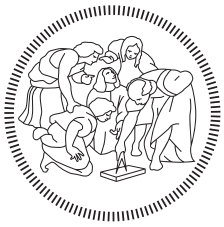

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Failure and Control of metals

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Author's preface

Dear Reader,
I am delighted to present this comprehensive collection of lecture notes for `'Failure and Control of metals'`. These notes have been thoughtfully structured to closely align with the course curriculum, providing an invaluable resource for your studies.

These lecture notes are a culmination of extensive research and diligent note-taking, incorporating insights from professor lectures, course materials, textbooks, and other reputable sources. By bringing together these diverse resources, I aimed to provide you with a well-rounded understanding of the subject matter.

While every effort has been made to ensure accuracy and clarity, it is essential to acknowledge that errors or discrepancies may exist within these notes. The complexities inherent in the subject matter, coupled with the limitations of human interpretation, make occasional inaccuracies unavoidable. Therefore, I encourage you to approach these notes critically, supplementing your understanding with additional academic sources and seeking clarification from your professors or peers when necessary.

I have written these lecture notes using LaTeX, a precise typesetting system widely used in scientific and academic writing. Its utilization ensures a visually appealing and organized document, enhancing the overall readability and accessibility of the content.

I sincerely hope that these lecture notes will serve as a valuable companion throughout your academic journey. They are designed to supplement your learning experience, providing a comprehensive overview of the course material. Remember to approach these notes as a guide, actively engaging in discussions, seeking further insights and embracing the collaborative spirit of academia.

Wishing you success and an enriching learning experience.

Milano, Italy
February 6, 2026

Contents

Part I

Models for material characterization

1 Principles of Fracture Mechanics

To effectively and comprehensively understand the study of material failure, it is necessary to begin by analyzing **fracture mechanics**.

> **Fracture mechanics** allows us to derive an understanding of the propagation of defects within materials, which, if left unchecked, would lead to their failure.
> Additionally, great emphasis is placed on the study of the stresses and deformations that materials undergo when subjected to a load.

Indeed, these elements are crucial both for defining the nature of a metal in relation to fracture and for discerning the safety conditions for it.

1.1 Classification of metallic materials based on the type of fracture

First and foremost, it is possible to classify metallic materials into three categories based on their behavior regarding fracture, namely:

- **Fully ductile metals** → These are metals that require a high threshold of deformation to propagate a defect within them stably and slowly. Therefore, they are more predictable, as they need a continuous increase in applied load to break, and their collapse is preceded by a considerable deformation.
- **Fully brittle metals** → In contrast to ductile metals, these metals have a very low threshold for defect extension within them, and it propagates in an unstable manner. In this case, the situation is more dangerous because there is no need for an increase in load to advance the process, and the fracture is not predictable.
- **Intermediate metals** → These correspond to metals that, as the name suggests, exhibit behavior that is intermediate between ductile and brittle. This is the category to which most materials belong, as it is very rare for a metal to behave in a strictly one-dimensional manner with respect to fracture.

1.2 Notch effect

> Notch effect
>
> The term **"notch effect"** refers to the impact that an anomaly in a material has on the region where it exists when stresses come into play that, due to instability reasons, lead to its propagation.

Naturally, this effect varies depending on the deformation regime under consideration.
Let's consider two examples: the first one applies to the elastic case, referring to brittle materials, while the second one pertains to the plastic case, which is characteristic of ductile materials.

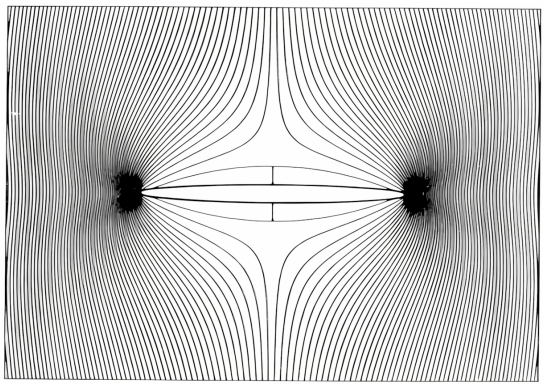

Figure 1: Notch effect

1.2.1 Elastic case

In the **elastic case**, the fracture resistance of a brittle material depends on the cohesive forces existing between the atoms within its crystal lattice. Indeed, the greater this value, the greater their resistance.
Generally, when considering a perfectly elastic regime, we can assert with a good approximation that:

$$R_f \approx \frac{E}{10}$$

where E corresponds to the Young's modulus of the material, which is indeed related to its elastic behavior.

