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VANADIUM IN TOOL STEELS

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Abstract: In the long history in producing the tool steels, vanadium was used just accidentally, when is introduced in steel from ores in local area. But many ores did not contain the vanadium in any form, so the role of positive effect of this alloying element on steel properties was not well known or explained. In a contemporary metallurgy the vanadium is recognized as an important alloying element, both in structural or tool steels. Vanadium is known as an element which is chemically highly active, and from that reason it could not be found in a native state, only as compounds. Such great chemical activity still is a problem in melting and alloying the steels by using vanadium (almost in small quantitatives) in traditional melting techniques. The increasing of strength properties and decreasing wear of a steel, when small amounts of vanadium was added, is discovered in the early 20th century. Vanadium reacts with almost of interstitial elements, but the reactions with carbon and/or nitrogen are of special interest for tool steels. In recent decades the powder metallurgy offers some advantages in producing pretty qualitative tools, with higher level of vanadium. Here is made an overview on the role of vanadium in tool steels.
Keywords: vanadium, tool steels, interstitial elements, wear resistance

1. INTRODUCTION

It seems that using of vanadium goes back in the 3rd Century BC [1], without extracting & using as a pure metal or ferroalloy, but rather as ingredient in local ores. Vanadium plays an important role in (micro)alloyed steels, but for severe working conditions of steel vanadium becomes more interesting alloying element, especially in tool steels in which is present up to a few percent. At the beginning of XX century Henry Ford used vanadium to make the body of one type of car to be stronger and lighter. Vanadium steels, with improved heat resistance, were used in portable artillery in the First World War.

Either of such applications, vanadium is present at supplements which are used in medicine (for treating diabetes, low blood sugar, high cholesterol, heart disease, tuberculosis, anemia, improving athletic performance, etc.).

Powder metallurgy (PM) technology find out an important role in producing of tool steels with high percent of vanadium, which commonly are unable to produce by conventional metallurgical methods.

2. MATERIAL AND METHODS

— Iron – vanadium phase diagram

Vanadium is a lighter element than pure iron, it has a density of 6.11gm/cm3, melts at 19100C, when in liquid state possess density of 5,5 gm/cm3, so it makes a problem during alloying the molten steel. Vanadium has a body centered cubic lattice. Every approach in understanding the role of vanadium in steel begins with the phase diagram iron–vanadium, Figure 1. Vanadium belongs to a group of alfa phase formers, and affects during the solidification process on narrowing the temperature interval during crystallization, same figure. As in high chromium steels, at high percentage of vanadium will be formed brittle sigma (σ) phase. The reduction of carbon solubility during temperature decreasing, with narrow γ–phase region as could be seen from Figure 1, leads to precipitation of vanadium carbides & nitrides in steel.

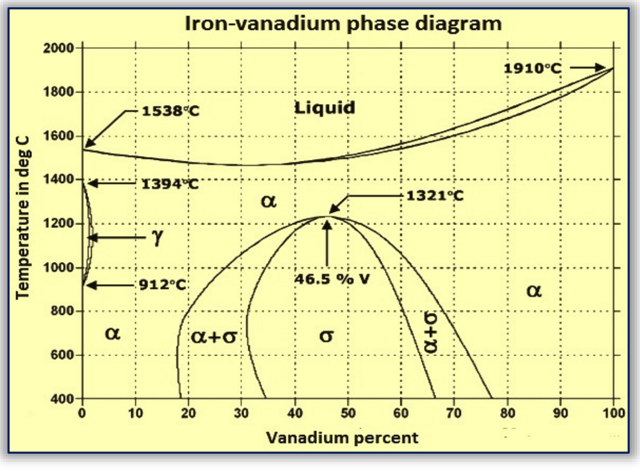


Figure 1. Iron – vanadium phase diagram

— Vanadium and interstitial elements in steel

Many steels contain a small amount of interstitial elements, as carbon, oxygen and nytrogen, which commonly show an important influence of many properties. Vanadium as an alloying element in steel makes a versatile phase, even compounds with mentioned interstitials. Those phases and com–pounds are present in structural or tool steels. In structural steels vanadium is used since a long time for producing so called micro alloyed steels. In small amounts vanadium increases both the yield and tensile strength of carbon steels. The presence of vanadium in structural (micro alloyed, HSLA or similar) steels commonly is on level from 0.10% up to 0.25%, while in tool steels could be reached up to a few percent, especially in tool steels produced by PM techniques this level is pretty higher, up to 10%, rarely higher.

