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Chapter 4

Steels for car bodies

4.1 The crystalline structure of metals

Metals, generally, consist of a crystalline structure. Technical metals are produced by a transformation from the liquid to the solid state. The growth of the metallic lattice starts locally at crystallization seeds. The crystals, resulting from different crystallization seeds, are called grains. In the final solid state of the metal the grain boundaries are in contact with each other [47]. In a perfect metal the electrons are not attached to a specific nucleus. This state of the electrons is called electron gas. Electrostatic forces are acting between the positively charged nuclei and the electron gas. Because of the nuclear structure of the metals it is possible for nuclei to change their position without affecting significantly the electrostatic equilibrium state [47].

4.2 The elastic behavior of metals

As long as a mechanical system returns to the initial state after load removal, the deformation is referred to as elastic. Loads applied to a structure consisting of metal atoms, cause a variation of the interatomic spacing of the nuclei. The atomic reaction is necessary in order to reach an equilibrium state with respect to the external load. After the load is removed, the nuclei return to their original position. Generally, elastic deformations change the volume of the metal. Provided, the metallic lattice is free of defects, the material will be deformed elastically until brittle fracture occurs [48].

4.3 The plastic behavior of metals

Plastic deformations are not reversible after load removal. The condition for the occurrence of a permanent deformation is the mentioned possibility of nuclei, to
change their position in a metallic lattice and the presence of defects that disturb the crystalline structure. Such defects usually occur in metals for technical applications during the growing phase of the crystalline structure. Typical defects are missing nuclei and foreign atoms, which are integrated in the crystalline structure. The mechanism of plastic deformation is based on the movement of dislocations, which are linear defects. Plastic yielding usually occurs in conjunction with an elastic deformation. At a low level of the external load, the material is deformed elastically, which generates the internal forces for the load balance. Higher load levels activate the movement of dislocations. In the simplest case the dislocations move along a line through the crystal, which is called slip line. Figure 4.1 illustrates the slip displacement of a dislocation [48]. For the movement of a dislocation from one lattice position to the next one, only the bonds in the vicinity have to be broken. Therefore the energy, necessary for the slip displacement, is relatively small [47] compared with breaking of the atomic bond. Since the movement of dislocation does not alter the crystal structure of the metal, the volume is not affected by this displacement mechanism [49]. The theory of plasticity assumes a macroscopically uniform strain distribution. However, as mentioned above, on microscopic scale the plastic deformation is confined to the slip of dislocations [50]. The force, necessary for the dislocation movement, is anisotropic with respect to the lattice axis. The lowest level of internal forces arises in planes with the highest density of nuclei. The lattice axes of the grains are randomly orientated in the metal. Statistically, the effect of the mentioned anisotropy disappears due to the high amount of grains. As the anisotropy does not affect the macroscopic behavior of the material, the metal properties are regarded as quasi isotropic [47]. Mechanical processes, such as cold rolling, can cause a preferred orientation of the grains, which leads to an anisotropy with respect to the plastic properties.

![Figure 4.1: Slip displacement of a dislocation [48].](image)

The strength of a metal is affected by several effects. With an increasing strain also the density of dislocations is increasing. In this case there is a need for a higher internal force level in order to move the dislocations, as the slip lines are blocking each other. This effect is called hardening. Provided the hardening effect would not exist, the maximum external force which could be applied to a structure would be determined by the force state initializing the dislocation movement. The
initial strength of a metal is also affected by the size of the grains and the presence of foreign atoms. Generally, the grain boundaries are obstructing the movement of the dislocations. The smaller the grains of a constant volume of metal are, the bigger the surface of the grain boundaries is. Therefore the size of the grains affect the slip displacement (Hall-Petch relation [51]). Additionally, the grain refinement also leads to an increased ductility of the material. Foreign atoms, dissolved in the metallic lattice, can also hinder the movement of the dislocations.

