

THEORETICAL FUNDAMENTALS OF THE DEVELOPMENT OF THE ADVANCED HIGH-STRENGTH STEELS (AHSS)

Subject: Materials Science

MSc presentation
Széchenyi István University

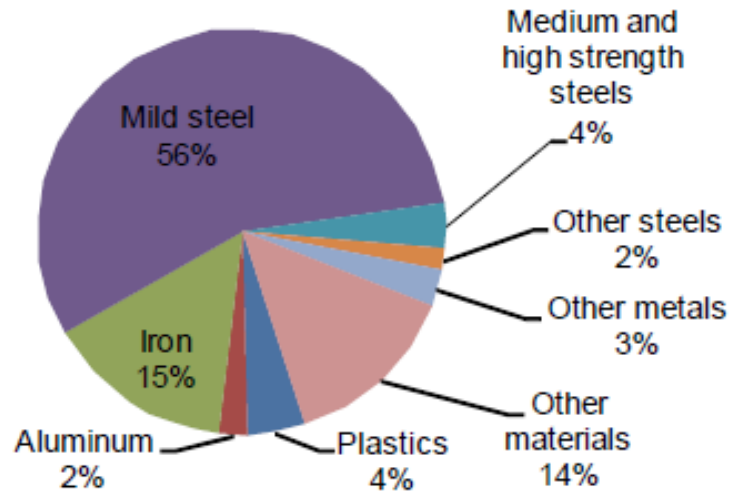
Dr. Zsoldos Ibolya

WHY HAVE WE BEEN LEARNING ABOUT STEELS FOR YEARS?

High rate in vehicle structures

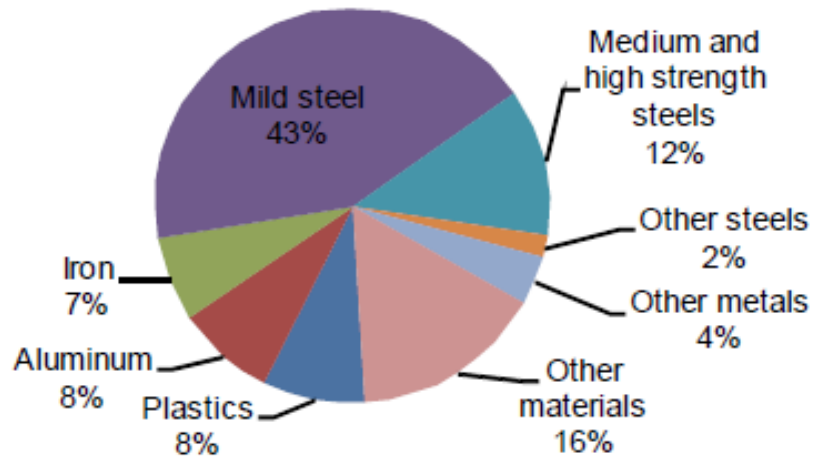
Average 1975 Vehicle

3,900 lbs.



Average 2007 Vehicle

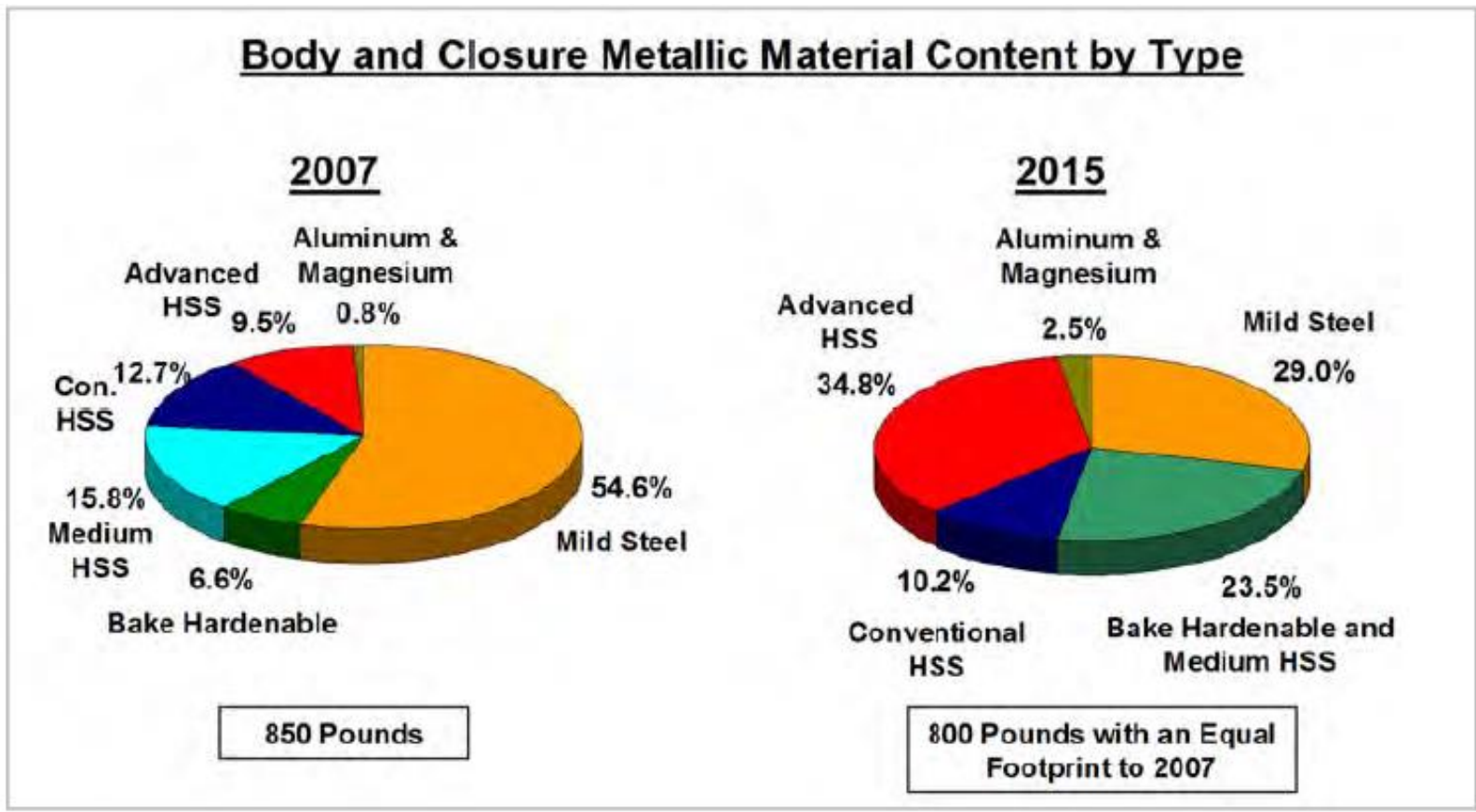
4,050 lbs.



