"If it works, use it"

Motto of the old smiths
(and modern medicine men)

Damascene Technique in Metal Working

Advanced

A version translated into Romanian (by Alexander Ovsov) can be found in this link

A version translated into Indonesian (by Fira Widagdo and ChameleonJohn.com company) can be found in this link

A version translated into Russian by a "translator group" can be found in this link

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A version translated into Dutch (by Arno Hazecamp) can be found in this link

A version translated into Sindhi (by Samuel Badree) can be found in this link

A version translated into Italian (by Ahsan Soomro) can be found in this link

Disclaimer:
I cannot guarantee for the accuracy of the translations nor for anything else for these links.

Helmut Föll

Far more about the subject can be found in the Hyperscript: "Iron, Steel and Swords"

A personal remark

- Before I started this page, I thought I had a sufficiently clear idea of what "damascene technique" meant: The forge-welding of **steel** and iron, or more generally, two types of steel. I also believed that this produced superior swords and mail, and - for obvious reasons - that this technique was pioneered in **Damascus** in ancient times.
- I also had a notion that this damascene technique was also used in **Toledo** (Spain) in ancient times, so when I visited Toledo in the spring of **2000**, I looked for some remnants of the famed Toledo sword smiths.
  - Indeed, there is a store selling swords, knifes and other metal stuff at about every corner. However, their merchandise are mostly "fantasy items" like the sword of Conan the Barbar, probably mass produced somewhere in the far east - you can find that everywhere in the world.
  - Then there was "artistic" stuff (e.g. ornamental dishes and plates) and especially jewelry done in what the Toledans called "**damascene technique**". What this meant was that some darkish metal was inlaid with silver or gold to obtain rich ornaments as shown on the right. It certainly was not what I had in mind when I searched for "damascene" technique

- Accidentally, I run across a shop connected to a real smithy[1)] - the last one left in Toledo, as the owner said.
  - There they made swords the old way; and with old he meant that they used to do this already for the *Romans* (so he said). At least, you could watch some rather special forging techniques and try the swords produced: They could be bent to a considerable degree without breaking or deformation - I actually bought one.
  - However, there was no damascene technique in this sword or in anything else in evidence; it was simply a solid piece of (hopefully) very good steel. Obviously, I got it all wrong, so I started to investigate a little. I chose the Internet rather than the science library because this is a "on the side" activity for me.

- Surfing the net for a few evenings, first created a tremendous confusion, because the word "damascene technique" seems to be used for many different things (see below). Now, I'm a lot less confused, but there are still some questions. This is no wonder, considering that steel was one of the main technical issues for about **2000** years all over the world, that its historical development would fill a small library, and that there ares still plenty of unresolved issues.
  - So some questions seem still to be open - there are no reliable answers or at least I couldn't find them. Interestingly, a lot of people, including serious "archeometallurgists" seem to share my interest - there appears to be an increasing number of publications and investigations in the last **10 - 20** years.
  - Most interestingly, even nowadays, steel technology seems to hold some mysteries and promises. And that brings us right back to the properties and the manipulation of defects in crystals.
- On this and some other pages I will share my confusion and my findings with you; as time progresses, *this material may become clearer*. I include a lot of documents, mostly found in the Internet, for those who want to investigate on their own.
- The material did become somewhat clearer, indeed. I include a few more remarks based on my present (May **2001**) understanding of damascene techniques: always indicated by a yellow triangle or button
  - But beware! Everything below or in the links thus represents **my** present knowledge and interpretations; it may well be wrong - take care!