However, this is an approximation because in reality, there are no materials characterized by a completely elastic regime.

> Experimentally, it can be observed that the strength values are much lower than what would be derived from the formula mentioned above. In fact, every material has a specific number of both microscopic and macroscopic defects that intensify the stress value near the tip of the defect.

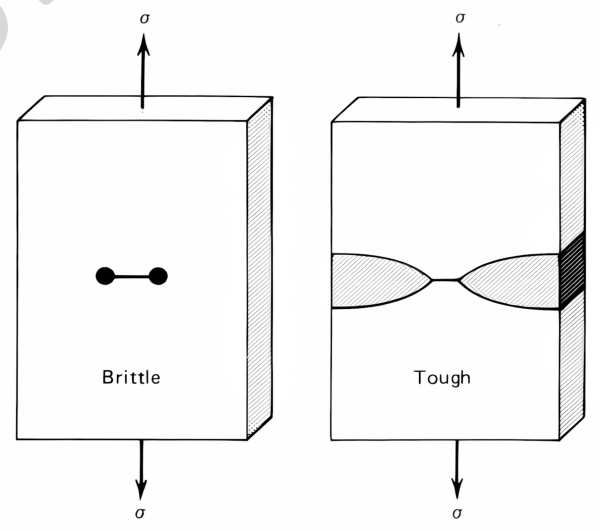

Figure 2: Notch effect in plastically deforming materials

Let us now observe the following figure, which depicts a crystalline lattice subjected to a load:

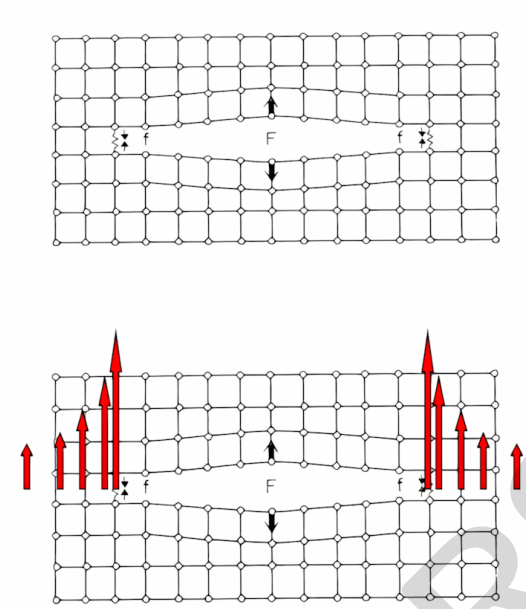

Figure 3: Stress field

and, as one can imagine, upon the application of a given force F, the stress experienced by the material near this crack will be maximum at the tip, which is the weakest point, and minimum at the center of it.

To analyze this phenomenon more effectively, let's consider the following model:

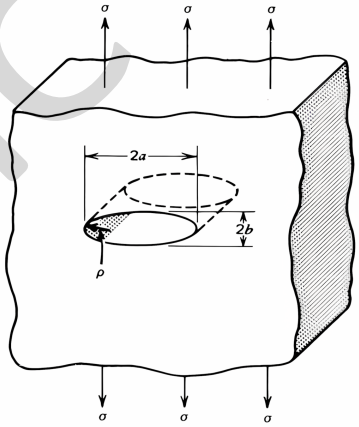

Figure 4: Stress model

which presents a simplified diagram of an infinitesimal element of a material subjected to a nominal stress σ_0, also referred to as σ_{nom}. Inside it, there is a crack with characteristic dimensions $2a$ and $2b$ and a radius of curvature ρ.
The **maximum stress** experienced by the material can thus be calculated as[(1)]:

$$\sigma_m = \sigma_{\text{nom}} \cdot \left[1 + 2\left(\frac{a}{\rho}\right)^{1/2}\right] \approx 2\sigma_0 \left(\frac{a}{\rho}\right)^{1/2}$$

[(1)] As can be observed from the equation provided here, the sharper the crack, the more dangerous the situation becomes.

The approximation presented in the formula is due to the assumption that the crack is long enough and has a very small radius of curvature.

