

Title of the lesson: Newest results in development of the steels

Title of the MSc subject: Materials Science

Author of the lecture notes: Zsoldos Ibolya

NEWEST RESULTS IN THE DEVELOPMENT OF THE STEELS

Key words of the BSc knowledge

Knowledge of the following terms (from BSc studies) are assumed:

- **Definitions:** construction materials, steels,
- **Materials properties:** tensile strength (R_m), yield strength (R_e), elongation at fracture (A (%)), Reduction in area at fracture (Z (%)), notched bar impact work (KV)
- **Crystal lattices:** body-centered cubic crystal lattice, face-centered cubic crystal lattice, crystal defects, dislocations
- **Heat treatment processes:** hardening, tempering, quenching, case hardening, annealing
- **Iron-carbon alloy phases:** phase diagram, melt, solid solution (solution limit, supercharged solid solution), ferrite, austenite, martensite, eutectoid, pearlite, eutectic, ledeburite, chemical compounds, cementite, precipitations

INTRODUCTION

On modern cars, most of the weight comes from steel. In 2007, for example, the average car contained 1090 kilograms of steel, and the average pickup truck or SUV used nearly 1360 kilograms. Consider that most cars now weigh around 1,810 kilograms -- that's a lot of steel!

In cars, steel is used to create the underlying chassis or cage beneath the body that forms the skeleton of the vehicle and protects you in the event of a crash. Door beams, roofs and even body panels created during auto manufacturing are made of steel on most cars today. Steel is also used in a variety of areas throughout the body to accommodate the engine or other parts. Exhausts are often made from stainless steel, for example.

Steel manufacturing has evolved greatly, so carmakers these days can make different types of steel for different areas of the vehicle that are rigid or that can crumple to absorb different impacts. These innovations in automotive manufacturing help keep us safe on the road.

In this lecture notes we generally give introductions, comments, examples and case-studies from the car industry. This was considered by the fact that the modern car industry generally applies the newest cutting-edge materials and technologies, moreover, the newest cutting-edge materials and technologies very often are developed by the car industry. This situation is particularly valid in the case of the newest developed steel families, for the advanced high-strength steels (AHSS).

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1. THEORETICAL PRINCIPLES OF THE DEVELOPMENT OF THE ADVANCED HIGH-STRENGTH STEELS (AHSS)