1975 and 2007 average vehicle mass breakdown by material
[Data from Ducker Worldwide]

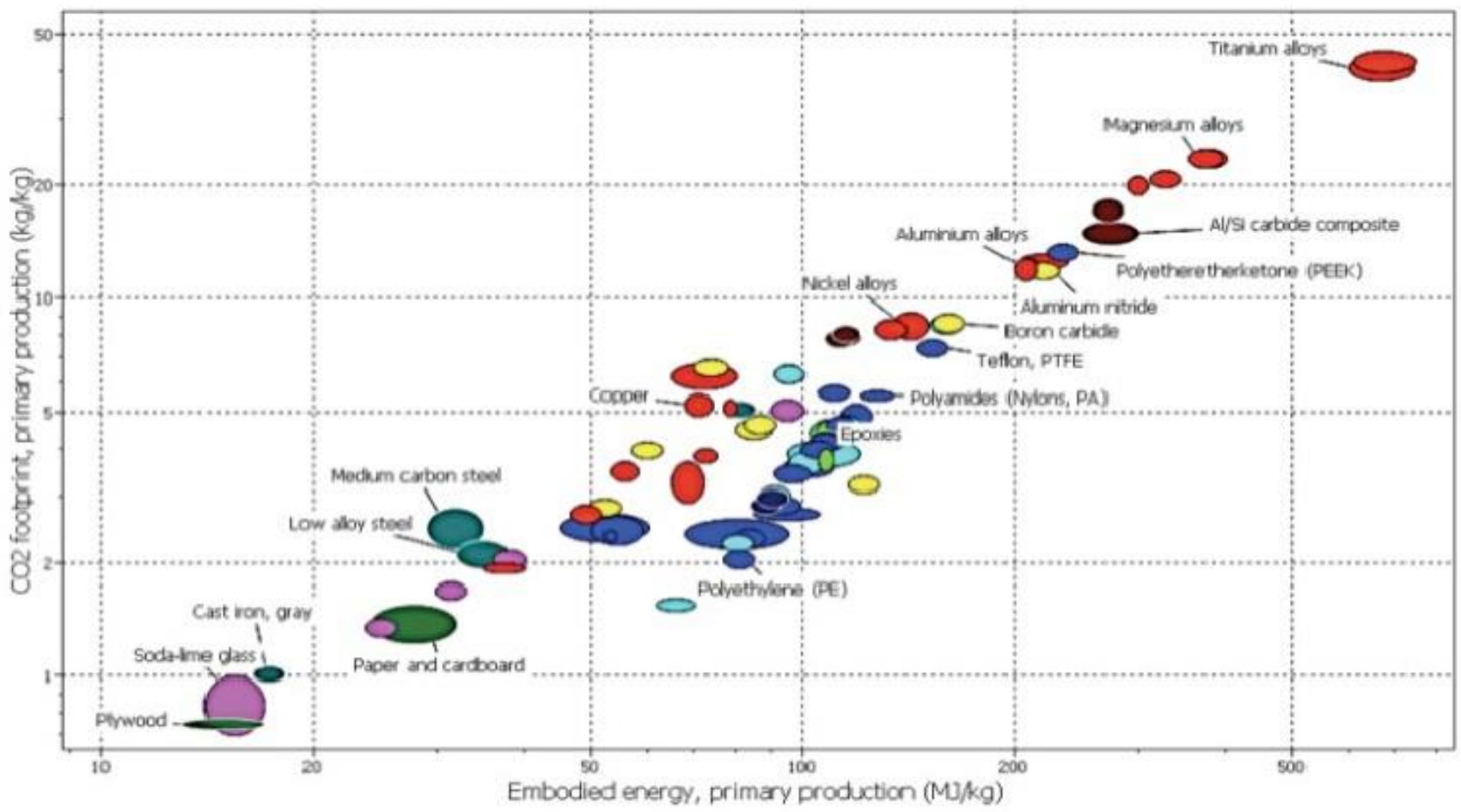
WHY HAVE WE BEEN LEARNING ABOUT STEELS FOR YEARS?