Starting Point

- For me, the term "damascene technique" until recently had the following detailed meaning:
  - The manufacture of iron-based artifacts, especially knifes and **swords**, from *two kinds of steel*. You got it by hammering together (at high temperatures of roughly **800 ^{o}C** or so; called "forge welding") a package of several sheets of the two kinds. The sheets will fuse or weld as a result of solid state reaction and diffusion - a solid "compound material" is formed. The layered package of two kinds of steel is frequently folded over; the resulting structure is similar to the cross-section through a folded and twisted cake made from two different doughs (e.g. chocolate and vanilla).
    Not wrong, but only covering a small part of what is meant with "Damascene".
  - The two types of steels were
    1. *soft iron*, relatively low in carbon content, called ***wrought iron***; the basic product of early iron production by solid state reactions at temperatures well below the melting point of iron.
    2. *carbon-rich iron*, often from an source in India (that had a monopoly for many centuries) called "**wootz steel**".
    You may find some basic information about the development of iron and steel technology (including wrought iron and wootz steel) in the link.
    Mostly wrong.
  - The resulting sword combined the positive properties of the two constituents while avoiding the negative ones. It was hard, but not brittle, could hold a sharp edge, did not deform easily, but could be bent to a considerable degree.
    Mostly wrong.
  - This "damascene technique" was invented, or at least brought to perfection, in Damascus and Toledo in ancient times.
    Totally wrong
  - The old Celts, Germans, Vikings, Anglo-Saxons and so on, imported their damascene swords from the south (in exchange, maybe, for ***amber*** or blond women); or at least some raw materials.
    Totally and inexcusably wrong
- As indicated, this view has a few correct points, but it is often totally wrong; it needs to be modified and enlarged. In what follows I give a brief outline of my present (May **2001**) understanding (which includes a lot of open questions and most likely some misunderstandings, too).
  - On two other pages are (commented) lists of articles which I found interesting and a cross-linked glossary of some issues I was looking for in the Net. *Use with care*.

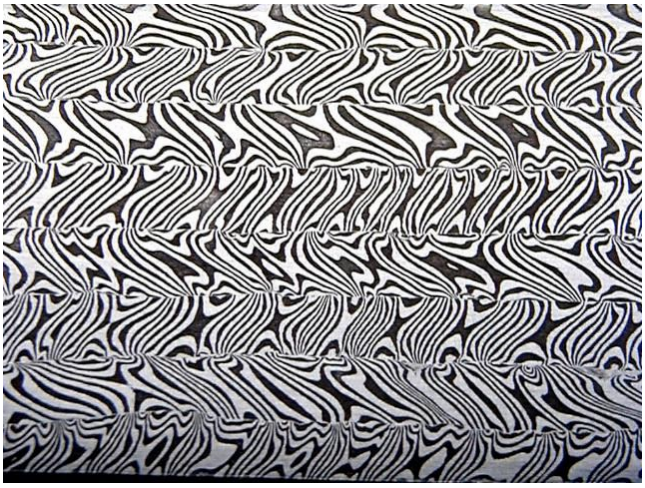
Some Variants of "Damascene" Technique

- As it turned out, "damascene technique" means quite different things to different people; but even within the defintion given above, there are many variants.
  - The "steel" part could consist of iron which is rich in Phosphorous and not necessarily Carbon (especially, maybe, in northern Europe?).
  - The **forge welding** could be done by folding over the same basic material which, however, may have been quite inhomogeneous. Lots of folding and forge welding created a homogeneous looking material - this is the **Japanese way** (horribly abbreviated).

- The welding technique was not only continued (and somewhat irregular) folding and hammering, but a more complicated technique, called "**pattern welding**". The result could look like this:

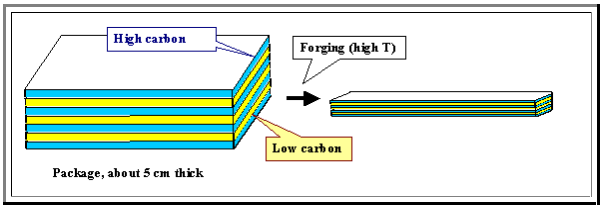
Part of a very old damascene (=pattern welded) sword blade. (from the Internet article "Blade Patterns Intrinsic to Steel Edged Weapons)" from Lee. A. Jones