Theoretical Stress Concentration Factor

Therefore, it is possible to define the **theoretical stress concentration factor** as the ratio between the maximum stress experienced by the material and the nominal stress to which it is subjected:

$$K_t = \frac{\sigma_m}{\sigma_{\text{nom}}} \approx 2 \left(\frac{a}{\rho} \right)^{1/2}$$

As can be seen from the expression mentioned above, this value depends solely on the geometry of the defect and is independent of the loading conditions to which it is subjected.

Note

Indeed, stress concentration should always be considered when there are discontinuities in the material, such as defects or impurities, both on the macro-scale and the micro-scale.

1.2.2 Plastic Case

In the **plastic case**, unlike the previous observation, the scenario is different: when the applied stress on the ductile material reaches the vicinity of the crack, there is NO concentration of such an effect. Instead, a plastic flow is established near the apex of the crack, which, ideally, would lead to a uniform deformation (see Figure 2 on the right).

Note

In other words, in the case of ductile materials, the notch effect proves to be negligible.

1.3 Griffith's Theory

Assuming that a metal with perfectly elastic behavior stores elastic energy when deformed, at the moment of defect propagation, two energy contributions can be observed: the first is related to the release of previously stored elastic energy, while the second is associated with the creation of new surfaces as the defect expands within the material.

Griffith's Theory

In this regard, **Griffith's theory** states that in a perfectly elastic material, a defect can propagate only when the elastic energy released during the deformation process is at least equal to the value of the interfacial energy required for the creation of new internal interfaces in the component.

In terms of formulas:

$$E_{\text{e}} \geqslant E_{\text{s}}$$

even though this condition, to be precise, is necessary but not sufficient for the propagation of a defect.

8 Methods for measuring residual stresses

Let's now revisit the main topic and discuss methods for measuring residual stresses within a component. For this purpose, three possible types of approaches exist:

- **Mechanical Methods** → These involve the mechanical analysis of a component, typically through sectioning, to determine the magnitude of the residual stresses originally present
- **Diffraction Methods** → These methods utilize optical techniques to investigate the deformation of the material's crystalline structure
- **Indirect Methods** → In contrast to the two previous approaches, indirect methods involve more sophisticated methodologies that use advanced means to study intrinsic parameters of a material that are modified due to stress

In all the described cases, we are, of course, dealing with macro-scale residual stresses, i.e., Type "I".

8.1 Mechanical Methods

As previously stated, mechanical methods involve destructive analyses conducted by removing material from the component to induce a new state of equilibrium. This process allows for the determination of the initially present stress in the component. The essential tool for performing such analyses is the **strain gauge**. Indeed, the strain gauge is a device that captures deformations in a specific area of the material.

By transferring the collected data to a computer, it enables the derivation of information regarding the residual stress in the material. The simplest experimental test for conducting this type of analysis involves bending a component, from which the residual stress can be calculated in two ways:

- Using the **Stoney equation**, which corresponds to the following formula:

$$\sigma_{\text{res}} = -\frac{4}{3}E \cdot \frac{h^2}{l^2} \cdot \frac{\mathrm{d}g}{\mathrm{d}h}$$

  where E corresponds to the Young's modulus of the material, h is its thickness, l is its length, and g is the deflection that the component exhibits
- by utilizing the data obtained from the **strain gauge**, which is processed to generate a graph illustrating the distribution of residual stress along the thickness of the component

8.1.1 Strain Gauge Drill Method

In the **hole drilling strain gauge method**, a situation similar to the previous case arises, although the obtained data proves to be much more precise. For this reason, it is the most widely used mechanical method overall. Essentially, as implied by its name, a mechanical drill is employed to bore into a specific area of a component where the calculation of residual stress values is intended.

Note

In this case as well, the strain gauge is connected to a computer that processes the data through finite element analysis of the same component, providing an output corresponding to the stress value referred to the exact center of the created hole.

The experimental procedure consists of three main steps:

1. Installation of the rosette, which corresponds to a support mounting multiple strain gauges, allowing the study of the three-dimensional distribution of residual stresses in the designated area

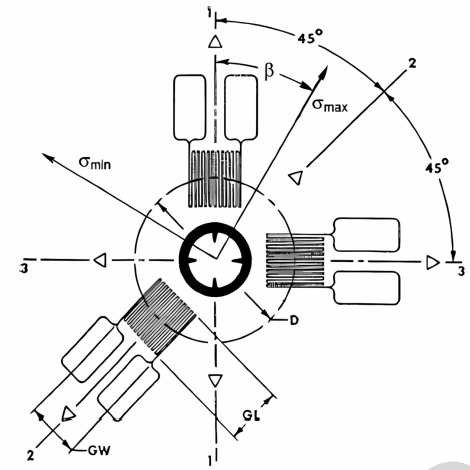

Figure 55

After placing this device, the "zero" is set for the aforementioned instruments.

