The right choice of steel – according to the Eurocode

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Abstract: In general, the choice of the steel grade is ruled in Eurocode EN 1993-1-1. Several requirements are specified: choice according to the material properties, ductility requirements, toughness properties and through-thickness properties. With reference to these requirements on the mechanical characteristics, modern hot-rolled structural sections are produced by precise control of the temperature during the rolling process. Fine grain steels, produced using thermomechanical rolling (delivery condition M according to EN 10025-4), feature improved toughness values which give a lower carbon equivalent and a fine microstructure when compared with conventional or normalised steels. This paper gives guidance on and background to the right choice of the steel grade according to the Eurocode. Furthermore, the influence of the production process on this choice is highlighted and the advantages of thermomechanical steels for each criterion are discussed.

1. Introduction

Eurocode 3 [1] applies to the design of buildings and civil engineering works in steel. It complies with the requirements and principles for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design. Requirements are provided for resistance, serviceability, durability and fire resistance of steel structures. These are based on the principle of limit state design, which mainly assumes that the resistance of cross-sections and members specified for the ultimate limit states are based on tests in which the tolerances are met according to EN 1090-2 [2], and the material exhibited sufficient ductility to apply simplified design models. Therefore, the material properties, for steel the steel grade, have to be specified in detail to comply with the safety level of Eurocode 3 ("Fig. 1").

These simplified design models and the safety concept of the Eurocode are based on tests at ambient temperature, for which ductile failure occurs as the steel is on the upper shelf region with sufficient toughness. In Fig. 2 (left), the conclusions from testing for the partial safety factors and the characteristic strength are shown. If brittle fracture takes place, the assumptions for the design models and the safety concepts are no longer met ("Fig. 2", right). Consequently, failure against brittle fracture must be accounted for with an appropriate choice of steel with sufficient toughness.

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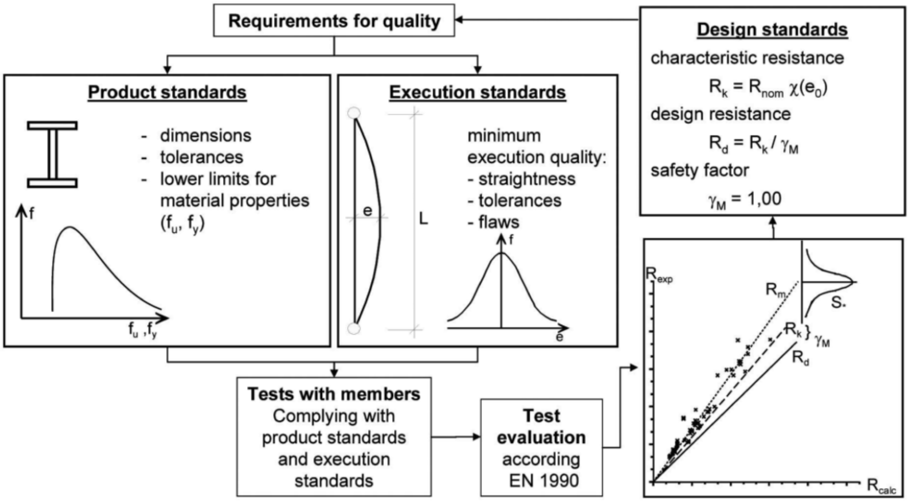


Figure 1: Reliability of strength verification [3]