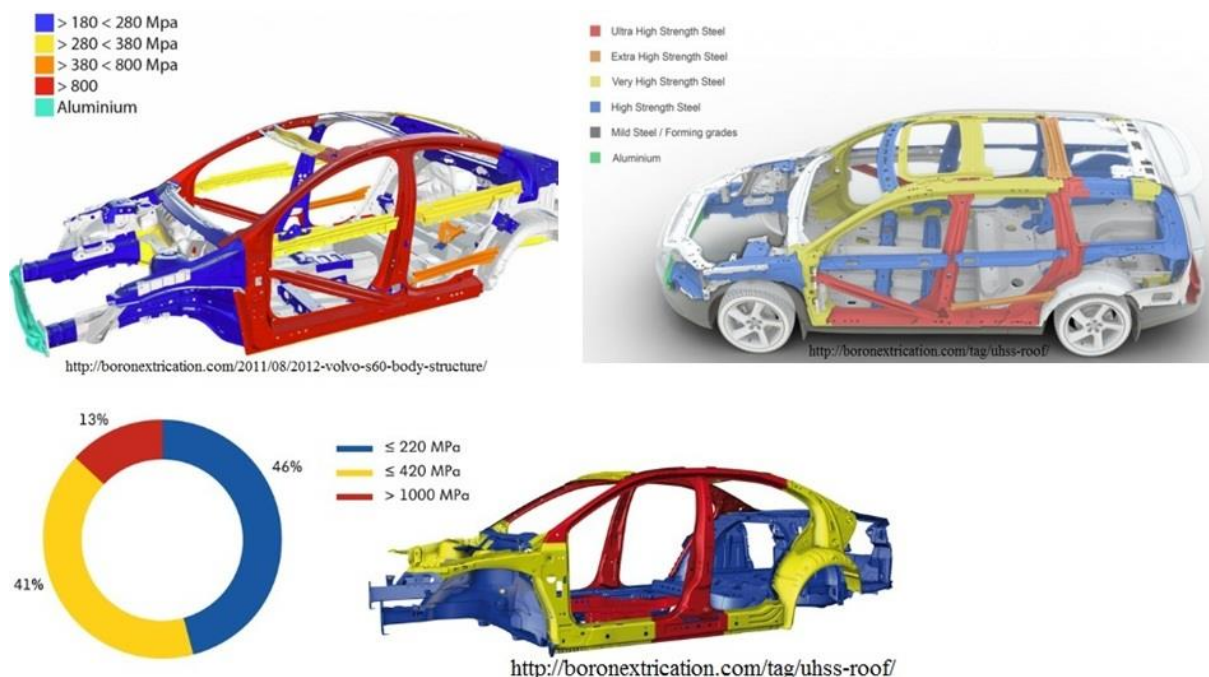
1.1. INTRODUCTION, WHY AHSS

In the years before the new millennium (2000) 35 international steel manufacturer companies (among others: Salzgitter, ThyssenKrupp Stahl, Usinor, Voest-Alpine) established a consortium which had the goals of developing, building and testing the Ultra Light Steel Auto Body (ULSAB) in a common R&D project. The requirements were: high strength, high stiffness, safety, easy construction and affordable price. The solution was carried out by the new materials family of Advanced High Strength Steels (AHSS). According to their results the stiffness increased by 80%, the mass reduction was 25%. Thanks to the development of the new materials, the rate of the AHSS in car bodies has reached 90 %.

The structure of the newest, cutting-edge car body is complex. Different elements subjected to different strains are built from steels having different strength, in order to get safety, easy construction, large mass reduction and affordable price together.

In Figure 1 the body structure of the Volvo S60 (from 2012), the Volvo V70 (from 2011) and the VW Jetta 2011 (from 2011) can be seen. The parts having different strength are signed by different colours:

- Parts having the highest strength are shown by red colour. These generally are the side parts of the body. The high strength is important here first of all because of the safety: these parts give the protection for the passengers against an accidental crash.



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Figure 1: Parts of different strength in cutting-edge car bodies.

- Parts having medium high strength are shown by yellow colour. The parts generally join to the side parts of the body. The high strength is important here because of the safety, as well. There are smaller differences between the different car trade, however the tendency, that the side parts have the highest strength because of the safety, is general in all car body.
- Parts having smaller strength are shown by blue colour. These are the front and back parts of the car body. They have to show a good energy absorption behaviour by an accidental crash. The crash energy is absorbed by the plastic forming of these parts and the high strength is not needed here.

The car body gives a considerable part of the car mass, so the mass reduction is extremely important for them. In order to reach mass reduction and improve the safety conditions together increasing of the strength is strongly needed. A well-known fact is however, that the increasing of the strength implies the failure of the formability, and - at the same time - the formability is an extremely important materials property at the car manufacturing, the engineers have to find the best balance between circumstances of contradictory. In the followings the principles of the strength increase and solutions for its disadvantageous consequences are studied. The descriptions are given for steel alloys, however these principles are true for all alloy families, as well.

1.2. STRENGTHENING (STRENGTH INCREASING) METHODS OF LOW ALLOYED STEELS

The strength increasing of the steels basically can be reached by changing *the chemical composition, the dislocation structure and the texture*.

1.2.1. EFFECT OF THE CHEMICAL COMPOSITION AND THE DISLOCATION STRUCTURE

The change of the chemical composition means the change of the carbon content in the case of low alloyed steels. In Figure 2 the effect of the carbon content on the mechanical and formability properties can be seen.

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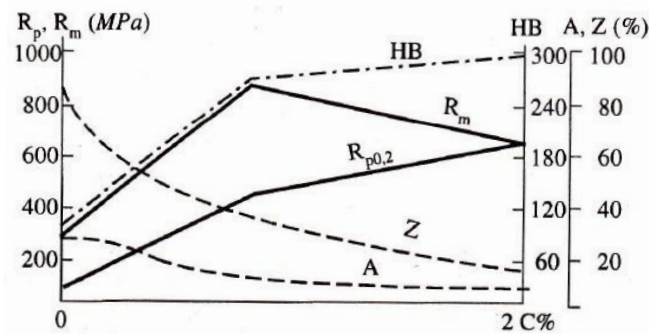


Figure 2: Change the strength and formability of the low alloyed steels depending on the carbon content

The strength parameters (yield strength: R_p , tensile strength: R_m) and the hardness (Brinell-hardness: HB) generally increase while the formability properties (specific elongation: A, specific section decrease: Z) generally decrease with the carbon content.