Vanadium alone or with other microalloying elements present in steel, as aluminium, niobium and titanium, contributes the increasing of strength, as first discovered in carbon–manganese structural steel. The action of vanadium for increasing the strength is explainable by formation of precipitates in the form of carbides, nitrides or carbonitrides. The refinement of the ferrite grain size could not be neglected, so the fine grains are also present in steel even at elevated temperatures. After tempering of quenched steel, vanadium (but not alone) causes secondary hardening. Those reactions are truly explanation for improving the strength with increased hardenability, even though the formability of such steels is better. As a result, vanadium steels are used in production of versatile structural components in civil engineering, automotive industry, etc. Vanadium in high–speed steels (HSS), of course with obvious presence of carbon, provide high values of hardness (above 60HRC). Some of these steels are used as surgical instruments.

Carbon and nitrogen as interstitial elements are responsible for reactions that took place in steels (micro)alloyed with vanadium. Those reactions led to so called precipitation strengthening, when strength is increased with increasing the carbon contest (at all levels), additionally by the presence of nitrogen, Figure 2 [3]. The precipitation strengthening and hardening is affecting by cooling regime (either during heat treatment or after hot deformation), in steels through a wide carbon content. The improving the strength, hardness and toughness is caused by formation of stable V–carbides and/or nitrides, which could be attributed as VC1–x and VN1–x, respectively. These vanadium carbides and nitrides are highly soluble in the ferrite and/or austenite, contributes to increasing the wear resistance. Fine austenite grains will produce a finer ferrite grains during cooling, causing a better toughness of a steel.

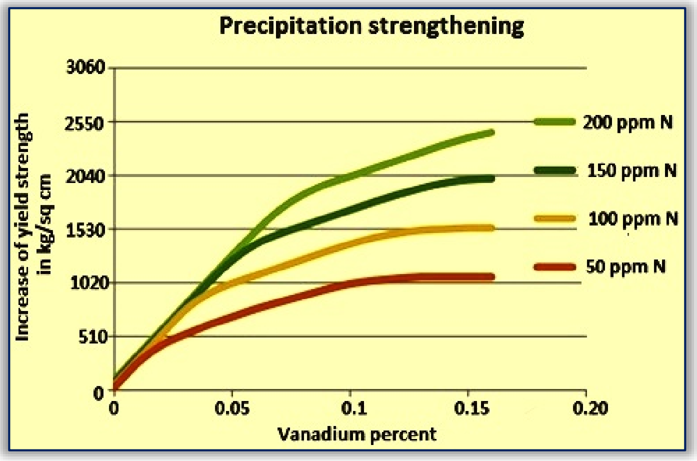


Figure 2. Increasing of yield strength as u function of vanadium contest for various nitrogen amounts

The concentration of vanadium according to nitrogen could be maintained at or above the ratio of 4:1, for formation of vanadium nitrides – which took place just below the liquidus temperature. It´s worthy to underline that the solubility of vanadium carbides into the austenite is higher than niobium or titanium carbides, but the solubility of vanadium nitride is lower than of vanadium carbide. In steel alloyed with vanadium is registered the absence of Widmannstetter ferrite (during cooling after hot deformation or long duration of heat treatment regime), and this is another explanation for improving the toughness of such alloyed steels. Hardnesses of the most important carbides, which commonly could be found in steels, are shown in Table 1. According to shown data is understandable that the role of vanadium in steels is to make hard carbides.