(North American data)



The use of high-strength steel (HSS) and AHSS grades are growing rapidly.

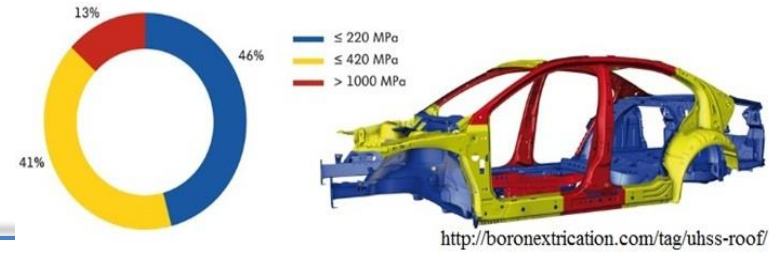
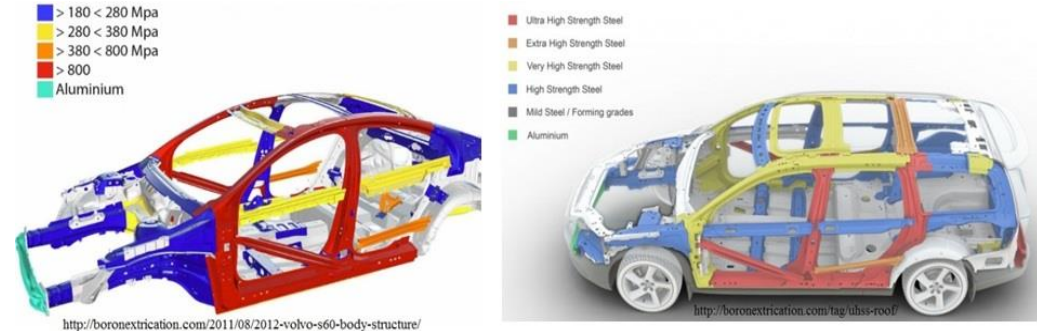
WHY HAVE WE BEEN LEARNING ABOUT STEELS FOR YEARS?



1.1. INTRODUCTION

AHSS steels were developed by the car industry.

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 %**.

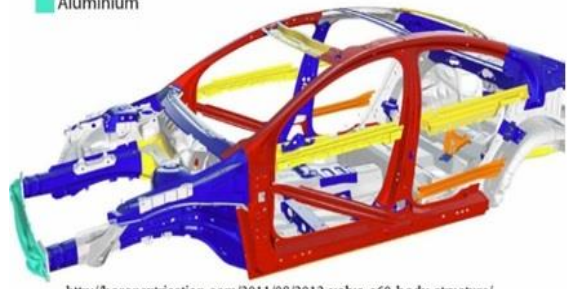


1.1. INTRODUCTION

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.**

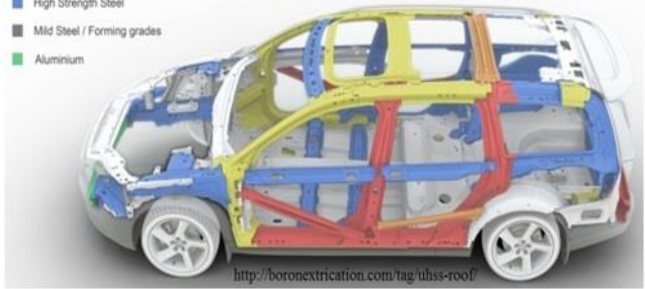
In Figure 1 the body structure of the Volvo S60 (from 2012), the Volvo V70 (from 2011) and the VW Jetta 2011 (from 2011) can be seen. The **parts having different properties are signed by different colours:**

- > 180 < 280 Mpa
- > 280 < 380 Mpa
- > 380 < 800 Mpa
- > 800
- Aluminium

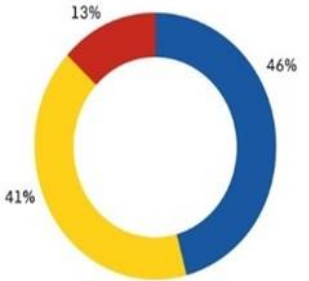


<http://boronextrication.com/2011/08/2012-volvo-s60-body-structure/>

- Ultra High Strength Steel
- Extra High Strength Steel
- Very High Strength Steel
- High Strength Steel
- Mild Steel / Forming grades
- Aluminium