- It also could look like the picture below. This is a photograph of a real piece of damascene steel recently made by the German master smith **Manfred Sachse** (whom we will encounter again) and taken from his Home page

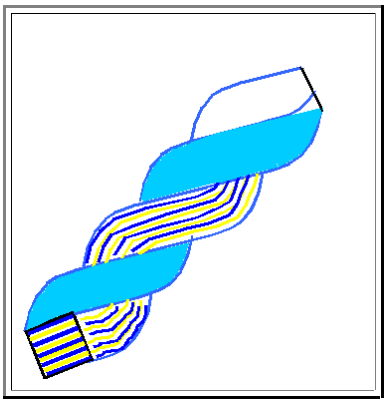


From the (by now abandoned) homepage of Master Smith Manfred Sachse with his gracious permission.

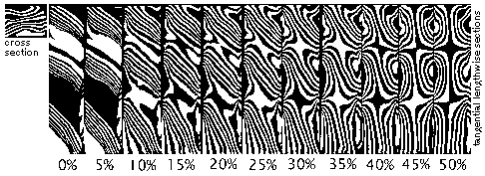
- In the "**Württembergisches Landesmuseum**" in Stuttgart I saw a very impressive sword from the time of the Merovingians (around **500 A.C.**) that was made by pattern welding (and found in **Ingersheim** - direct neighbour of the town of Geisingen where I grew up). This **sword from Ingersheim** was reproduced by the modern smith - **Manfred Sachse** mentioned above - as follows:



- The loose stack of steel plates is banged into a rod with a cross section of about **1cm^2** - some work! Several of those rods, about **1 m** long are produced. The labelling "High carbon" in the drawing could, perhaps, also mean "high Phosphorous".
- Next, these rods are twisted and ground flat on two sides. The twisting is hard to draw, but you get the idea.

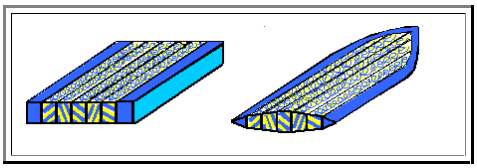


- What it looks like on the surface if you now grind the twisted rod to increasing depth is this:
  (From the Internet article of Lee A. Jones: The Serpent in the Sword: Pattern-welding in Early Medieval Swords)



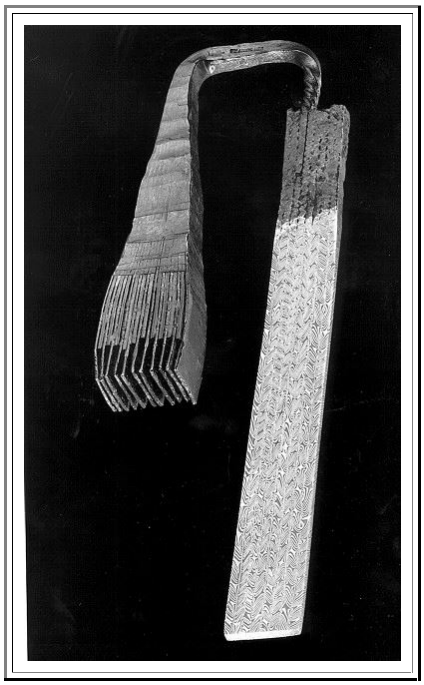
Original Fig. Captions:
Patterns disclosed by successively grinding a facet along the length of a twisted rod demonstrated in a clay model of a rod composed of sixteen alternating layers prepared by bladesmith Dan Maragni. The rod has been mildly squared and joined along side another rod, shown only focally at the edge. The rod was progressively ground and photographed at each interval, reduced in overall thickness by the percentage shown in the scale below. Further leveling of the rod will reverse this trend, as a mirror image of the patterns first disclosed.

- Several of those rods were than forged welded; with possibly a pure steel rod on the outside. Banged into shape, and ground to a sharp edge, we have a fine sword, it represented about the value of a car in todays currencies.