2. Drilling, where a hole is excavated to a depth of approximately $0.5 - 1\,\text{mm}^3$ at the exact point where the rosette is positioned. This step is particularly delicate as it is crucial to avoid inducing any type of stress in the material, whether thermally (due to friction) or mechanically (caused by the pressure of the machine tip), which could lead to work hardening phenomena

3. Data processing by a computer follows, from which the measurement of the residual stresses $\sigma_{\min}$ and $\sigma_{\max}$, along with their respective orientations in the plane, is derived through finite element analysis

The data obtained from the conducted analysis corresponds to the magnitude of the residual deformation near a specific strain gauge of a rosette, which is then used to derive the aforementioned data.
Let us consider the following schematic representation:

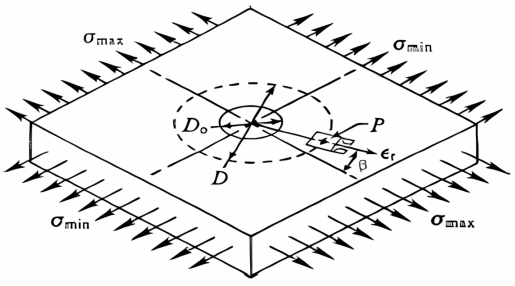

Figure 56

where P corresponds to the point where the measurement of residual stresses is desired, and D_0 is the diameter of the created hole. The **residual deformation**, which is attributed to the relaxation of the component, is defined and calculated as follows:

$$\varepsilon_r = [A + B\cos(2\beta)] \cdot \sigma_{\max} + [A - B\cos(2\beta)] \cdot \sigma_{\min}$$

with β being the angle relative to the direction related to the same parameter, while A and B are two constants related to the elastic behavior of the material, denoted as:

$$A = -a \cdot \frac{1+v}{2E} \quad , \quad B = -\frac{b}{2E}$$

where a and b are two indices dependent on the placement of the rosette.
Since the residual deformation of the material is related to the components ε_1, ε_2, and ε_3 and their respective angles, it will be possible to obtain the sought-after data by applying the following formulas:

$$\sigma_X = \sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{\sqrt{2}}{4B} \cdot \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}$$

$$\sigma_Y = \sigma_{\max} = \frac{\varepsilon_1 - \varepsilon_3}{4A} + \frac{\sqrt{2}}{4B} \cdot \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2}$$

with:

$$\beta = \frac{1}{2} \cdot \arctan\left(\frac{\varepsilon_3 - 2\varepsilon_2 + \varepsilon_1}{\varepsilon_3 - \varepsilon_1}\right)$$

8.1.2 Resistance Strain Gauge

One last aspect that is important to mention within the realm of mechanical methods is the nature of the instruments employed, which can be identified by the **resistance strain gauge model**. This concept justifies the structure of such extensometers, as they contain a cable with a certain resistance through which an electric current flows.

From an electrotechnical perspective, we leverage **Ohm's law** to describe this phenomenon:

$$I = \frac{V}{R}$$

where I is the intensity of the electric current flowing through the circuit, V is the potential difference, and R corresponds to the resistance of the material, which can be calculated as:

$$R = \rho \frac{L}{A}$$

where ρ is the resistivity of the material used as the cable, and A is its area. The formulas presented here are quite useful, as a rosette under the action of a force will deform along different directions[(18)]. Consequently, as the cross-sectional area of the cable decreases, its resistance will increase, and therefore, the current intensity within it will decrease.

Note

In other words, using this type of instrument involves converting the deformation work into a change in the electrical resistance of the device, which is precisely correlated to the presence of residual stresses in a given area of the material.

8.2 Diffraction Methods

Another widely used approach, unlike mechanical techniques, is non-destructive and can be performed directly on components. This approach is based on **diffraction methods**, which leverage optical phenomena to obtain information about the deformed crystalline structure of the analyzed material. This strategy allows for determining the degree of deformation in the material and, consequently, the residual stress within it.

[(18)] For practical reasons, each rosette is sensitive only to a single loading direction. In this case, it is referred to as a "bonded strain gauge".