It is a general law in the metallurgy, that the strength of the metals and alloys increases with the number of the dislocations (if the dislocations are fixed, i.e. we do not let them move).

The number of the dislocations can be increased by plastic cold-forming strongly. The energy level of the formed crystals increases, and the strength properties get better, this phenomenon is described by the Nádai's power law:

$$\sigma' = K \varphi^n$$

where σ' is the true stress, φ is the true strain, K is the so called strengthening factor (the value of the true stress needed for a unit true strain), n is the strengthening index (n approximately equals to the true strain in strain hardening zone of the stress-strain curve).

The strength increase caused by plastic forming can be given by the function of the dislocation density:

$$\Delta\sigma = k\sqrt{\rho}$$

where ρ is the dislocation density (it can be computed by electron microscopes automatically), k is a materials parameter depending on the type of the dislocation.

1.2.2. EFFECT OF THE TEXTURE (MICROSTRUCTURE)

Changing the texture (microstructure) is a more effective possibility in order to improve the strength of an alloy. The mechanical properties of the alloys having the same chemical composition can vary in wide intervals, if different cooling rates are applied in order to get different textures. In the BSc studies, it was shown at the heat treatment of the steels, in the case of the austenite-perlite transformation, that when the cooling rate is increased than first the perlite lamellas will be finer, next bainite texture evolves, in the end, in case of a cooling rate

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of larger than the critical cooling rate martensitic texture grows up. The strength of the resulted structure of the latter case is the highest.

Various strengthening mechanisms come off during the martensitic transformation:

- Because of the difference of the specific volume of the austenite and the martensite (and because of the fixity of the crystal structure) a considerable deformation comes off, which increases the dislocation density of the austenite by several order of magnitudes (from $\rho=10^6 \text{ cm}^{-2}$ to $\rho=10^{12} \text{ cm}^{-2}$). This results in a strength increasing which equals to a plastic shaping with $\varphi=0.6-0.8$ of strain.
- A larger strength increasing effect comes from the crystal distortion caused by the carbon atoms, which trapped inside the martensitic lattice. This effect is the same as the solid solution strengthening of the solute alloying elements, which will be studied in the next chapter.

1.3. STRENGTHENING METHODS OF ALLOYED STEELS

Beside the strengthening methods of the low-alloyed steels (shown in the previous chapter) additional methods can be reached for alloyed steels. The strengthening effect generated by alloying depends on the fact that the alloying element dissolve in base metal or it composes precipitations as a separated phase. Accordingly, we can talk about strengthening effects generated by

- *solid solution strengthening*,
- *dispersion strengthening* or
- *precipitation hardening* mechanisms.

1.3.1. EFFECT OF THE SOLID SOLUTION STRENGTHENING

When the alloying elements (beside the carbon) form a solid solution with the base metal, the interstitial or substitutional atoms form localized strain fields that can increase the strength and hardenability, although they may simultaneously decrease ductility.

In Figure 3 it can be seen, that a part of the atoms of the alloying elements is located in the **surroundings** of the dislocation:

- the atoms which are smaller than the atoms of the base metal are located above the sliding plane of the dislocation (in the so called pressed zone),
- the atoms which are larger than the atoms of the base metal are located under the sliding plane of the dislocation (in the so called pulled zone)

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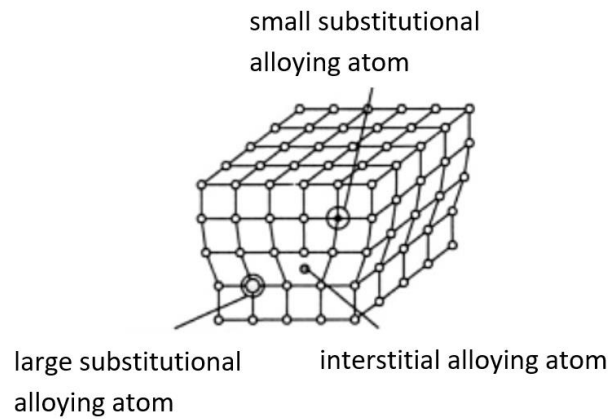


Figure 3: Dissolved atoms in the surroundings of the dislocation

The surroundings of the dislocation having many alloying atoms is called Cottrell-atmosphere. The strengthening effect is caused by the fact that the dissolved atoms block the movement of the dislocations, moreover the lattice distortions around the dissolved atoms give additional strengthening effect.