- only it was even more complicated: Two independent layers were used for the center part, so that the front and backside od the sword looked different; and the twisted regions were alternated with non-twisted regions to form specific pattern down the lenght of the sword. Well, look at it yourself.
- This is probably as close as you can get to a **magical** or simply **famous sword** like **Notung** (**Wagner's** sword for **Siegmund** and **Siegfried**), **Excalibur** (**King Artus**), **Balmung** (What Siegfried made from the Notung pieces in the **Nibelungen saga**, **Tourendal** (**Roland** saga), **Mimung** ("**Wieland der Schmied**" made it for his son **Wittich**), **Eckesachs** and **Nagelring** (**Dietrich von Bern**), **Colada** and **Tizona** (**El Cid)** - and so on.
- More about "magical swords" can be found in this (German) link.

Alltogether, in a model showing all process stages and also on display in the "Landesmuseum" mentioned above, it looks like this:



- The picture is from the wonderful book: Manfred Sachse: "Damaszener Stahl - Geschichte, Mythos, Technik, Anwendung" (Verlag Stahleisen, Düsseldorf) and reprinted here with permission of the author.

- It seems that pattern welding and **P**-rich steels were especially popular in northern Europe; but some kind of "damascening" or pattern welding can be found all over the world.
  - It would be totally wrong, however, to credit ancient smith with the invention of something very sophisticated. The truth is: They had no choice but to come up with some kind of pattern welding!
  - The reason is that nobody could melt wrought iron or mild steel with a melting point of **1550 ^{o}C** during the first **2000** years of iron technology. Only **cast iron** (eutectic melting point at about **4% C** is **1130 ^{o}C**) could be molten (and was used in large quantities in ancient China)
  - Everybody had to work with small lumps of iron out of a "***bloom***" obtained by a solid state reaction. This small lumps needed to be forge-welded, i.e. banged together at high temperatures, to obtain large pieces. Invariably, the little lumps had on occasion different **C** or **P** content; the forge welded blades showed some structure. Iron blooms obtained in different regions from different ore deposits also would be different; with a little trading it could not escape notice that forge welded parts showed structures, and that some parts were hard and others soft.
  - It is then a small step to first forge-weld some kind of iron to relatively homogeneous stuff, then some other kind (easily distinguished by color or hardness, produced in some special way, or traded from some other smiths) - and having two kinds of iron plus knowing about forge welding, pattern welding is something that does not need a big innovation.

- Even so, it took almost **1000** years of forge welding and simple pattern welding before welding reached its zenith around **700 - 800 AD**, producing extremely complicated and certainly very beautiful and valuable works of art (the performance in real fights was probably no better than that of simpler swords, however).
  - And, to be clear, the whole process was not simple at all! It took a lot of knowledge, experience and practice, to produce a "good" pattern-welded sword! Those ancient and medieval smiths were not barbarian brutes but highly educated and skillful man!

- First questions come to mind; some answers are contained in the commented list of articles
  - Who did it when (and how)? Which cultures just copied, and which ones invented or improved?
  - Were those pattern-welded swords really much better than "regular" ones? Or was the whole thing more for show, a status thing? Was damascening or pattern welding a major innovation or something you couldn't avoid discovering?
    Crude Answer: The better pattern-welded swords were superior to swords from plain iron (or soft, inhomogeneous steel), but inferior to swords from good homogeneous steel. See the table below for data on "true" damascene swords.
  - What were the ingredients? How where they obtained? How did different types of starting materials influence or determine the forging process and the final result?
  - What exactly was the role of Damascus or Toledo?
  - What exactly were the famous Damascus blades? How were they made, and how good were they really?