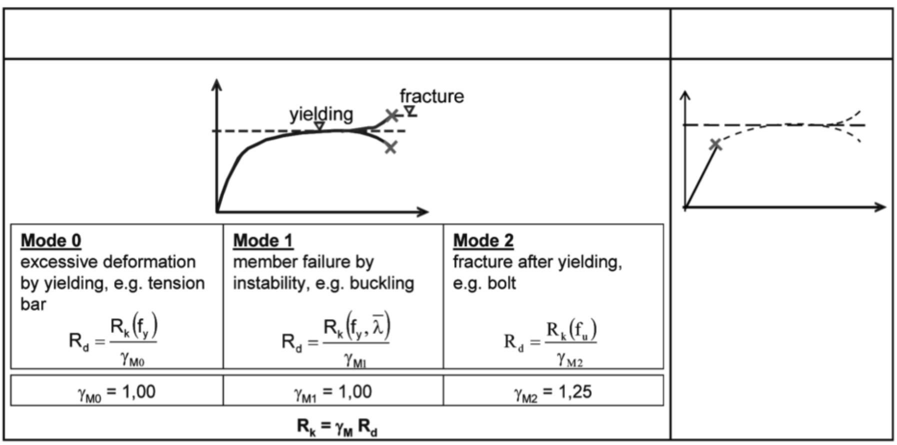


Figure 2: Brittle fracture and ductile failure [3]

2. The choice of the steel grade

In general, the choice of the steel grade is ruled in Eurocode EN 1993-1-1 (2005). Several requirements are specified:

- Choice according to the mechanical material properties
  Nominal values of material properties are defined as characteristic values in design calculations.
- Ductility requirements
  For steels, a minimum ductility is required.
- Toughness properties

Simplified aids are given to choose the appropriate material with sufficient fracture toughness to avoid brittle fracture.

- Through-thickness properties.
  Guidance on the choice of through-thickness properties is given in EN 1993-1-10 (2005).

With reference to these requirements, the designation of the steel grade is defined in the product standard for hot-rolled products and structural steels in EN 10025 (2004) (“Fig. 3”). The classification of steel grades is accordingly based on the minimum specified yield strength at ambient temperature.

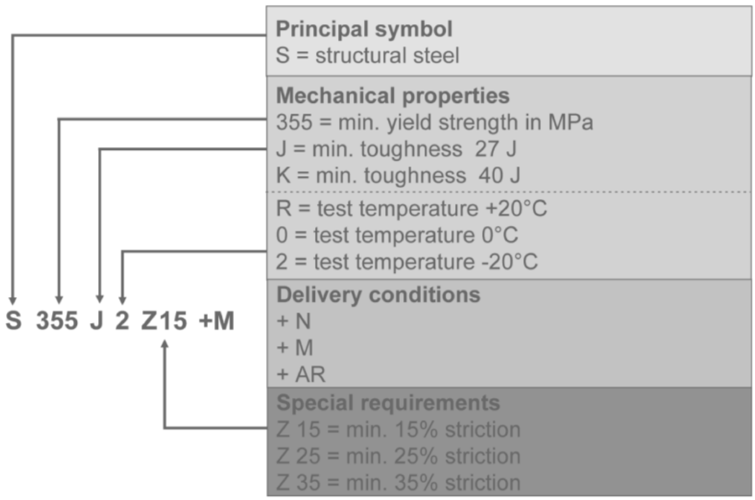


Figure 3: Designation of the steel grade according to EN 10025 (2004)

The product standard also differentiates the delivery condition. These are defined by the rolling process of the steel. Conventional hot rolling takes place in the recrystallised austenitic phase (γ) and is followed by a subsequent air cooling, see Fig. 4. Without any special rolling control or heat treatment, this material delivery condition is specified to be “as rolled” (AR) in the EN 10025. With an additional normalising thermal treatment (N), the steel microstructure can be refined leading to improved properties specifically described in EN 10025-3, if alloying elements have been added to the steel. The reduction of the grain size leads to an increase of the specific surface of the grain boundaries within the material. Since these grain boundaries represent an obstacle to deformation the yield strength increases. The fine grained structure of normalised steels may further be improved with restriction of the alloying elements via a thermomechanical treatment. This may be quenching (Q) with water or oil, an accelerated cooling to about 500°C after rolling and lastly slower cooling to the room temperature, and a successive tempering (T) to regain ductility. A fine grained microstructure may also be obtained if the hot rolling process is carried out with a control of the temperature during the final deformation (CR). Another possibility to refine the microstructure is to apply a thermomechanical rolling process according to EN 10025-4. Hereby, rolling is also performed with a controlled rolling process in the recrystallised austenitic and further rollings in the non-crystallised austenitic phase, in cases even into the austenitic-ferritic phases (α + γ) (M/N). For thermomechanical steels (TM), rolling is carried out at lower temperatures than normalising rolling; the rolling temperature in the finishing stand is typically close to the transformation temperature of the austenite ($\gamma_{non\text{-}recr.}$ ® $\alpha + \gamma$). The grain size of austenite is about 20 µm or larger before the last rolling passes. After rolling, the austenite grains are usually elongated because of the sluggish recrystallization of the microstructure due to the low rolling temperature.