Table 1. Hardness of quenched steel and important carbides in steels

Kind of distribution in rolled steel	Material	HRC
	Quenched steel	60 – 65
	Chrome carbides	65 – 68
	Molybdenum carbides	72 – 77
	Wolfram carbides	72 – 77
	Vanadium carbides	82 – 84
	Boron carbides	82 – 84

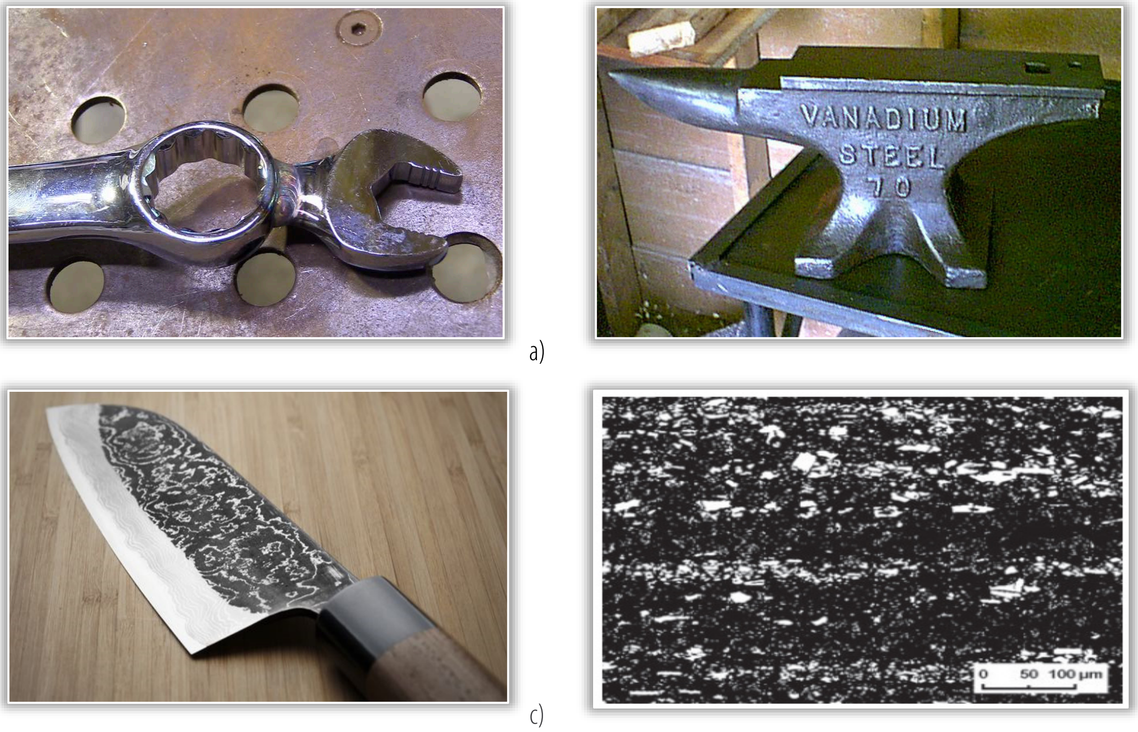
— Vanadium in tool steels

Vanadium is used in all kinds of tool steels, almost in limited amounts. So, it could be found in variety of cold and hot working tool steels. In recent years is increased the use of vanadium in special kinds of steel, when a high wear and/or abrasion resistance is needed.

— Vanadium in tools for cold work

A lot of tools for cold work obviously contain carbon and chromium, commonly with 0,10–0,30%V, some of them up to 1%V. Cold work steels generally contain another alloying elements as wolfram and molybdenum, when high hardness, strength and wear resistance are demanded. Quenchability of steels with vanadium,

generally, is on satisfied level, first of all according to medium or large amount of carbon, sometimes up to 2%C. When vanadium is present than the strength and wear resistance are increased in steel, these properties are however suitable for tools as like: for cutting, forming die applications, cold extrusion, deep drawing, etc.
From the metallurgical point of view, the role of vanadium in steels is considered in relation to the temperature over Ar3 point, more precisely it is important for heat treatment purpose. Hardened cold work tool steels achieve hardness generally in range of 58–64HRC, mainly 60–62HRC, and only occasionally up to 66HRC. A few examples of tools, known to everyone, are shown in Figs. 3a÷c).



a) b) c) d)

Figure 3. Common tools for hand use a÷c) and microstructure of rolled tool steel (2%C, 12%Cr)

Coarse carbides, as in Figure 3d), usually should be avoided.