<http://boronextrication.com/tag/uhss-roof/>

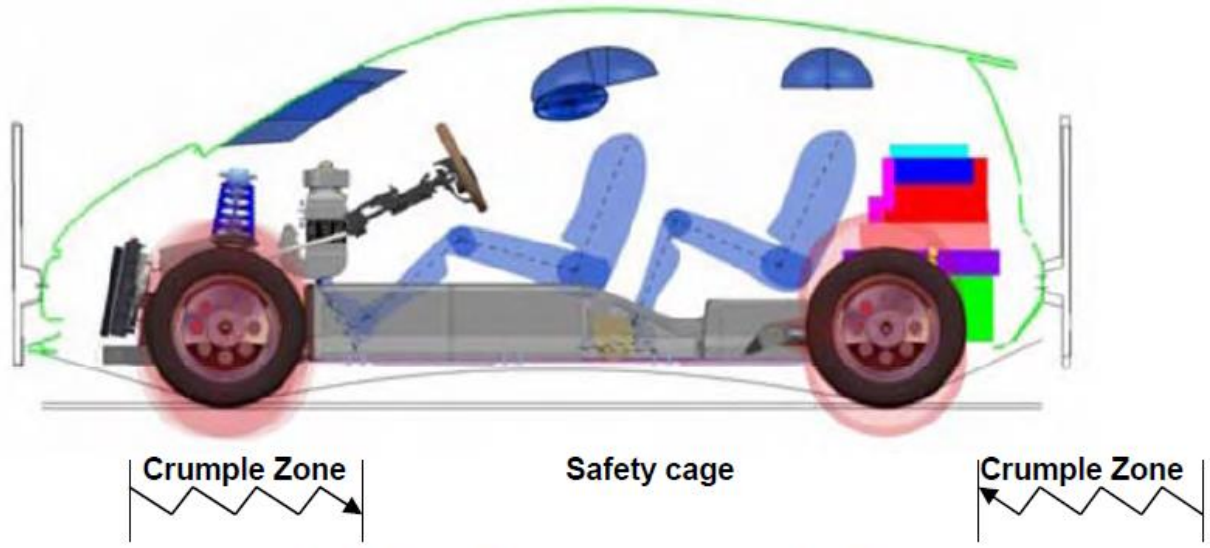


- ≤ 220 MPa
- ≤ 420 MPa
- > 1000 MPa



<http://boronextrication.com/tag/uhss-roof/>

1.1. INTRODUCTION



The Major crash management zones of a vehicle.

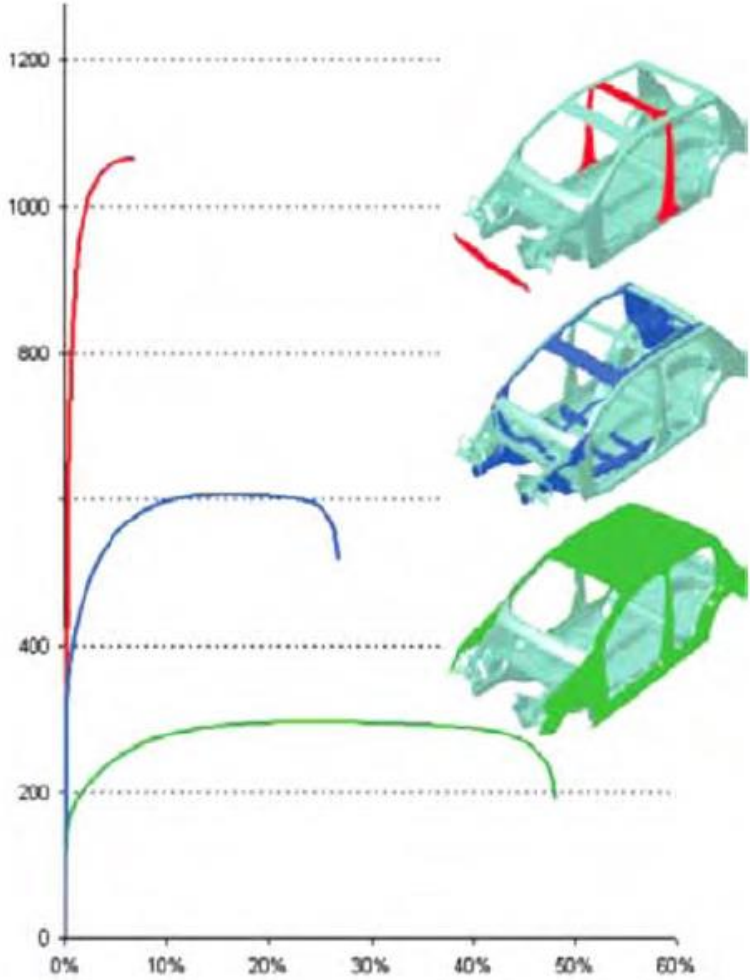
Source:
 AHSS Application
 Guidelines
 Version 6.0
 Technical Editors:
 Stuart Keeler,
 Menachem Kimchi
 Peter J. Mooney

Differing Safety Requirements of Vehicle Structures.