Although controlled rolling leads to an attractive combination of strength and ductility, it also includes substantial disadvantages. The reduction of the rolling temperature brings an increase of the rolling loads and many mills are not designed to resist the additional stresses. Because a waiting time is usually incorporated in the rolling schedule, controlled rolling can increase rolling time and adversely reduce productivity. Moreover, with higher material thickness, the rolling temperature increases and the air cooling rate after rolling decreases, which induces rougher microstructures. To reach the tensile properties, the content of alloying elements has to be adapted. Due to weldability requirements and the limit in equivalent carbon, beams in grade S460 are not produced for thickness larger than 50 mm. To overcome the limitations of thermomechanical rolling, accelerated cooling process of beams after rolling has been developed (TM + QST). Hereby, the fine grained structure is achieved by a minimum of alloying elements with the complex rolling process and a strict temperature control. As the ferrite grain size of conventionally rolled steels is 10 to 30 µm, the grain size of TM + QST steels is usually between 5 to 10 µm. These fine grained steels benefit from a low carbon equivalent value and are to be predominantly used for large material thicknesses in high strength steel to address weldability.

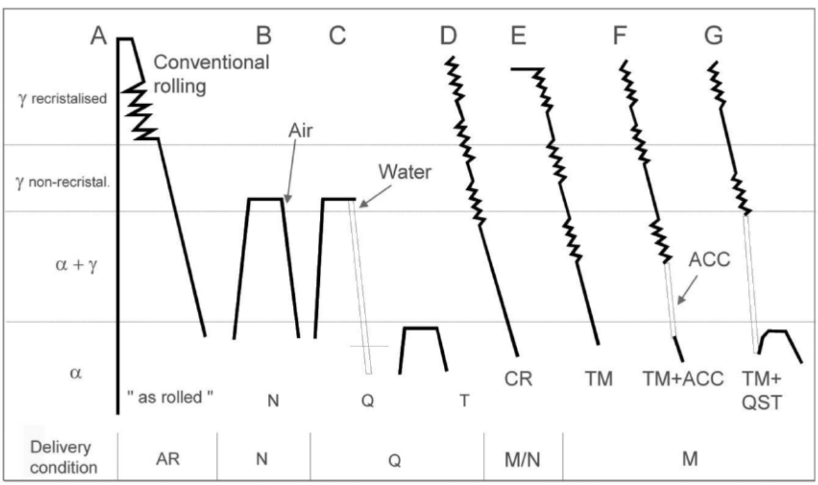


Figure 4: Relation of the delivery condition to the rolling process

In addition to the group of thermomechanical steels delivered according to EN 10025-4, ArcelorMittal has developed steel grades to fully valorise the potential of quenching and self-tempering (QST) process. These fine grained TM-steels are branded HISTAR® steels [Z-30.2-5] and are characterised by more stringent requirements in terms of mechanical properties and chemical composition.

2.1 Mechanical properties

The nominal values of the yield strength f_y and the ultimate strength f_u for structural steel should be obtained by adopting the values $f_y = R_{eh}$ and $f_u = R_m$ direct from the product standard, see Tab. 1, or by a Tab. drafted from this standard in EN 1993-1-1. It has to be noticed, that the required yield strength decreases with increasing material thickness. This takes into account the effect, that with the increase in material thickness, the addition of alloying elements need to be higher to achieve constant yield strength over the thickness. However, with the increase in addition of alloying elements, the carbon equivalent value raises and welding becomes problematic. Welding is substantial to the application of structural steels. Thus, the normative rules have considered this fact by lowering the required yield strength for thicker plates to account for weldability.