If the alloying element content is not more than several percent, the solid solution strengthening effect can be defined by the following relationship:

$$\Delta\sigma = G\varepsilon^2c, \quad \text{where}$$

- $\Delta\sigma$ is the growth of the yield strength caused by the alloying,
- G is the shear modulus (modulus of rigidity),
- c is the concentration of the alloying element,
- ε is the so called specific ion-diameter difference:

:

$$\varepsilon = \frac{d_0 - d}{d_0}, \quad \text{where}$$

- d_0 is the diameter of the base metal,
- d is the diameter of the alloying atom.

1.3.2. EFFECT OF THE PRECIPITATION HARDENING

When the alloying elements (beside the carbon) form a chemical compound with the base metal (or with each other), the precipitation hardening mechanism occurs. Considerably larger strengthening effect can be reached by the precipitation hardening than the solid solution strengthening mechanism.

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Examples for the chemical compound with the base metal are the iron carbide: Fe_3C and the iron nitride: Fe_2N , or Fe_4N . Examples for the chemical compound between the alloying elements are chromium carbide: Cr_2C_3 , the aluminium nitride: AlN and the titanium nitride: TiN , moreover double carbides can occur, as well: $(\text{Fe,Me})_x\text{C}_y$ where Me can be the chemical symbol of optional metal.

The growth of the strength, which can be reached by the precipitation hardening mechanism, can be defined by the following relationship (in case of coherent boundary surfaces of the phases):

$$\Delta\sigma=2G\varepsilon c$$

The effect of the precipitation hardening is considerably larger than the effect of the solid solution strengthening mechanism according to the above relationship, as well:

- partly because of the multiplier of 2,
- partly because $\varepsilon < 1$ and its exponent is 1 (smaller than in the previous relationship: 2).

The growth of the strength is caused by the fact that the movement of the dislocations is blocked by the boundary surfaces between the phases in case of the precipitation hardening.

1.3.2. EFFECT OF THE DISPERSION STRENGTHENING

Dispersion strengthening means increasing of the strength caused by precipitations of small dimension, dispersed homogeneously. In an alloy containing dispersed precipitations the dislocations being in move cannot get through the precipitations, they go round them. This process is shown in Figure 4 where the rings evolving around the precipitations can be seen, as well. This mechanism was shown first by the Hungarian researcher Orowan.

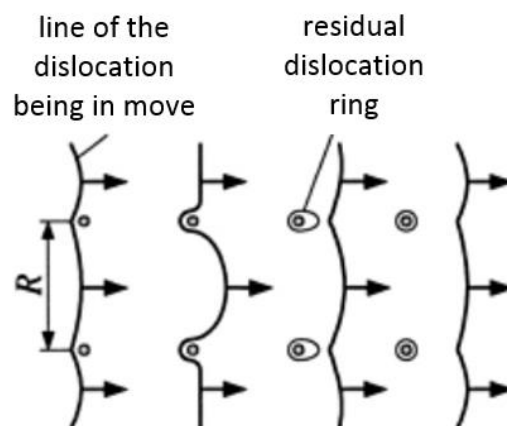


Figure 4: Dislocation rings evolving around the precipitations

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The closer the disperse precipitations are to each other, the higher strain the movement of the dislocations needs. The effect on the strength growth is given by the following relationship:

$$\Delta\sigma = \frac{Gb}{R}$$

where

- R is the distance between the disperse precipitations,
- b is the absolute value of the Burgers-vector of the dislocations.

The stability (heat-stability) of the strength-growth generated by dispersion strengthening depends on the fact how the rate of the disperse precipitations change with the temperature. The amount of Fe₃C, Fe₂N, Fe₄N decreases with the increase of the temperature, i.e. these chemical compounds decompose at high temperature. This leads to an over-ageing and strength-decrease in case of numerous materials. The strength-growth caused by dispersion strengthening is considerably more stable in case of alloying elements where the rate of the disperse precipitations does not change with the temperature. Such disperse precipitations are SiO₂ and Al₂O₃ which are indissoluble in some metals.