Crash Zone	Performance Requirements	Material properties to meet need	Evidence of Performance	Potential Steel Selection
<i>Crumple Zone</i>	High energy absorption over a distance in crash event	High work hardening, strength, and ductility	Large area under the stress-strain curve	Dual Phase, Complex Phase, Transformation-Induced Plasticity
<i>Passenger Compartment</i>	No deformation/intrusion during crash event	High yield strength	Ultimate tensile strength of σ - ϵ curves	Martensitic, Hot Formed, Dual Phase (>980 MPa)

1.1. INTRODUCTION

Source:
AHSS Application
Guidelines
Version 6.0
Technical Editors:
Stuart Keeler,
Menachem Kimchi
Peter J. Mooney



> Steels for safety-critical parts, especially for maintaining a passenger survival space in crash events

> High-strength steels with a good balance of strength, formability, energy absorption and durability

> Steels with excellent formability (eg. for deep drawing)

Stress (in MPa) vs. percent elongation for different steel types and their applications in body structure

1.1. INTRODUCTION

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.

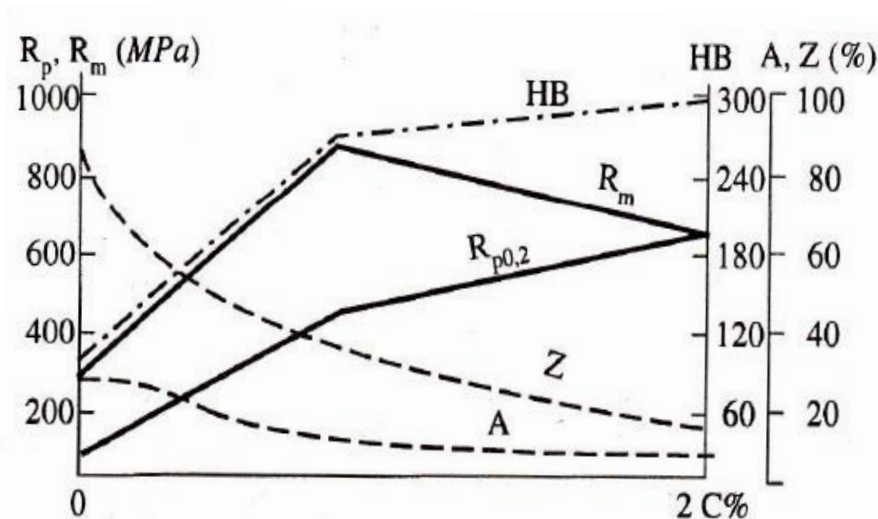
1.2. STRENGTHENING (STRENGTH INCREASING) METHODS OF

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



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**.

1.2.1. EFFECT OF THE DISLOCATION STRUCTURE

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).

1.2.1. EFFECT OF THE DISLOCATION STRUCTURE

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**.

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

1.2.2. EFFECT OF THE TEXTURE (MICROSTRUCTURE)

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.

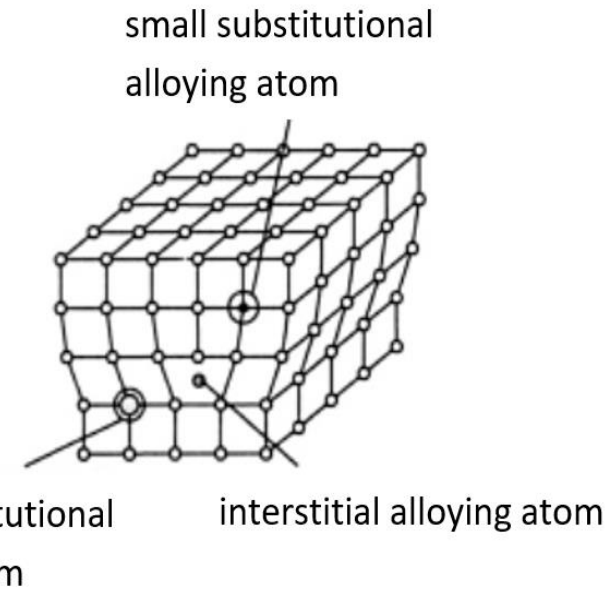
Accordingly, we can talk about strengthening effects generated by

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

1.3.1. EFFECT OF THE SOLID SOLUTION STRENGTHENING

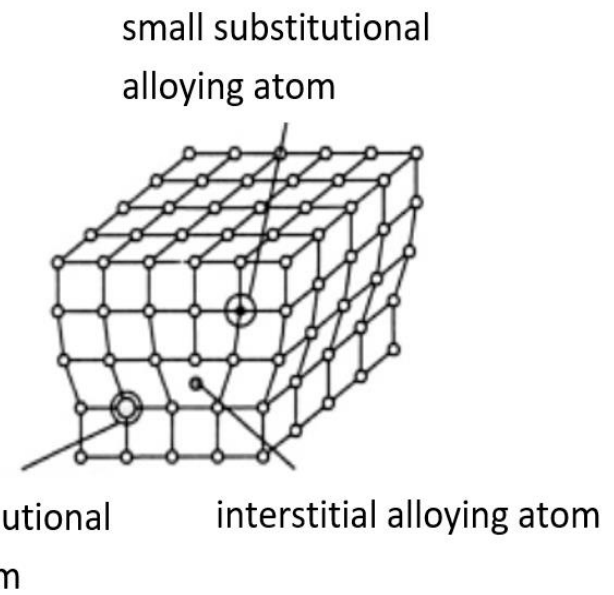
A part of the atoms of the alloying elements is located in the surroundings of the dislocation:

- 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).