Table 1: Mechanical properties at ambient temperature for thermomechnical rolled steels [4]

Designation		Minimum yield strength R_{eH} [a] MPa [b] Nominal thickness mm						Tensile strength R_m [a] MPa [b] Nominal thickness mm					Minimum percentage elongation after fracture [c] % $L_0 = 5,65\sqrt{S_0}$
According EN 10027-1 and CR 10260	According EN 10027-2	≤ 16	> 16 ≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 120 [d]	≤ 40	> 40 ≤ 63	> 63 ≤ 80	> 80 ≤ 100	> 100 ≤ 120 [d]	
S275M S275ML	1.8818 1.8819	275	265	255	245	245	240	370 to 530	360 to 520	350 to 510	350 to 510	350 to 510	24
S355M S355ML	1.8823 1.8834	355	345	335	325	325	320	470 to 630	450 to 610	440 to 600	440 to 600	430 to 590	22
S420M S420ML	1.8825 1.8836	420	400	390	380	370	365	520 to 680	500 to 660	480 to 640	470 to 630	460 to 620	19
S460M S460ML	1.8827 1.8838	460	440	430	410	400	385	540 to 720	530 to 710	510 to 690	500 to 680	490 to 660	17

[a] For plate, strip and wide flats with widths ≥ 600 mm the direction transverse (t) to the rolling direction applies. For all other products the values apply for the direction parallel (l) to the rolling direction.

[b] 1 MPa = 1 N/mm²

[c] For product thickness < 3 mm for which test pieces with a gauge length of L_0 = 80 mm shall be tested, the values shall be agreed at the time of the enquiry and order.

[d] For long products a thickness ≤ 150 mm applies.

The producers verify the conformity of their products with the standard by tensile tests, in which for each section, the location of the test specimen is also defined, see e.g. Fig. 5 for beams. The result of the tensile test is the stress-strain curve from which the relevant parameters, yield strength f_y and tensile strength f_u, are determined. These parameters are exemplarily indicated in Fig. 6, a typical stress-strain curve for a HISTAR®460 (or S460 steel grade according to EN 10025-4 for thermomechanical rolled weldable fine grain structural steels).

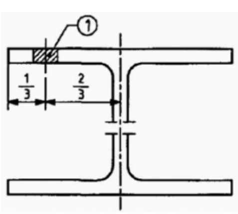


Figure 5: Location of test specimen for tensile test

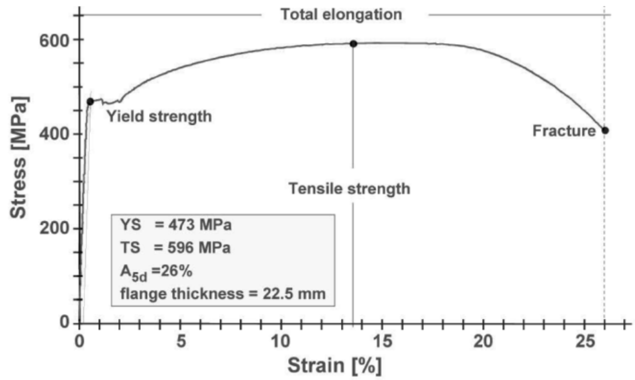


Figure 6: Stress-Strain diagram from a HISTAR®460 steel

For thermomechanical rolled fine grained steels of the new generation using the QST process (e.g. HISTAR® steels), it is remarkable that a decrease of the yield strength in respect to the material thickness can be avoided without an increase of the alloying elements and the carbon equivalent value. A comparison of the material thickness to yield strength in relation to steels according to EN 10025 (2004) and modern HISTAR® steels according to Z-30.2-5 (2008) is given in Fig. 7. As a result, the right choice of thermomechanical steel gives the designer an economical advantage in design, as presented in the example of application of this paper.