4.4 Metallurgy of steels

The remaining part of this chapter will be focused on steels. Iron carbon alloys, which can be forged without any additional treatment are called steels (concentration of carbon $< 2\%$ [52]). Even small variations of the carbon concentration can lead to remarkable changes of the steel characteristics. The crystalline structure of steels depends on the temperature. Some structures are just stable in a specific temperature range [53]. The lattice structures of steel are the cubic centered crystals of ferrite and the face centered crystals of austenite (figure 4.3). The iron-carbon phase diagram (figure 4.2) describes the crystalline structure in dependence on the carbon concentration and the temperature. The diagram is valid for very low cooling rates, which means the system is always in a thermodynamic equilibrium, and in the absence of other alloying elements. For example, if the melt with a carbon content in the range between 0.02\% and 0.8\% is cooled from 1600 degree Celsius to room temperature under the condition of the thermodynamic equilibrium, the austenite, which exists above 723$^\circ$C [47] (figure 4.2), is transformed into a cubic centered lattice. The face centered crystals of austenite can dissolve more carbon atoms than the cubic centered ferrite. The carbon, which cannot be dissolved by the cubic centered lattice, precipitates as cementite and forms a lamellar structure with the ferrite. The characteristics of the ferrite phase are low hardness and high formability, whereas the cementite exhibits a high hardness and brittleness [47]. The phase, consisting of ferrite and cementite, is referred to as perlite. Provided, the cooling rate is violating the thermodynamic equilibrium, the diffusion of the carbon atoms is hinted. In this case a very fine distributed cementite phase is formed, which is also called bainite [52]. At high cooling rates the austenite transforms into a cubic centered lattice and the carbon atoms are trapped, which means they do not have enough time to diffuse out of the crystal structure. This leads to a distorted cubic centered lattice, which is called martensite. The formation of martensite causes a rising strength and mechanical hardness of steel. A side effect is the decreasing formability and the brittle material behavior [53]. In order to reduce the brittleness of martensitic steels, it is possible to perform a heat treatment, which is called tempering. This procedure enables the precipitation of iron carbides, which reduces the distortion of the cubic centered lattice. Finally a steel is obtained, which shows a compromise between a high hardness and an acceptable brittleness. Because of the high cooling rate, martensite is not shown in the iron-carbon phase diagram [54].
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Figure 4.2: Illustration of an Iron-Carbon phase diagram [54].

Figure 4.3: Left: Model of a cubic centered crystal.; Right: Model of a face centered crystal.
4.5 STEELMAKING

The diffusion rate of carbon can be decreased by adding additional alloying elements. As a consequence, the required cooling rate for obtaining martensite is reduced [47]. Alloying elements can also lead to the existence of austenite at ambient temperature and increase the strength of the steel based on finely dispersed carbides [52]. These carbides hinder the movement of the dislocations.

4.5 Steelmaking

The primary source material for the steel production is iron ore, lime and coke. Iron ore, occurring in the nature, is consisting of iron oxides and sulphides ($Fe_3O_4$; $Fe_2O_3$; $FeCO_3$; $FeS_2$), accompanied by other molecules like silicon oxides, manganese oxides and phosphorus oxides ($SiO_2$; $Al_2O_3$; $CaO$; $MgO$; $P_2O_5$) [55]. The conversion of iron ore to raw iron is performed in a furnace and is mainly consisting of the chemical reduction of iron oxides. The coke provides the carbon, which is necessary for the reduction process. Carbon has a higher affinity to oxygen than iron. Hence, the carbon removes the oxygen from the iron oxides. Additionally the silicon oxides, the manganese oxides and the phosphorus oxides are also reduced by the carbon. The sulphur is removed from the iron sulphides by the lime [55]. Finally raw iron is obtained from this process step. Raw iron is used for casting processes and for the steel production. The latter will be discussed in more detail in the next section.

For steelmaking, a converter is charged by hot raw iron. The task of the converter is to reduce the carbon concentration of the raw material. This is done by blowing oxygen into the converter, which leads to a chemical reaction between the oxygen and the carbon of the raw iron. The reaction product ($CO$) is gaseous and leaks out of the converter. The primary metallurgy ends with this process step. Other converters are used for the final composition of the alloying elements and for obtaining extremely low carbon contents, which is called secondary metallurgy. For the subsequent production steps the material is casted and transferred to the hot-rolling mill. If the production process is not immediately continued, slabs are cast.