1.4. EFFECT OF THE GRAIN SIZE

The alloying elements result the strength-growth by their grain-refining effect in numerous cases. This can be explained by the fact that the dislocations cannot go through the grain boundaries, consequently, the finer the grain structure is the higher the strength is.

The effect of the grain size on the strength is defined by the Hall-Petch equation:

$$R_p = R_0 + \frac{k}{\sqrt{d}}$$

where:

- R_p is the yield stress,
- R₀ is a materials constant for the starting stress for dislocation movement (or the resistance of the lattice to dislocation motion),
- k is the strengthening coefficient (a constant specific to each material),
- d is the average grain diameter.

Figure 5 shows the change of the yield stress on the grain size for different metals. This diagram is the linearized version of the Hall-Petch equation. It can be observed, that the grain size has the strongest effect in case of the steels: the slope of the line belonging to the steel is the largest.

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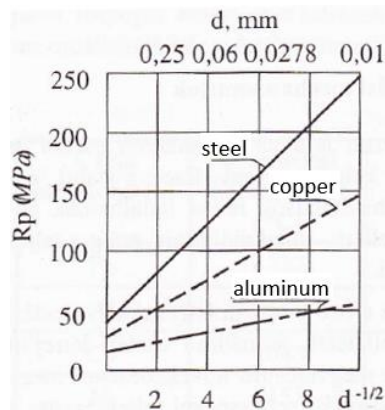


Figure 5: Change of the yield stress on the grain size

The fine-grain microstructure is important regarding the strength properties however it is a determining feature considering the toughness properties as well which is characteristic for the resistance against dynamical loads. Therefore the grain refinement of the alloys is a standard goal.

The crystallization rate is independent on the cooling rate, however the crystallization ability significantly depends on the cooling rate, therefore it generally is true that many crystal-seeds (being able to grow) are born in a metal melt owing to high speed cooling and undercooling. This is the base of the production of fine-grain structured alloys.

The grain refinement can be aided by micro-alloying, as well. In case of steels the alloying elements of Nb, V, Ti and Al have significant grain refining effect. Regarding the grain refinement, it is favourable if the solvability of the alloying element in the austenite is not good. In this case, the alloying elements inhibit the grain growth by precipitating to the grain boundary. (The grain refinement of the austenite is important because the grain size of the product during a phase-transition always is smaller than the grain size of the austenite.)

At the start of a cooling process, at high temperature the micro-alloying elements are in solution in the austenite. During the decrease of the precipitating starts. The precipitations inhibit the recrystallization: the more precipitations are in the austenite the more difficult the start of the recrystallization is.

Figure 6 shows the temperatures where the carbides and the nitrides of the four micro-alloying elements start to precipitate. In the vertical axis, the concentration of the micro-alloying element is signed. In the horizontal axis, the carbon or the nitrogen concentration is signed:

- carbon concentration is given if the precipitation is a carbide (in case of niobium and titanium),
- nitrogen concentration is given if the precipitation is a nitride (in case of vanadium and aluminium).

The isothermal curves mean the temperatures of the start of the precipitation process. It can be seen that these temperatures depend on the concentrations. By the help these diagrams the micro-alloying of the steels can be planned.

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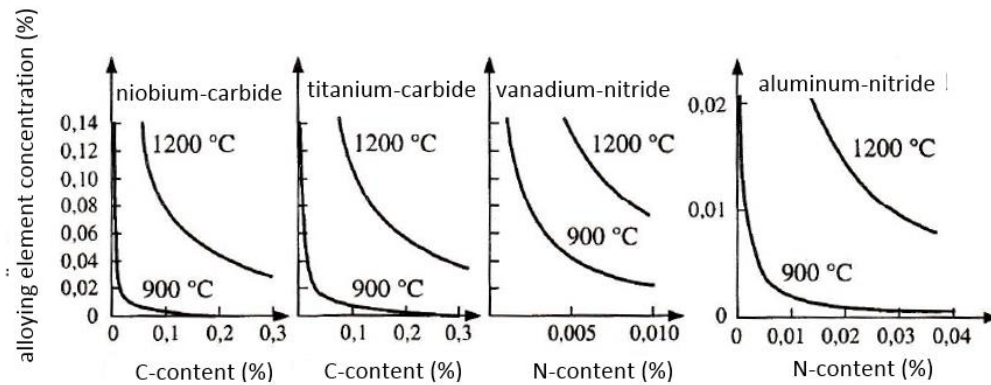
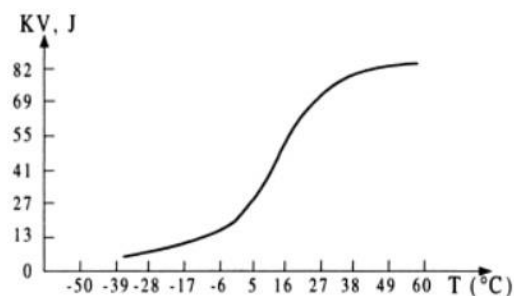