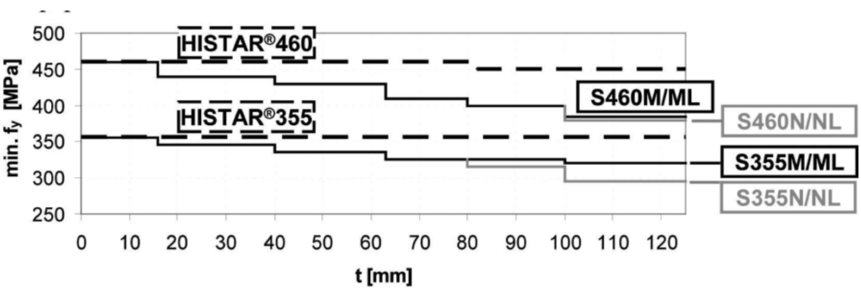


Figure 7: Comparison of the material thickness t to yield strength f_y in relation to steels according EN 10025 (2004) and modern HISTAR® steels according to Z-30.2-5 (2008)

2.2 Ductility

Ductility is required to avoid brittle failure of structural elements. For steels, a minimum ductility is required that should be expressed in terms of limits for:

- the elongation at failure on a gauge length of $5.65\sqrt{A_0}$ (where A_0 is the original cross-sectional area); Eurocode recommends an elongation at failure not less than 15%;
- the ratio f_u / f_y of the specified minimum ultimate tensile strength f_u to the specified minimum yield strength f_y; Eurocode recommends a minimum value of f_u / $f_y \geq 1.10$.

Both criteria are of particular interest for high strength structural steels as the grade S460 due to the fact that the higher the yield strength, the less elongation will be present at failure (“Fig. 8”). The minimum required elongation for structural steels is given in Tab. 1. Therefore, the product standard offers more ductility than required in EN 1993-1-1. However, Fig. 5 also illustrates that the minimum required elongation is in general met with a high safety margin by modern steels of higher strength. The ratio f_u / f_y is in general more critical than the minimum elongation. Therefore, various tensile test have been compiled and the ratio f_y / f_u has been plotted over the yield strength (“Fig. 9”).

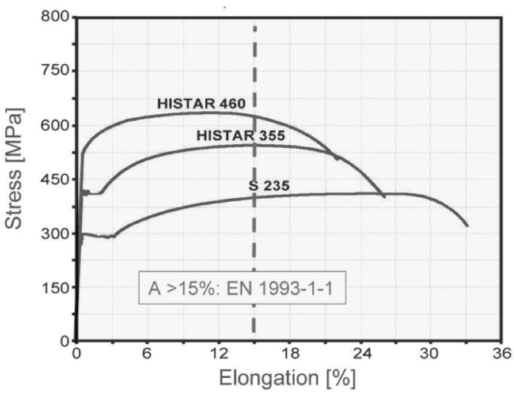


Figure 8: Comparison of stress-strain curves for S235 to S335 and S460 steel of the modern generation

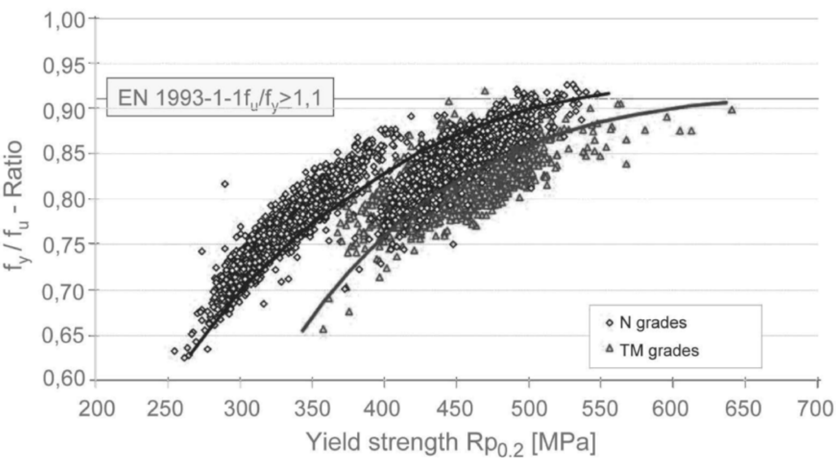


Figure 9: Ratio of yield strength to tensile strength for structural steels of ArcelorMittal

The conclusion from the diagram is that structural steels up to 460 MPa fulfil the ductility criteria. Structural steels with yield strengths higher than 460 MPa seem, on the first look, not to be able to fulfil the ductility criteria. Thermomechanical steels are well adopted to fulfil these criteria with thanks given to their specific strengthening mechanism (refined microstructure and reduced microalloying content).