≡ Chromium – vanadium steels

These steels are in using for hand tool manufacturing, one of the most known example is from Figure3a). Those tools are made from medium carbon steel (0,5%C), alloyed with: 0.7–0.9% manganese, 0.8–1.1%Cr and 0.18%V. Anvils, one example is shown in Figure 3b), frequently are making from steel or cast iron by using vanadium or wolfram, even molybdenum as alloying element. It is understandable that those steels or irons must possess high hardness, strength, toughness and wear resistance, some of these at elevated working temperature during hammering. Small amounts of boron in this kind of steel is welcome. Various tool steels for cold working, as cutting (see Figure 3c) or die tools, contain vanadium.

≡ Manganese – chromium – vanadium steels

These steels usually contain about 0.9%C with greater amount of manganese 2.0%, less chromium (0.3%) then previous steel, and vanadium ≈0.10%. The main characteristic of this kind of steel is in stable dimensions, so is used for measuring tools, in Yugoslavia this steel (Č3840) is called merilo.

— Vanadium in tools for hot work

Hot working took place through few different manners: forging, rolling, extrusion and die–casting, Figure 4. In named processes simultaneously act both the high temperature and pressure, it means that tools should retain their properties in such circumstances. So, the chemical composition of those steels must be precisely determined.
This great group of tool steels also contain vanadium in amount from 0,4 up to 1,0%, carbon is on level 0,35–0,45%, with chromium (up to 5%), wolfram and molybdenum. Tools for hot die forging should contain this valuable element. Die–casting is provided by using a high pressure, for fulfil the mold cavity by molten metal, according to that in these molds the main failure mode is erosion and wear. In such environment the presence of vanadium is just needed. Design of die–casting mold is pretty complex, so there are various used steels for a large number of components, with their hardnesses, as can be seen from Table 2 for the most used casted metals.