1.3.1. EFFECT OF THE SOLID SOLUTION STRENGTHENING

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.



1.3.1. EFFECT OF THE SOLID SOLUTION STRENGTHENING

If the alloying element content is not more than several percents, 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.

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.

1.3.2. EFFECT OF THE PRECIPITATION HARDENING

The **growth of the strength**, which can be reached by the precipitation hardening mechanism, can be defined by the following relationship:

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

The effect of the precipitation hardening is considerably larger than the effect of the solid solution strengthening mechanism:

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

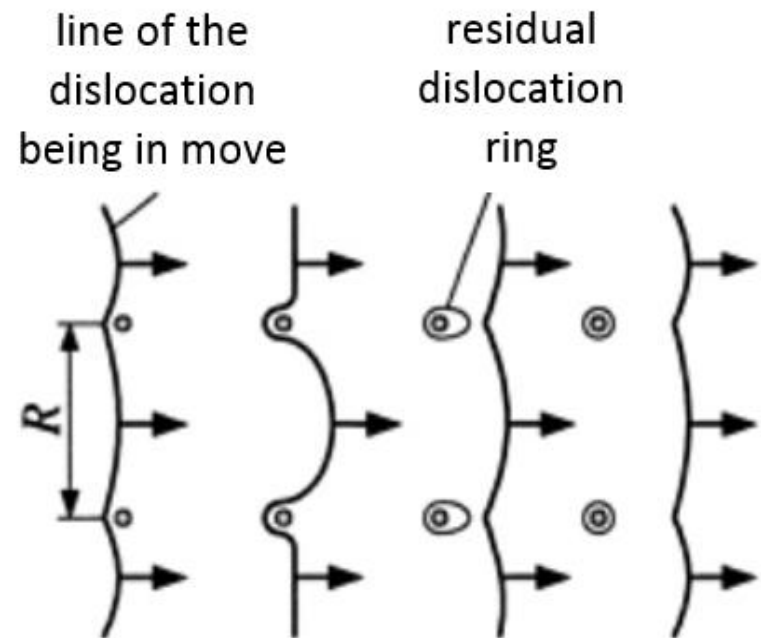
The growth of the strength is caused by the fact that **the movement of the dislocations is blocked by the boundary surfaces between the phases in case of the precipitation hardening.**

1.3.3. 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.



This mechanism was shown first by the Hungarian researcher Orowan.

1.3.3. EFFECT OF THE DISPERSION STRENGTHENING

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.

1.3.3. EFFECT OF THE DISPERSION STRENGTHENING

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 **Fe_3C , Fe_2N , Fe_4N** 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 **SiO_2 and Al_2O_3** 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,

R_0 is a materials constant for the starting stress for dislocation movement
(or the resistance of the lattice to dislocation motion),

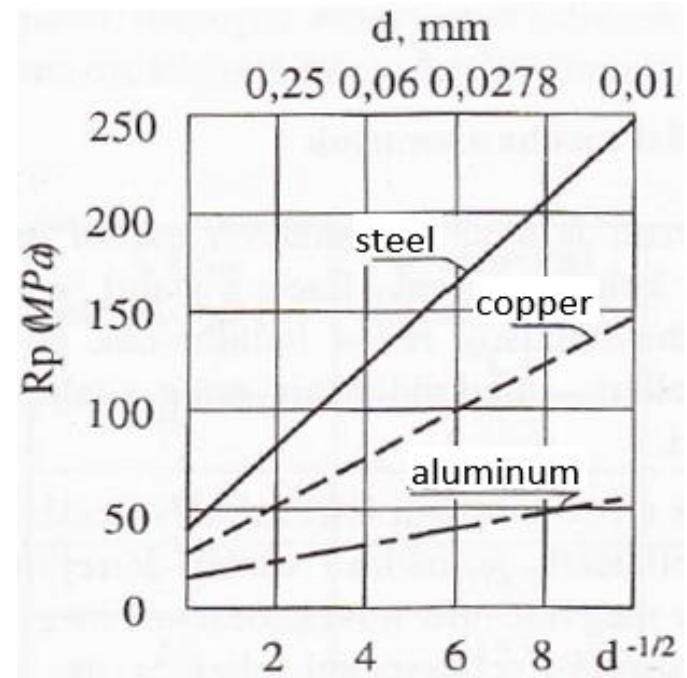
k is the strengthening coefficient (a constant specific to each material),

d is the average grain diameter.

1.4. EFFECT OF THE GRAIN SIZE

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.