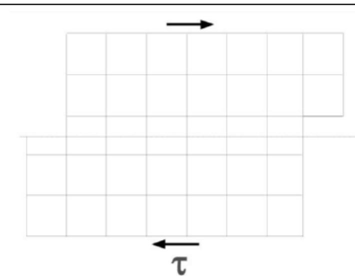
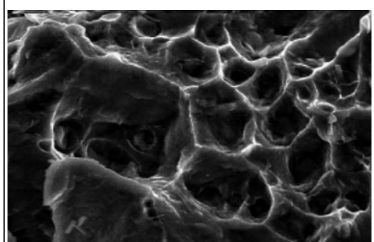
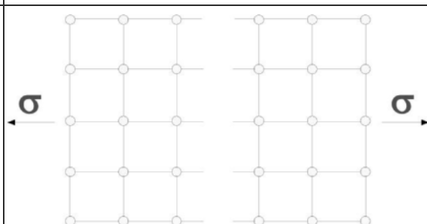
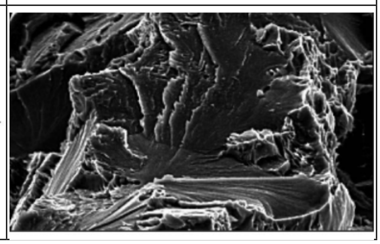
In the Hong Kong Code of Practice for the Structural Use of Steel (2005) [5], a ratio f_u / f_y = 1.2 is required and therefore 9% more conservative compared to the Eurocode and therefore does not allow for high strength, high toughness steels. Further, the elongation at failure to be not less than 15% is required which is in line with the Eurocode requirement. The ration 1.2 used in the Hong Kong Steel Code is reasonable for conventional steels.

2.3 Toughness

2.3.1 Introduction

There are two ways of material failure: ductile failure and brittle fracture (Tab. 2).

Table 2: Failure mechanisms of materials

Failure mode	Deformation of crystal lattice	Fractography
Ductile failure ▪ shear ▪ slipping ▪ toughness ▪ dull		
Brittle fracture ▪ cleavage ▪ decohesion ▪ brittleness ▪ shiny		

Toughness is the resistance of a material to brittle fracture when stressed. Toughness is defined as the amount of energy per volume that a material can absorb before rupturing. The material toughness depends on:

- Temperature
  Materials lose their crack resistance capacity with decreasing temperature ("Fig. 10"). This relation can be displayed in an impact energy A_v – temperature T curve with an upper shelf region (3: ductile failure), lower shelf region (1: brittle fracture) and a transition region (2: crack shows shares of cleavage and shear area).
- Influence of loading speed
  The higher the loading speed, the lower the toughness ("Fig. 11").
- Grain size
  The orientation of the crystal lattice varies in the adjacent grains ("Fig. 12"). Whenever the crack tip reaches the grain boundary, the crack would subsequently change his

growth direction and thus energy is dissipated. Consequently, fine grained steels are more resistant to brittle failure.

- Cold forming
  With an increase in cold forming, the yield strength increases with decreasing ductility (“Fig. 13”).
- Material thickness
  In the two dimensional stress state, steel plastic deformation starts at the yield point. In the three-dimensional stress state, the crystal lattice of the steel is compacted from all sides and therefore the steel yield strength is increased significantly. Thus, thinner plates with a higher share of material in the two-dimensional stress state do have more ductility than thicker plates (“Fig. 14”).

The material toughness is in general experimentally investigated by the Charpy impact test with the resulting impact energy – temperature curve.

Further relevant factors which have also an influence on the resistance of members to brittle fracture are:

- Notch detail
  Crack initiation highly depends on the notch detail and the resulting stress, crack position and crack shape expressed by the notch intensity factors (“Fig. 15”).
- Load utilisation level of member
  The higher the tension in the member, the higher the failure probability (“Fig. 16”).