In the case the hot-rolling process is run based on slabs, it is necessary to heat up the material again. In the hot-rolling mill the material is descaled, rolled for obtaining the desired sheet thickness, cooled and coiled. The result of this production step is referred to as hot-rolled strip. Additionally it is possible to produce hot-dip or electrolytically coated hot-rolled strips, if the material is not cold rolled. The production path of cold-rolled sheet comprises pickling, cold-rolling, annealing, cooling, temper-rolling and coiling. A hot-dip coated sheet is produced based on a modified annealing and cooling operation. Electrolytically coated cold-rolled sheets are made in a subsequent process step.

Hot-rolled strips are usually produced in thickness range of 1.6mm to 6 mm. Instead of cold-rolled sheets the hot-rolled strips tend to shrink and show less accuracy regarding the planarity and the thickness. The advantage of the latter mentioned type of sheet is the lower price as the cold-rolling process is not
required. Cold-rolled sheets are available with a thickness below than 1.6mm.

4.6 Steels for the automotive industry

In the following section, some cold-rolled steel types, for the application in the automotive industry, are discussed (for further details see [56]).

As mentioned above, carbon can be dissolved in the lattice structure of steels. This non stoichiometric compound between the iron and the carbon is referred to as interstitial bond. Steels, which consist of a ferrite structure without any dissolved carbon, are called interstitial free steels (IF-Steels). The structure of these steels comprises extremely small amounts of carbon. In order to remove the carbon from the ferrite structure the steel is alloyed with niobium or titanium. The alloying elements cause the formation of carbides and nitrides. The pure ferrite structure leads to an excellent formability and hardening properties. Furthermore such steels show a high resistance to aging [57]. These steels are applied for geometrical highly complex parts, as door inners or fenders.

In contrast to the IF-steels, the micro-alloyed steels show on the one hand a higher initial strength but on the other hand a lower formability. The reason for the mechanical characteristic of this steel type is the structure, consisting of fine grains and the finely dispersed carbides. Additionally, the amount of carbon is higher compared to IF-steels. The fine grains and the carbides hinder the movement of the dislocations, as discussed above, which finally increases the strengths of the steel. The carbides are formed by alloying the steel with niobium, titanium and vanadium. The fields of application of micro-alloyed steels are structural parts and crash relevant parts.

Lastly, dual-phase steels are discussed in this section, which consist of a martensite and a ferrite phase. Dual-phase steels show a relatively low initial strength, due to the ferrite, and a high tensile strength caused by the martensite. Another property of such steels is high energy absorption capacity, caused by the pronounced hardening effect. During the annealing process in the cold-rolling mill, the steel is partially transformed to austenite. The remaining non transformed phase is ferrite. Subsequently, the steel is fast cooled and the austenite transforms into martensite. Usually, dual-phase steels also contain very small amounts of retained austenite and bainite. Alloying elements like, manganese, chromium, molybdenum, silicon and vanadium are used in order to decrease the critical cooling temperature. The alloying concept has to be adapted to the possible cooling rates of the annealing line, which depends on the cooling facilities, the sheet thickness and the line speed. Hot dip galvanizing is performed during the annealing processes. As such production lines are characterized by a lower cooling rate, the amount of alloying elements has to be increased for suppressing the formation of bainite [58]. Dual-phase steels are used for geometrical complex structural parts and for crash relevant parts because of the high energy absorption capacity.
4.7 Summary

Today, the modeling of the elasto-plastic material behavior of sheet metals at the atomic level is computationally too expensive for industrial applications. Consequently, a suitable approximation of the microscopic level is needed to obtain applicable mathematical formulations for modeling the material response. Thereby, on the one hand a reduction of the complexity of the material behavior is necessary. On the other hand, the dominating characteristic of the material response needs to be reflected by such material models. An introduction of these models is given in chapter 5.2. The above mentioned anisotropy, which is induced by the cold rolling process, is a crucial material property of sheet metals, which are applied for car body parts. This effect also has to be considered by material models, which are used for forming simulations.