1.4. EFFECT OF THE GRAIN SIZE

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.)

1.4. EFFECT OF THE GRAIN SIZE

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 temperature the precipitating starts.

The **precipitations inhibit the recrystallization**: the more precipitations are in the austenite the more difficult the start of the recrystallization is.

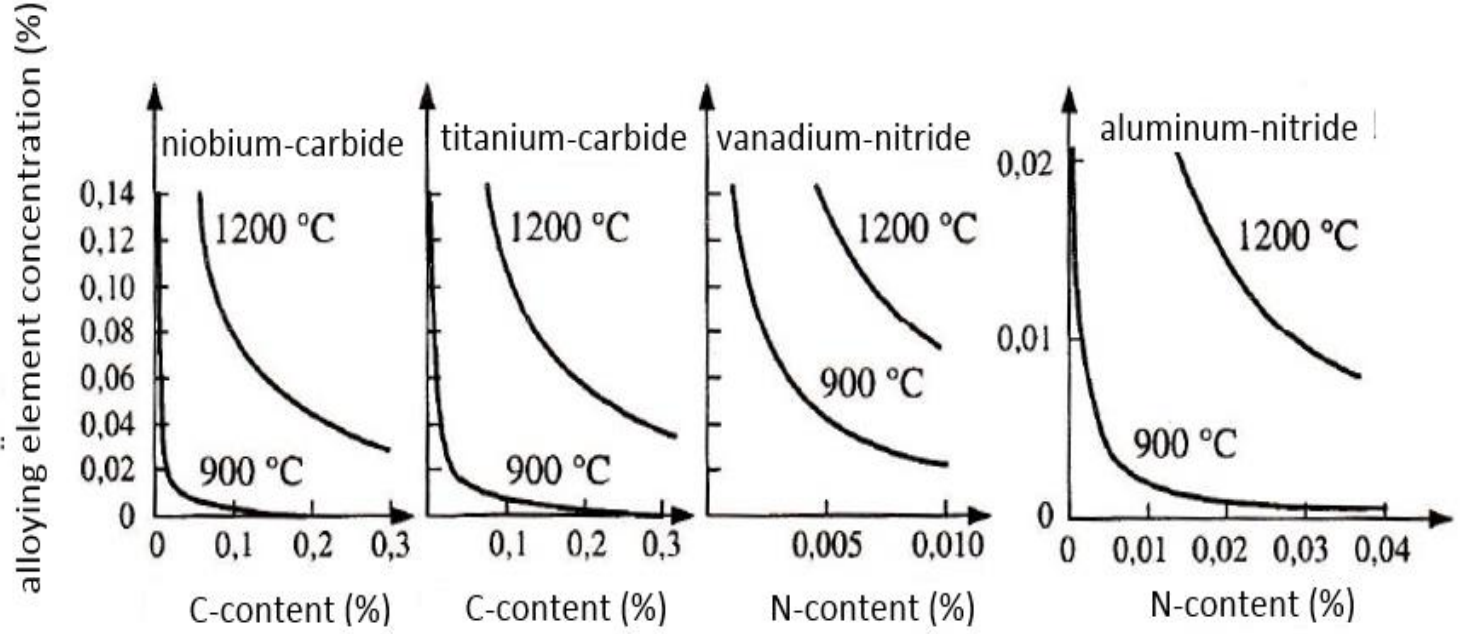
1.4. EFFECT OF THE GRAIN SIZE

The figure shows the **temperatures where the carbides and the nitrides of the four micro-alloying elements start to precipitate.**

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.**



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 centered cubic crystal structure** (e.g. Cu, Ni, Al) **keep their ductility even by 0 K in some measure**, while the **metals having body centered cubic crystal structure (Fe) fully lose their ductility with the decrease of the temperature.**

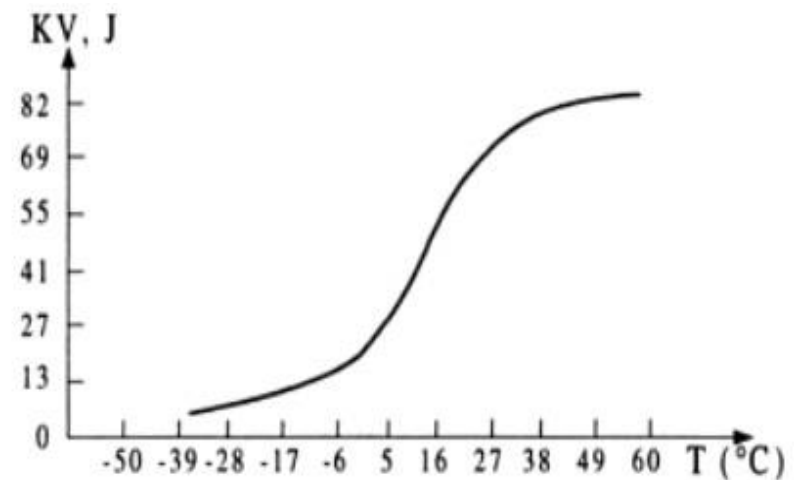
This phenomenon is called by **embrittlement**. The embrittlement **depends on the temperature**, the load rate and the stress state.