The "True" Damascene

- The last question seems to have an answer:
  - "True" Damascene blades were made from **wootz steel** only. The Damascene (or water) pattern comes from a striated precipitation of **Fe_3C** particles and not from folding and welding two kinds of material.
  - The "secret" art was how the high carbon wootz steel (coming close to cast iron) was treated to yield a highly flexible and extremely sharp blade - check in the commented list of articles.
  - It now appears that it was cricial to have traces of Vanadium (or somethimg similar) to enable proper nucleation of the **Fe_3C** particles - see the latest article to this subject
- What seems less clear, however, is how good these blades really were. Obviously, the crusaders, wielding quite respectable swords themselves, were mightily impressed.
  - Trying to forge similar blades lead European sword smiths astray, however. They believed that these blades were composed of two types of steel and re-invented the "old" pattern welding technology in new variants - seemingly without much success. The explanation given above seems to be a pretty recent discovery!
  - How good "true" damascene blades were was something an early metallurgist actually did find out to some extent. Prof. Zschokke (from Switzerland) was lucky enough to get a few true damascene blades for (destructive) investigations (this is quite unusual because these blades ar valuable and museums and collectors do not easily agree to have some destroyed).
  - Some of this results (taken from the book of M. Sachse) were

General composition					
Sample	**[C]**	**[Si]**	**[Mn]**	**[S]**	**[P]**
1. Knife	1,677	0,015	0,056	0,006	0,086
2. Knife	1,575	0,011	0,03	0,018	0,104
3. Saber	1.874	0,049	0,005	0,013	0,127
4. Saber	0,569	0,119	0,159	0,032	0,252
5. Saber	1,324	0,062	0,019	0,008	0,108
6. Saber	1,726	0,062	0,028	0,020	0,172
7. Modern welded steel (Solingen)	0,606	0,059	0,069	0,007	0,024
8. Modern cast steel (Solingen)	0,499	0,518	0,413	0,038	0,045

Properties						
Sample	**3**	**4**	**5**	**6**	**7**	**8**
Bending toughness	13,4	15,2	11,5	14,5	21,6	30,0
Work to bend	94	221	55	63	361	622
Angle of bending	27	59	19	17	69	78
Hardness	216	233	193	248	347	463

  - What ever the numbers mean (no units were given), the modern blades always "win". Otherwise blade **No. 4** is best. In any case - the properties of what was (and is) traded as "true" damascene vary widely, there are very good and very lousy specimen.

The new "High-Tech" Damascene Technique

- The word "Damascene Technique", if uttered in a gathering of materials scientists dealing with functional materials, will carry yet another meaning, completely different from everything above.
  - Here we mean a special technique for the production of structured Cu connections - in the **0,5 mm** range - on **Si** integrated circuits. Check for yourself in the Link.
  - The naming "in honor of the metallurgists of old Damascus" is a bit misleading, however, because the damascene chip technology is related to what is called damascene today in Toledo.