8.2.1 X-ray Diffraction Method, Uniaxial and Biaxial Cases

The **X-ray diffraction method** is the most widely used diffraction technique, utilizing X-ray diffraction to gather information about the crystal lattice of the material. A crucial aspect of this method pertains to the experimental instrumentation, which involves the apparatus known as a **"diffractometer"** and is configured as follows:

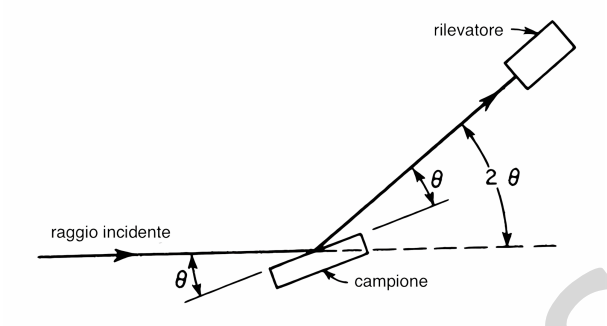

Figure 57: Diffractometer

where it can be noted that there is a source of monochromatic and coherent rays, i.e., rays with the same wavelength λ and the same phase.

> There is a sample to analyze, which can be either a component or a powder. Additionally, there is a movable detector that captures the intensity of the refracted ray as the angle of inclination varies. Furthermore, considering it as a problem related to geometric optics, we also know that when a ray strikes the surface of a component, part of it is absorbed while the remaining part is diffracted.

Consequently, two phenomena related to the **interference** between the light ray and the crystal lattice can be observed:

- Constructive interference, where the diffracted ray has the same phase as the incident ray and carries more energy than the latter
- Destructive interference, in which, unlike the previous case, the diffracted ray is out of phase with the incident ray and therefore carries less energy than the latter

At this point, it is necessary to employ **Bragg's law** (2), which states that if there is constructive interference between a light ray and a medium, and if the incident rays have a certain phase, then all the diffracted rays will also have that phase. Consequently, to meet this condition, the additional path traveled by one ray compared to another must be a multiple integer of their wavelength.

This law, particularly the latter expression, can also be translated into a formula:

$$n\lambda = 2d\sin(\theta) \tag{2}$$

where d corresponds to the interatomic distance of the crystal lattice, and θ is the angle at which a ray is diffracted.

2 Defects from Plastic Deformation

Concluding the analysis regarding solidification processes, let's now discuss **defects from plastic deformation**, which, as the name implies, result from operations carried out under non-ideal conditions.

> These procedures, involving the movement of dislocations within the worked component, are not always executed optimally and can consequently lead to phenomena related to both non-uniform deformation and inconsistent system temperatures. In other words, this type of defect is caused by the presence of a non-dynamic process, which creates complications from a microstructural perspective.

For this reason, these types of defects are easily identified in large-sized components that, due to their volume, are more prone to structural inhomogeneities. In this regard, maps have been created to illustrate the mechanical collapse behavior of materials concerning temperature T and the strain rate $\dot{\varepsilon}$:

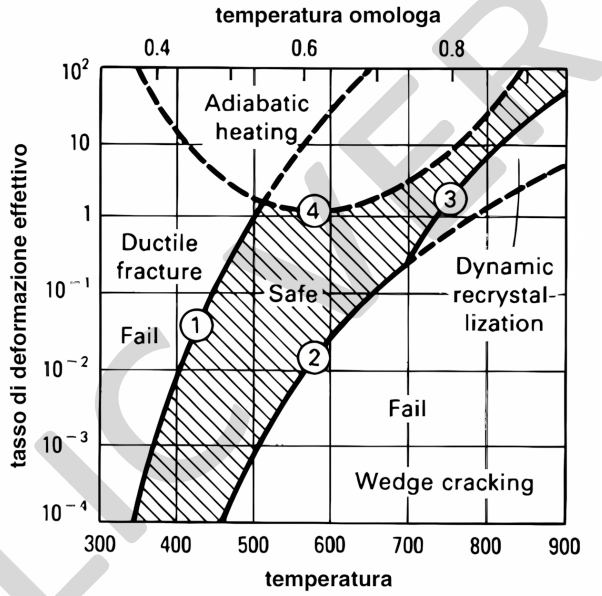

Figure 77

Such graphs (Figure 77), precisely correlating the mechanical strength of a material with its workability conditions, prove to be essential for component analysis.