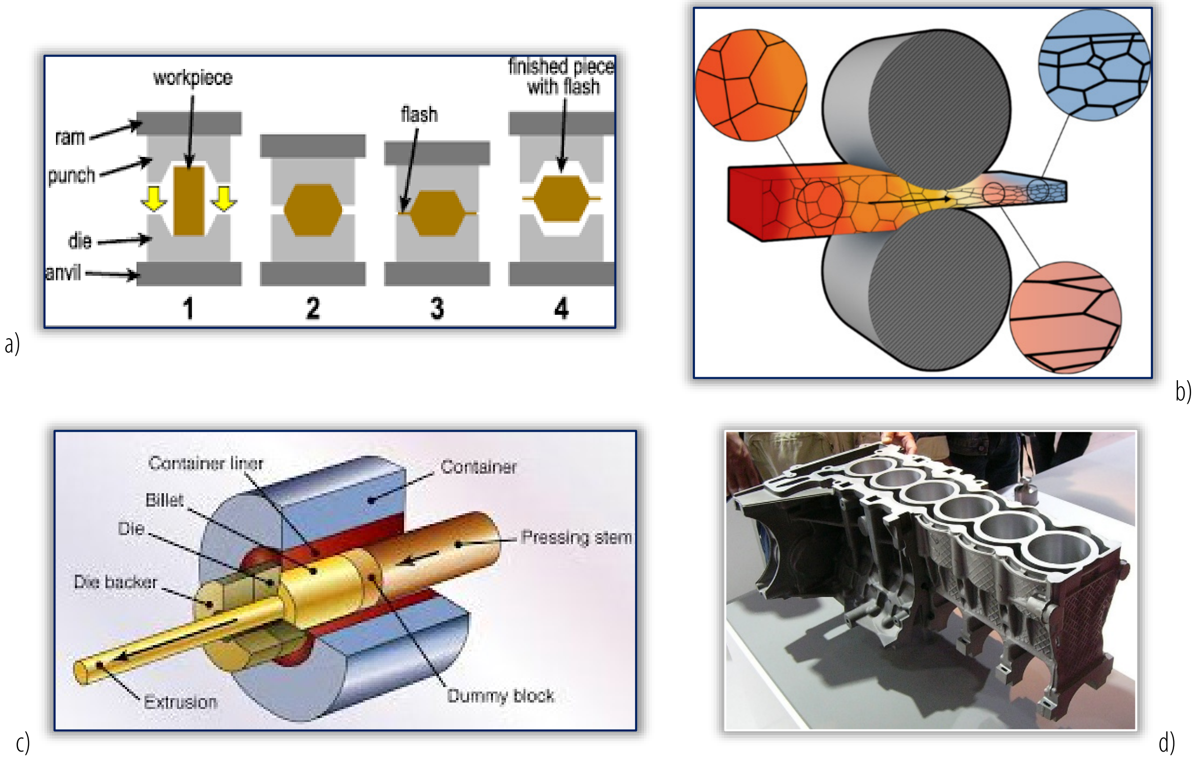


Figure 4. Main hot working processes in metal fabrication: a) forging, b) rolling, c) extrusion and d) specific castings obtained by die–casting

Table 2. Tool steels and their hardness for important die components for various cast alloys

Dee component	Cast metal					
	Tin, lead & zinc		Aluminium & magnesium		Copper & brass	
	Material	Hardness	Material	Hardness	Material	Hardness
Cavity inserts	P20	290–330 HB	H13	42–48 HRC	DIN1.2367	38–44 HRC
	H11	46–50 HRC	H11	42–48 HRC	H20,H21, H22	44–48 HRC
	H13	46–50 HRC				
Cores	H13	46–52 HRC	H13	44–48 HRC	DIN 1.2367	40–46 HRC
			DIN 1.2367	42–48 HRC		
Core pins	H13	48–52 HRC	DIN 1.2367 prehard	37–40HRC	DIN 1.2367 prehard	37–40 HRC
Sprue parts	H13	48–52 HRC	H13 DIN 1.2367	46–48 HRC 44–46 HRC	DIN 1.2367	42–46 HRC
Nozzle	420	40–44 HRC	H 13	42–48 HRC	DIN 1.2367 H 13	40–44 HRC 42–48 HRC
Ejector pins	H 13	46–50 HRC	H13	46–50HRC	H 13	46–50 HRC
Plunger shot sleeve	H 13	46–50 HRC	H 13 DIN 1.2367	42–48 HRC 42–48 HRC	DIN 1.2367 H 13	42–46 HRC 42–46 HRC
Holder block	4140 prehard	~300 HB	4140 prehard	~300 HB	4140 prehard	~300 HB

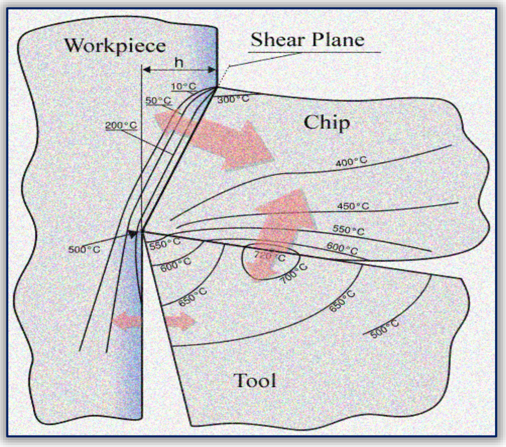
— Vanadium in high speed steels

High speed steels are exceptional group of tool steels, with the highest demands in many properties. As one of those properties is high hardness and wear resistance just at the cutting edge. During cutting the temperature is rising in workpiece, cutting edge and chip, see Figure 5a) for details.

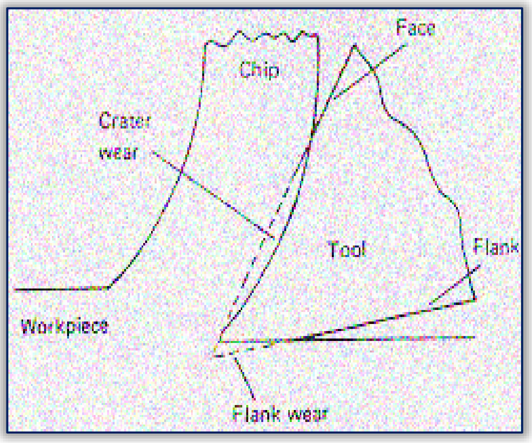
Wearing zones of cutting tool edge is shown in Figure 5b). Hard compounds in a tool steel, as vanadium carbide or nitride, contribute to the decreasing of wearing. So, this group of steel contain a higher level of carbon, usually about 1%, and must be high alloyed with wolfram, molybdenum, cobalt, etc., but most of them contain vanadium, usually about 1.5–2%V, and for a heavy working conditions some of HSS steel contains up to 5%.