All the Meanings of Damascene Technique at a Glance

- The expression "Damascene Technique" thus has a lot of different meanings. In the listing below I include some techniques that are not "officially" listed as damascene, but follow the general idea. The adjectives used in differentiating the diverse techniques are mostly my invention
- **Folding Damascene**; two kinds of steel:
  - Folding over a stack of different steels several times; gives many layers with beautiful, but irregular patterns. The kind of damascene that many modern smiths do today.
  - This technique was to some extent re-invented in the West after encountering "true" Damascus swords in an attempt to emulate these famous weapons
  - Many myths abound. In truth, the finished product has a rather homogenized **C** content (i.e. is not a real "compound" material from two different steels and no better that a homogeneous blade from good steel). But the damascene pattern obtained after suitable treatment (etching) gives this Damascus steel a special beauty and appeal. It does not so much reflect the different C concentration of the layers, but probably (I'm not so sure about this) the different amount of other impurities, especially P (which, supposedly, does not diffuse as fast as **C**).
- **Folding (Damascene)**; one kind of steel
  - What the Japanese did to get sword material. Not usually called Damascene, but not so different, because the small lumps of iron or steel selected from a bloom were, after all, rather different in composition and contained slag inclusions and other inhomogeneities. The speciality of the Japanese was a lot of folding and hammering; the finished product therefore does not show evidence of folding to the naked eye - it is now quite (but not totally) homogeneous on the outside.
- **"Simple" pattern welding or laminating**
  - This could be, e.g. just some mild steel in the middle and hard steel at the edges; or a core of soft iron surrounded by harder stuff. What (maybe) the Romans had and the early Celts. There is no particular pattern besides the simple geometry of the design.
  - The Japanese also used this technique; their swords consisted of up to three different kinds of steel (each one obtained through multiple folding as described above) welded together or laminated in quite complicated arrangements.
- **"Decorative" pattern welding** - like the technique shown above.
  - While the twisting had also technical advantages compared to forge welded untwisted rods, its main purpose - at least in later - times, was the decorative effects possible with this technique. Designs much more complicated than the one shown above were in use.
  - In later times - lets say around **1000 BC** - when smiths had learned how to make swords form homogeneous steel (especially in Toledo, it seems); the blade may still have been adorned with a thin layer of pattern welded foil only for the look of it!
- **"True" Damascus**
  - Swords and other implements made from one kind of steel - the famous **wootz steel** - obtained from Indian sources from sometime before **300 BC** up to the **7th** century **AD**. After that, the people in Damascus, in Toledo and probably other places also, could produce this high-carbon steel themselves.
  - Treated the right way, **Fe_3C** (cementite) forms in striations, producing the special "damascene" pattern (often referred to as "water pattern", too). These were the swords of tall tales that emerged when the crusaders met the arab owners of these beauties.
  - One recent scientific paper reproduced the ancient technique successfully and claims it needs three thing to produce "true" Damascus sword:
    - The right combination of time/temperature firing during ingot making
    - the proper thermomechanical sequencing during the forging process.
    - and the right chemical composition (especially minor element additions, e.g. V in sufficient concentrations

We are right back to point defects in crystals!

- At least one more modern smith works on "true" damascene made from wootz steel (he send me an e-mail). You may jump to an article about him and his art by activating the link. (if the link does not work any more, here is the stored version)

"Mysterious" Damascus

- There are some people out there, who honestly believe (more or less based on a scientific background) that everything was either quite different or that the technology is truly lost.
- But then there are also those, who cook up some pseudo-scientific bullshit including some magic - usually in the attempt to sell their "magic" product.

"Inlay" Damascus (what they sell in Toledo)

- While this is certainly a technique to intimately combine two metals (not necessarily by forging, but e.g. by soldering); it is not a technique usually associated with the making of swords, knifes, armor or other "functional" products. It may have been used in Toledo for adornments of the sword hilts, though.

"Microelectronic" Damascene technique.

- "Damascene technique" (even "double damascene") has become a common name in microelectronic technology; everybody in this business knows what it means.
- It has, however, nothing to do with all the variants given above that could produce a sword, but is a kind of "inlay" damascene technique, albeit on a **<1µm** scale.

Whow!!

How wrong can you be? But then, how confusing can it be? My "quick" attempt to figure out exactly what "Damascene" really means, in order to include nothing wrong in this (rater unimportant) addition to the "Defects" Hyperscript, took several evenings and weekends! But there were rewards: I learned a lot of very interesting things about the history of technology, including some points which I always wanted to know a little better. Then there were a few unexpected but rather interesting finds:

- Most of the serious knowledge comes from recent to very recent times. A whole new field of research is developing: **Archeometallurgy**! Some of its findings already changed the way we look at ancient history, and promises are that there is much more to come.
- There is a lot of interest in these issues out there - at least in the anglo-american world. Try any search engine with keywords like "steel" "Damascus" or "swords" and you will get an overwhelming response.
- Then try it with the German equivalents: Essentially you will end up with Karl **May** and the bible. This can be seen as a comment on the attitude to technology in these cultures!

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1) Here is the name and the address of "my" smith:

Mariano Zamorano; Fabrica de Espadas y Armas Blanca ; 45002 Toledo; C/. Ciudad, n.º 19