Figure 6: Start temperatures for precipitating of chemical compounds of micro-alloying elements

1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

The strength properties of the steels improve with the decrease of the temperature, while the ductility properties fall off. The metals having face centred cubic crystal structure (e.g. Cu, Ni, Al) keep their ductility even by 0 K in some measure, while the metals having body centred cubic crystal structure (Fe) fully lose their ductility with the decrease of the temperature. This phenomenon is called by embrittlement. The embrittlement depends on the temperature, the load rate and the stress state.

The tendency to embrittlement can be studied by the Charpy-test. This already was taught at BSc studies, however we repeat it shortly. By this test, a notched specimen having section of 10x10 mm is broken by an only impact. Carrying out this test by different temperatures, the characteristic curve shown in Figure 7 arises. It can be noticed that the impact work (KV) is large at high temperature, accordingly to the ductile behaviour, while the impact work is small at low temperature, accordingly to the brittle behaviour (brittle, rigid state means that fracture occurs without significant residual – plastic – deformation).



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Figure 7: Impact work (KV) depending on the temperature

The tendency to embrittlement is characterized by the transition temperature (DBTT is its agreed notation), which means the temperature where the ductile behaviour goes through to rigid behaviour. The DBTT is defined as the inflexion point of the KV-T diagram, or, according to steel standards, DBTT is the temperature where the impact work is 27 J.

The DBTT is influenced by the chemical composition strongly. Figure 8 shows the effect of the carbon content on the transition temperature. It can be seen that an increase of 0.6 % increases the DBTT with about 180°C, carbon makes the steel strongly rigid.

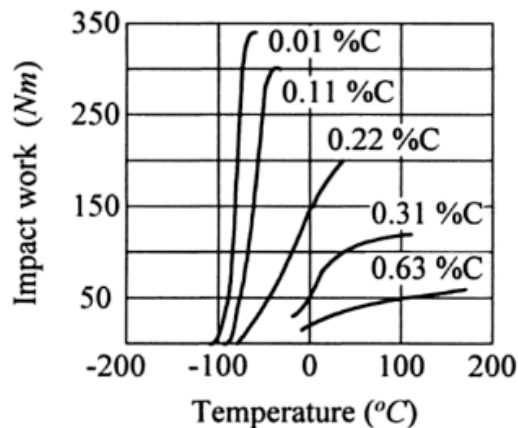


Figure 8: The effect of temperature on the impact work of mild steels with various C-content

Most of the alloying elements of the steels influence the DBTT similarly to the carbon. The Mn has a contrary effect. Figure 9 shows the effect of the manganese content on the transition temperature. It can be seen that an increase of 2 % increases the DBTT with about 180°C, manganese strongly can moderate the negative effect of the carbon.

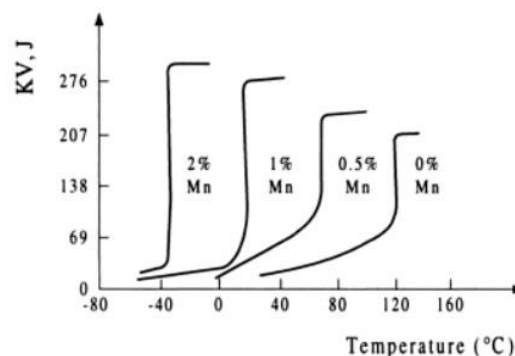


Figure 9: The effect of temperature on the impact work with various Mn-content

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