— Vanadium in abrasion resistant tool steels

Vanadium is the most used alloying element for improving the wear & abrasion resistance. This is particularly special kind of tool steel, mainly used in mining for mineral crushing, etc. Vanadium is irreplaceable in this kind of steel (chromium–molybdenum), offering both high hardness and abrasion resistance, thanks to the hard vanadium carbides, see table 1.



a)



b)

Figure 5. Temperature distribution during turning a) and wear at turning nife edge b)

Main problem in using of vanadium during melting & alloying of a steel is in great chemical activity of vanadium to oxygen, carbon and/or nitrogen, so the contest of vanadium in such produced steels is limited. Problem in alloying with high percent of vanadium in common melting procedures is solved by using another technique – so called powder metallurgy. Main advantage of this technique is in mixing of powder(s) of pretty different metals, including compounds. After that, the powders are compacted and sintered. On this way is possible to produce a kind of high alloyed tool steel with contest of vanadium at 10%, even more. Such alloyed steel practically is impossible to obtain by classical metallurgical schedule.

Another suitable technique for improving the surface against the wear & abrasion is a surface treating, in this case it means cladding rather than heat treating or nitriding of the vanadium steel. Because the powder to be used for cladding must contain a heavy melting metals or compounds, the laser beam is acceptable as a high energy beam. Plasma beam also offers a needed high temperature for melting, but the plasma stream is too fast & strong and usually blow up a powder to be cladded. One example of used powder for laser cladding is given in Table 3.

Table 3. Chemical composition of MicroMelt 23 powder used for laser cladding, Fe bal, [18]

Element	C	Si	Mn	Cr	Ni	W	Mo	Co	Cu	V
mas. %	1.26	0.6	0.37	4.2	0.28	6.45	5.0	0.6	0.16	3.1

As a carrier and shielding gas was used argon. It is evidenced [8] that by using a laser cladding is possible to obtain a thick coating up to 3mm, see Figure 6.

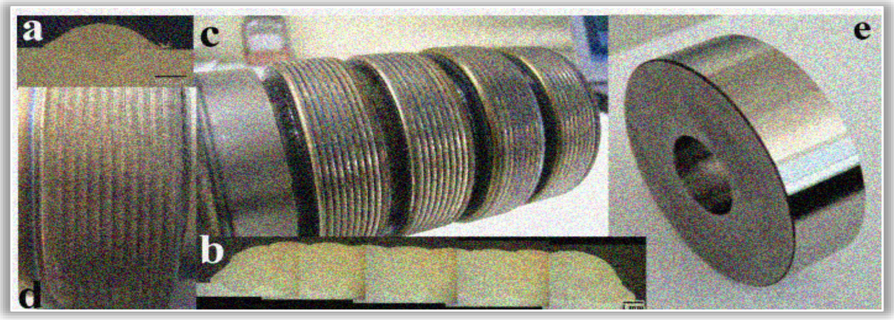


Figure 6. Laser cladding of Vanadis23 powder on ring (20mm wide and 60mm in diameter) form C45 (Č1530) steel substrate: a) single layer; b) 3mm thick layer (with 30% overlapping); c) and d) single and double layer and e) after machining and grinding

CONCLUSION

The most tool steels are exposed to a heavy working conditions. It is established that vanadium is a pretty useful alloying element in many tool steels, from cold & hot working conditions, and/or in high–speed steels. Tools for severe working conditions, especially when abrasion resistance is of great importance, simply must contain vanadium, it is explainable by formation of very hard vanadium carbides or nitrides.

By classical metallurgical melting and alloying procedures could be achieved vanadium concentration in tool steel on level up to 2%, rarely 5%, but by using a powder metallurgy technique (including sintering) now is possible to produce a high alloyed tool steel up to 10%V, even more. The newest technology may use a laser beam for cladding, with increased contest of vanadium. When cladding technique is applied than as a parent, material could be used a kind of cheaper structural steel, as here is reported.

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