> They indicate the conditions under which a specific process must be conducted to avoid issues related to fracture.

2.1 Comparison between hot deformation and cold deformation

As we have previously discussed plastic deformations, it is necessary to comprehensively explain the differences between hot and cold processes. First and foremost, the fundamental parameters to consider are **temperature** and the **workability** of the material, while the state of the material becomes a secondary factor influencing the latter characteristic.

Let's consider the following diagram[24]:

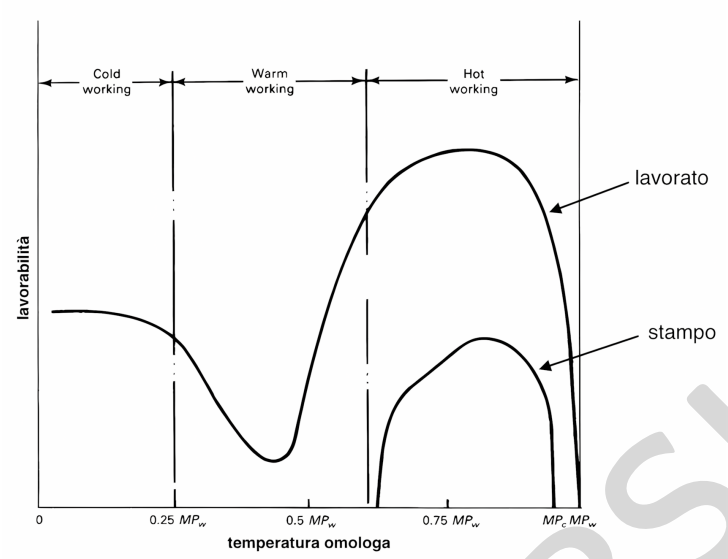

Figure 78

where it can be noted that there are two classes of materials, namely:

- **Cast materials** → These materials exhibit negligible workability, differing from the normal scenarios due to the presence of constituents and segregates that anticipate their effect. Additionally, they possess a rather coarse grain, resulting in increased fragility. However, this parameter can be improved through subsequent processes, extending the workability range and refining the grain structure of the component
- **Wrought materials** → As mentioned earlier, this represents the optimal case compared to the aforementioned conditions. Here, a finer grain leads to enhanced workability and superior mechanical performance of the considered component

Another crucial observation from the above-mentioned graph is the workability ranges, defined based on the temperature at which they occur and correspond to:

- Conditions of **"cold working"** → In this case, cold processes are employed, which are also the most critical as they can induce residual stresses within the component. As we are well aware, these stresses can lead to fracture, even though there is still a moderate workability at such temperatures
- Conditions of **"warm working"** → These are intermediate working conditions where operations take place at a temperature that doesn't fall strictly under either cold or hot processes. Generally, this zone is critical as there is an absolute minimum observed in the workability of the component
- Conditions of **"hot working"** → In this scenario, the processing is carried out at high temperatures. Since mechanisms related to plastic flow come into play, a material becomes highly workable. In fact, the condition of maximum workability can be observed in this case

[24] Obviously, there will be multiple graphs related to the workability of a component. In fact, each diagram is designed for a specific process, and consequently, a material may exhibit different workabilities at the same temperature, depending on the considered metallurgical systems.

Note

In light of the aforementioned, it is easy to understand how both the temperature of the system and the microstructure of the material, especially concerning its internal second phases, play a fundamental role in its workability.

2.1.1 Analysis of hot embrittlement in a material

As mentioned in the preceding paragraph, during conditions of warm working, there is a rapid decrease in the workability of the material, reaching its minimum[25].

This phenomenon is referred to as **"hot brittleness"**, and to analyze it, various tests are conducted on specimens of the same material at different temperatures to evaluate their workability. This phenomenon generally occurs within the temperature range of approximately $700 - 1100\,^{\circ}\mathrm{C}$ and poses significant challenges to the mechanical performance of the material.
Specifically, this effect is crucial in the following instances:

- In continuous casting plants during the straightening of the casting, where compression and tension effects occur on the component within the curvature of the plant. Since the temperature is lower than the entry temperature, cracking may occur internally
- In hot forming processes, where the deformed material may reach a critical temperature, leading to unexpected embrittlement

The occurrence of this phenomenon can be attributed to two main factors:

- **Presence of ferrite** ▸ In the temperature range of $700 - 1100\,^{\circ}\mathrm{C}$, considering steel, we refer to a region of the Fe−C diagram between the fields of $\mathrm{Fe} - \gamma$ and $\mathrm{Fe} - \alpha$, corresponding to austenite and proeutectoid ferrite, respectively. In reality, what is observed is the covering of austenitic grains by a thin layer of ferrite, which is a fragile microstructural constituent. Depositing near the grain boundaries of austenite, it causes localized embrittlement, making the material less ductile.
  This phenomenon is also observable at lower temperatures, where even in the presence of martensite, aggregates of ferrite can be recognized near these grain boundaries.

