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Some mathematical models and numerical simulation of heat treatment of steel

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Steel is an alloy of iron and carbon. Steel used for industrial purposes, has a carbon content up to about 2 wt%. Other alloying elements may be present, such as Cr and V in tools steels, or Si, Mn, Ni and Cr in stainless steels. Most structural components in mechanical engineering are made of steel. Certain of these components, such as toothed wheels, bevel gears, pinions and so on, engaged each others in order to transmit some kind of (rotational or longitudinal) movement. As a result the contact surfaces of these components are particularly stressed. The goal of heat treating of steel is to attain a satisfactory hardness. Prior to heat treating, steel is a soft and ductile material. Without a hardening treatment, and due to the surface stresses, the gear teeth will soon get damaged and they will no longer engage correctly.

In this course, we will be interested in the mathematical description and the numerical simulation of the hardening procedure of a certain workpieces, for instance a car steering rack (see Figure 1). This particular situation is one of the major concerns in the automotive industry. In this case, the goal is to increase the hardness of the steel along the tooth line and at the same time maintain the rest of the workpiece soft and ductile in order to reduce fatigue.

Figure 1: Car steering rack.

Solid steel may be present at different phases, namely austenite, martensite, bainite, pearlite and ferrite. For a given wt% of carbon content up to 2.11, all steel phases are transformed into austenite provided the temperature has been raised up to a certain range. The minimum austenization temperature (727°) is attained for a carbon content of 0.77 wt% (eutectoid steel). Upon cooling, the austenite is transformed back into the other phases (see Figure 2), but its distribution depends strongly on the cooling strategy.

Martensite is the hardest constituent in steel, but at the same time is the most brittle, whereas pearlite is the softest and more ductile phase. Martensite derives from austenite and can be obtained only if the cooling rate is high enough.

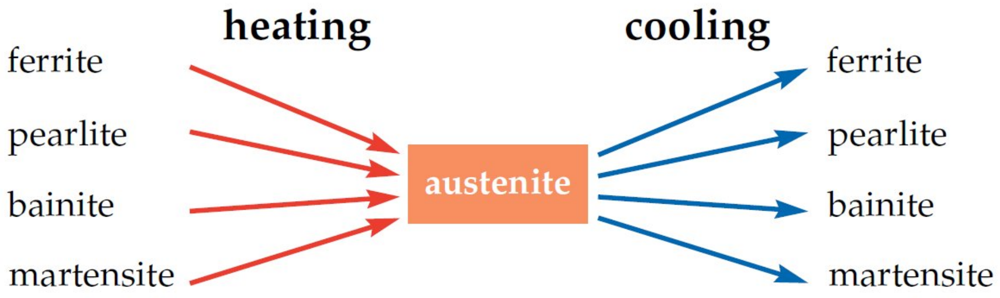

Figure 2: Microconstituents of steel. Upon heating, all phases are transformed into austenite, which is transformed back to the other phases during the cooling process. The distribution of the new phases depends strongly on the cooling strategy. A high cooling rate transforms austenite into martensite. A slow cooling rate transforms austenite into pearlite.

Otherwise, the rest of the steel phases will appear.

The hardness of the martensite phase is due to a strong supersaturation of carbon atoms in the iron lattice and to a high density of crystal defects. From the industrial standpoint, heat treating of steel has a collateral problem: hardening is usually accompanied by distortions of the workpiece. The main reasons of these distortions are due to (1) thermal strains, since steel phases undergo different volumetric changes during the heating and cooling processes, and (2) experiments with steel workpieces under applied loading show an irreversible deformation even when the equivalent stress corresponding to the load is in the elastic range. This effect is called transformation induced plasticity.

The heating stage is accomplished by an induction-conduction procedure. This technique has been successfully used in industry since the last century. During a time interval, a high frequency current passes through a coil generating an alternating magnetic field which induces eddy currents in the workpiece, which is placed close to the coil. The eddy currents dissipate energy in the workpiece producing the necessary heating.

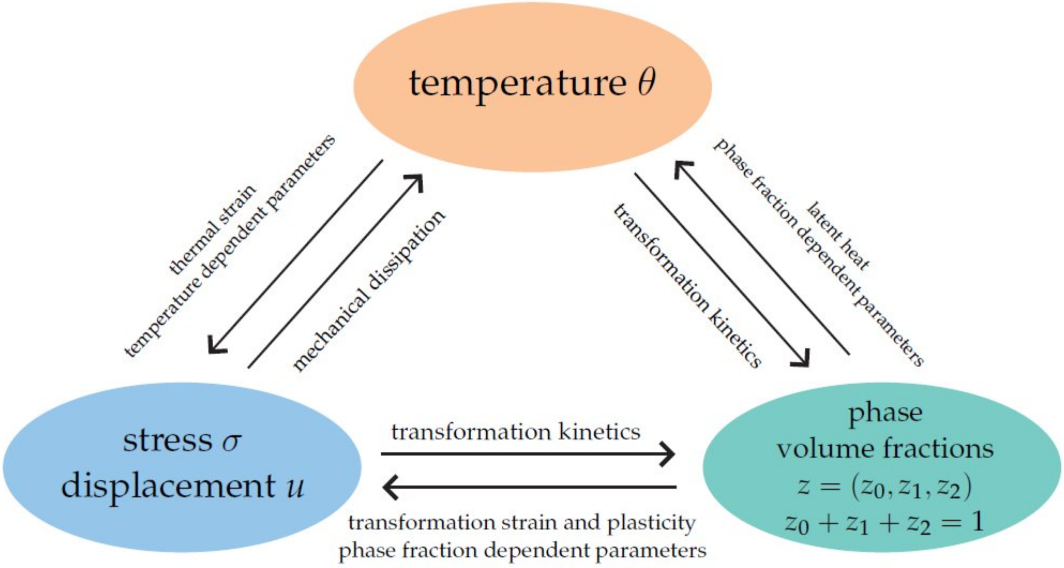

Figure 3: This scheme put in evidence the fact that every physical unknown is coupled to the rest of unknowns. This situation is independent of the industrial heating process, usually by an induction-conduction procedure, and is governed by certain nonlinear coupled PDEs and ODEs.