	Dull Red
1100°	Slight Red
1000°	Very Slightly Red, Mostly Grey
800°	Dark Grey
575°	Blue
540°	Dark Purple
520°	Purple
500°	Brown/Purple
480°	Brown
465°	Dark Straw
445°	Light Straw
390°	Faint Straw

Forge Welding

Forging

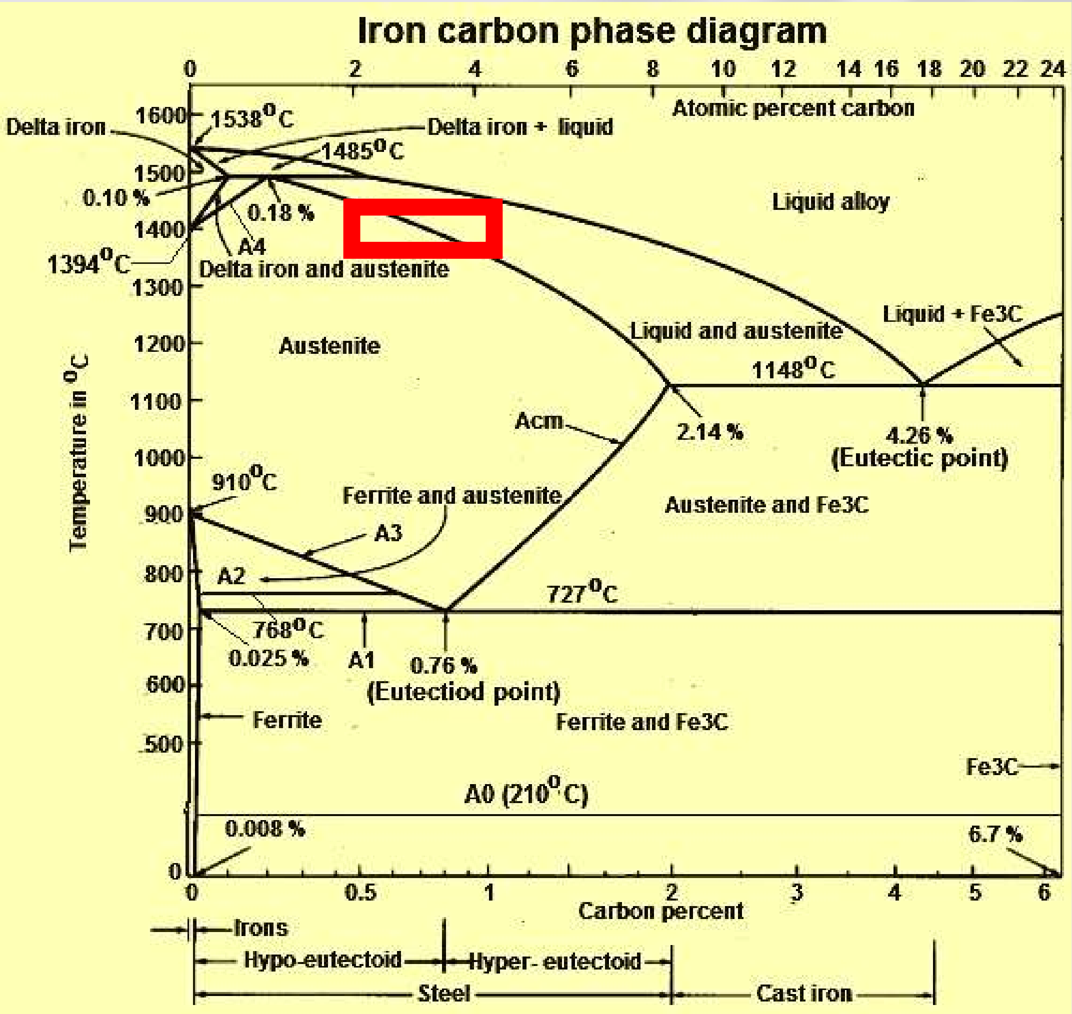
Tempering

Forge Welding

- By carefully controlling heat and eliminating contaminants, steel parts can be welded together to make one piece out of two or more.
- Different types of steel can be joined to utilize the properties of both. Combine strength and hardness with ductility. Reduce cost.
- Examples of forge welded common items are chain, axes and tomahawks, knives, Damascus steel, tongs, tools…..