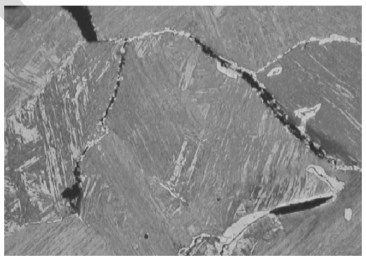

Figure 79

- **Uneven precipitation of fine compounds** ▸ The use of alloying elements such as titanium, niobium, and vanadium is often associated with precipitation mechanisms of second phases aimed at enhancing the mechanical performance of steel.
  However, it can happen that grain boundary deposits are not uniformly distributed, leading to areas deficient in particles of these elements. As evident from this fact, such regions, also referred to by the acronym **"PFZ" (Precipitates Free Zones)**, will be more brittle, thereby undermining the ductility of the material.

[25] From experimental data, it is observed that this issue particularly affects microalloyed steels, namely steels that contain small quantities of alloying elements such as titanium, niobium, and vanadium.

Note

Additionally, nitrogen, like titanium, can pose several challenges as it can lead to the formation of nitrides within the component. In fact, these compounds are highly brittle, and when they combine, for example, with aluminum, these elements can create critical zones in the material's microstructure.

Consequently, to mitigate these issues as much as possible, two temperature-related approaches can be employed: lowering the temperature to increase the amount of ferrite in the medium and thereby make the respective effect less pronounced, or raising the temperature to leverage recrystallization and recovery mechanisms to reorganize the crystalline structure of the medium.

2.2 Defects due to abnormal grain growth

Another highly significant phenomenon in the study of defects from plastic deformation of materials is **abnormal grain growth**. This event, occurring at elevated temperatures, stems from non-uniform grain growth, leading to the formation of grains with much larger dimensions compared to the rest of those present in the material[(26)].

This occurrence implies heterogeneity in the material, both mechanically and in terms of its structure. It is primarily governed by the presence of so-called **"secondary elements"** within a component – small quantities of compounds that regulate the growth and development of grain size in a material.

Indeed, as the concentrations of these elements are stochastic, identical materials often exhibit different grain sizes.

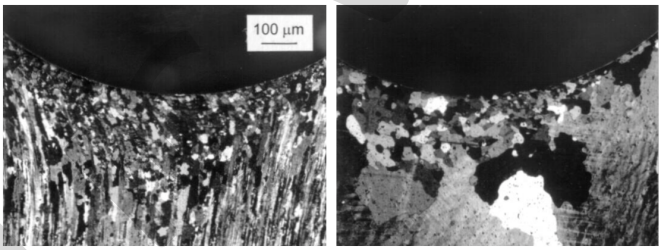

Figure 80

The only way to prevent this problem is to add specific elements to the alloy so that the growth of the crystalline grain can be as homogeneous and controlled as possible.

2.3 Texture defects

Another very important topic concerns the **texture** of materials, which was already introduced in a previous chapter.

In a very general sense, this parameter corresponds to two contributions: the texture, which is linked to the preferential crystallographic orientation of a component, and the fiber structure, which qualitatively expresses the alignment of the microstructure of a material.

In addition to these two factors, a third very important element to consider is **banding**, which corresponds to a possible fiber structure caused by the presence of second phases within a

[(26)] Generally, we refer to grains with dimensions in the millimeter range compared to grains with micrometer-scale dimensions.

medium, which, in most cases, proves to be highly detrimental (a very common case is that of phosphorus-carbon banding).

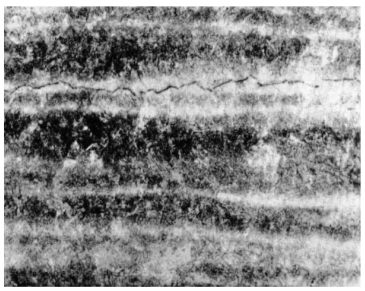

Figure 81: Banding

The main effect observed in materials affected by this type of imperfection is their heterogeneity in terms of mechanical performance. As we have seen, a component tends to exhibit directions where it is more brittle and others where it is more resistant.