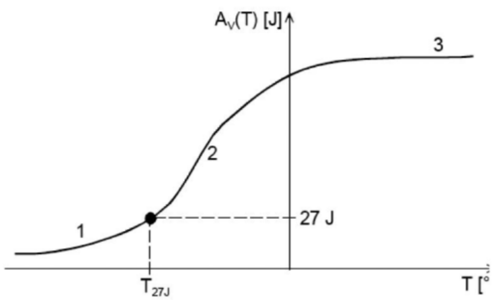


Figure 10: Impact energy A_v – temperature T curve

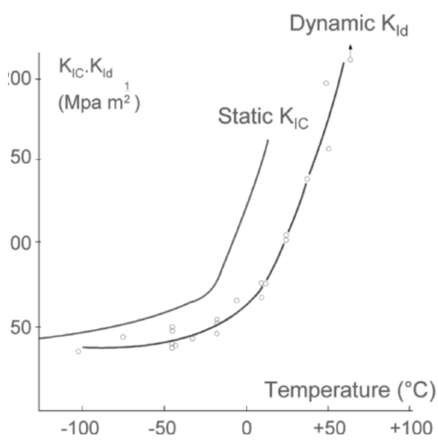


Figure 11: Stress intensity factor – temperature curve for quasi-static and dynamic loading

Figure 12: Model of crack propagation in the crystal lattice

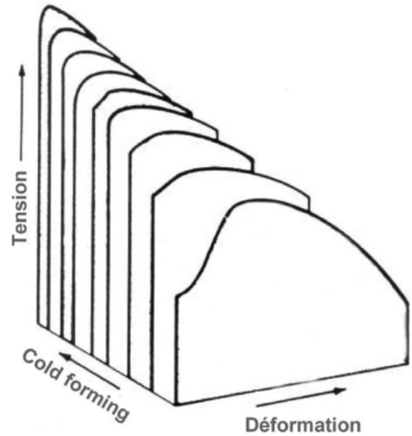


Figure 13: Stress-strain curve in dependency of the degree in cold forming

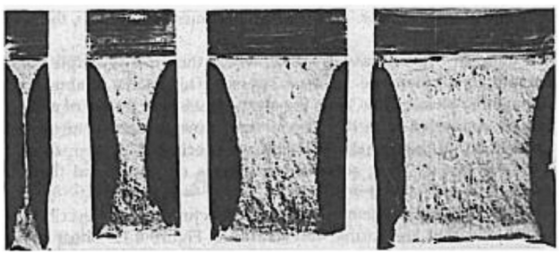


Figure 14: Fracture surfaces of Charpy impact tests for plates with different material thicknesses

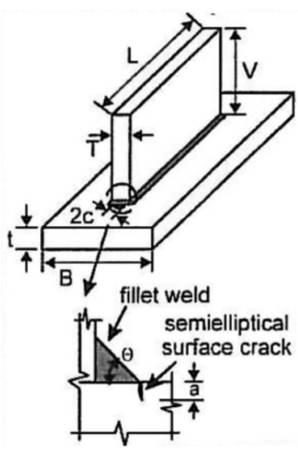


Figure 15: Specification of a notch for the determination of the notch intensity factor

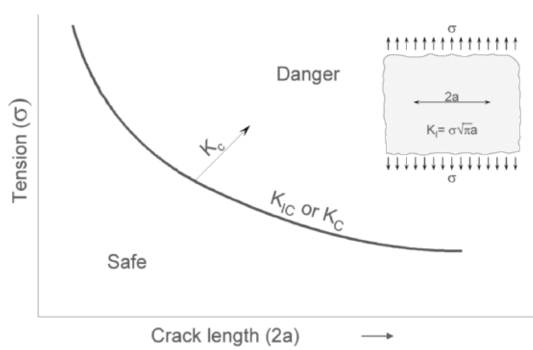


Figure 16: Relation of the failure loading to the crack length

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