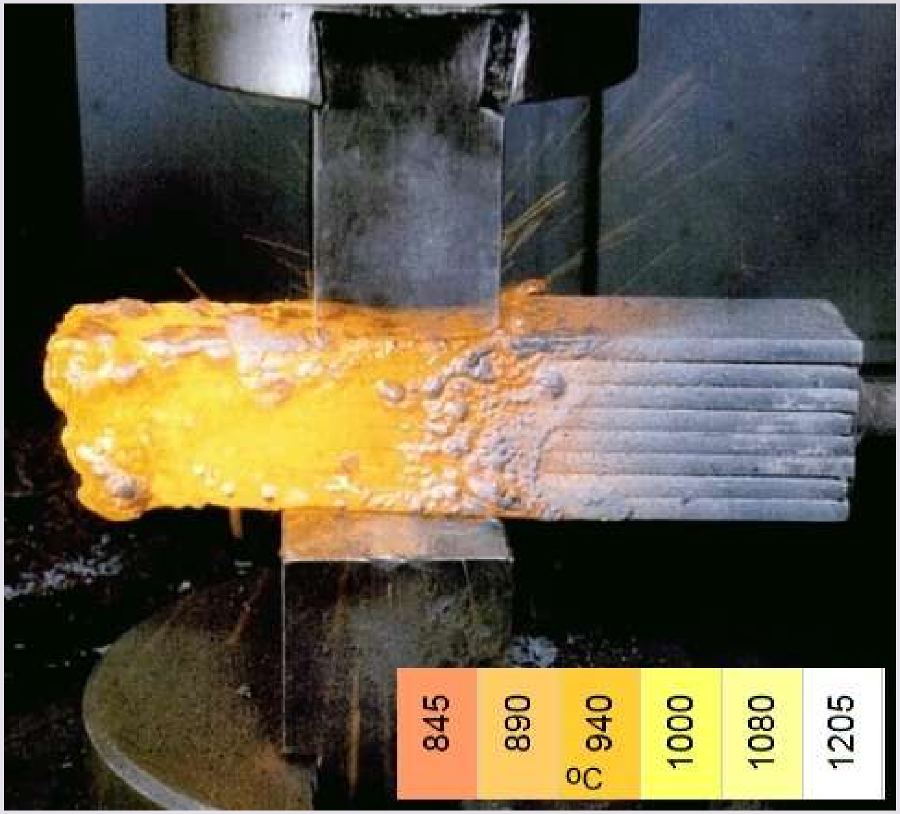
Forge Welding

- Above ~2,500°F steel begins to melt.
- If 2 pieces of steel at that temperature touch each other they will stick together
- Speed and cleanliness are key. Any debris will weaken the weld.
- A flux (Borax) on the mating metals keeps them clean.



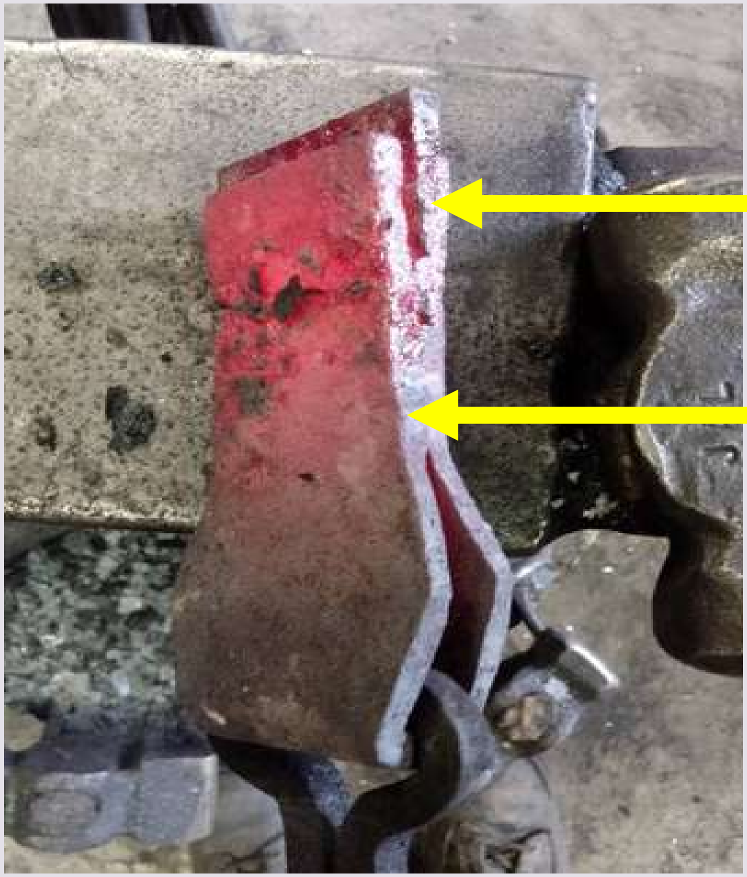
Forge Welding

- Layers of steel being welded into a larger billet
- ~2,000ºF



Forge Welding - Damascus and Mokume Gane

Forge Welded Axe Head



- Tool steel blank
- Mild steel body

Questions?

THANK YOU!