1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

The tendency to embrittlement can be studied by the **Charpy impact 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 arises.

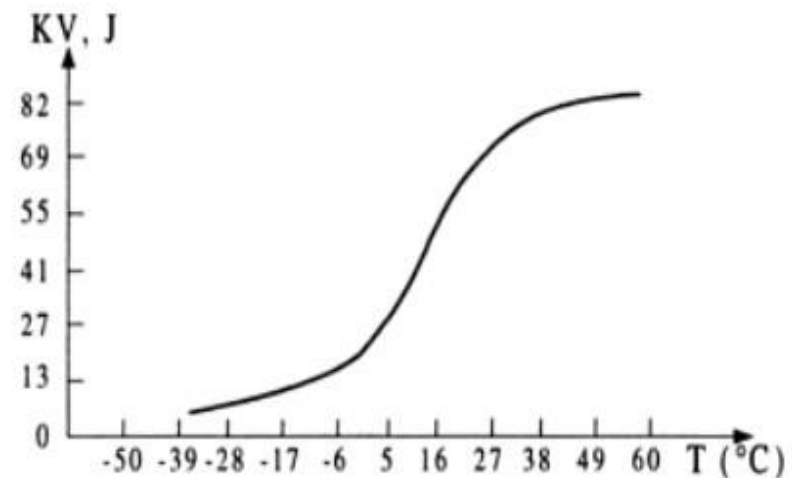


1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

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

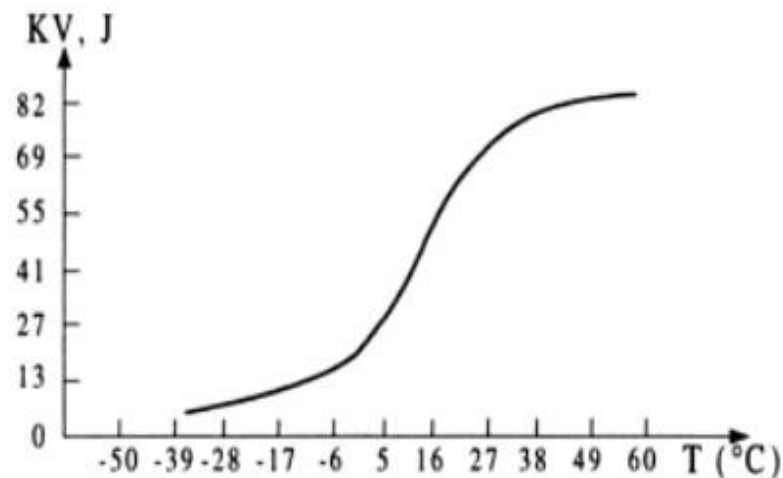
(brittle, rigid state means that fracture occurs without significant residual – plastic – deformation).



1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

The tendency to embrittlement is characterized by the **ductile-brittle transition temperature (DBTT)** (its agreed notation), which means the **temperature where the ductile behaviour goes through to rigid behaviour.**

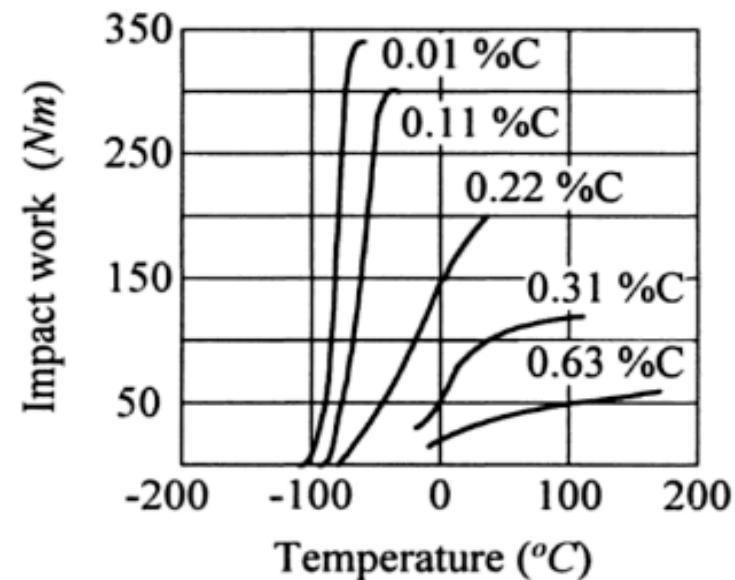
The **DBTT** is defined as the **inflexion point** of the KV-T diagram, or, according to steel standards, **DBTT** is the **temperature where the impact work is 27 J.**



1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

The **DBTT is influenced by the chemical composition** strongly. The figure 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.

Most of the alloying elements of the steels influence the DBTT similarly to the carbon.



1.5. DYNAMICAL LOAD, DUCTILE-BRITTLE TRANSITION TEMPERATURE

The **Mn** has a **contrary effect**. The figure 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 160°C**, **manganese strongly can moderate the negative effect of the carbon**.