Note

However, to address this issue, special attention is required during the molding process. By using molds with serrated shapes, the plastic flow will be much less linear, resulting in a more varied fiber structure and a more homogeneous material structure.

2.4 Defects from plastic flow

In technological processes, it often happens out of necessity that a component is brought to high temperatures for further processing, as in the cases of **rolling** or **extrusion**. During both of these processes, plastic flow occurs within the material, which, as reiterated in the previous paragraph, is dependent on the geometry and structure of the medium.

A common defect encountered in these instances is the so-called **"dead zones"**, referring to the internal regions of the material where plastic flow is hindered, and consequently, deformation is not uniform compared to other parts. Naturally, these regions will be critical from a mechanical standpoint because reduced processing results in an inhomogeneous structure.

2.5 Oxidation defects

During high-temperature metallurgical processes, processed components are often exposed to the **atmosphere**, leading to the phenomenon of **oxidation** on their surfaces. This, caused by the presence of oxygen in the air and not always detrimental, can be considered a problem as the surface oxide layer of the material may be pushed into the material, creating inclusions.

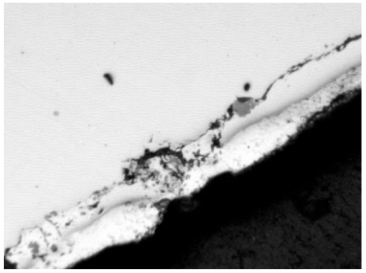

Figure 82

8 Ultrasound Method

Concluding the chapter on the induced current method, we will now introduce the topic of non-destructive testing supported by the use of mechanical waves. The first type of analysis to be addressed in the following chapter is the **Ultrasonic method**, which relies on the use of ultrasonic waves to investigate the internal composition of a material.

8.1 General Principles

> Exploiting the principles of physics to qualitatively describe this approach, we can assert that ultrasonics are **elastic waves** that propagate within a medium through its deformation, specifically the compression and subsequent expansion, of its crystal lattice.

The information obtained from this analysis is derived from the reflection of the signal within the component, and depending on its intensity upon return, it can quantify the difficulty of the traversed path.
These particular mechanical waves, as such, exhibit the following characteristics:

- **Wavelength (λ)** ▸ The distance between successive points of the same phase
- **Frequency (f)** ▸ In the case of ultrasonics, it ranges from approximately 100 kHz to 150 MHz[32]
- **Velocity (v)** ▸ Calculated as $v = \lambda f$
- **Acoustic Intensity (I)** ▸ This corresponds to the average energy carried by the wave

From a graphical perspective, these waves can be defined as sinusoidal functions. However, the mentioned elastic vibrations cannot exist in the absence of matter, and consequently, these waves cannot propagate within a system where a vacuum is present. This is indeed a distinctive characteristic of sound waves, which differ from electromagnetic waves.

8.2 Ultrasound

> As previously defined in the preceding paragraph, **ultrasound** refers to mechanical waves that propagate within a medium, causing elastic deformation of its crystalline structure. Similar to light waves, ultrasound waves are subject to optical phenomena such as reflection, refraction, and diffraction when encountering a defect during their path within a medium.

However, since the solid particles of a component can vibrate along different directions, various types of waves can be defined:

- **Longitudinal waves** ▸ These waves propagate through compressions and expansions along the longitudinal direction of the crystal lattice, corresponding to the same direction of atomic vibration within
- **Shear waves** ▸ Propagating normal to the direction of atomic vibration within the material's lattice
- **Rayleigh waves** ▸ Consisting of elliptical waves that preferentially propagate on the surface of a medium

[32] This data proves to be much higher than the range of frequencies audible to the human ear, which is capable of detecting frequencies in the range of 20 Hz to 20 kHz.

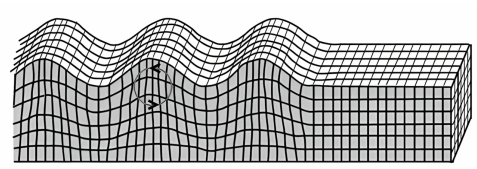

Figure 96: Rayleigh Waves

- **Lamb waves** ▸ Propagating in two normal directions and exclusively associated with thin components

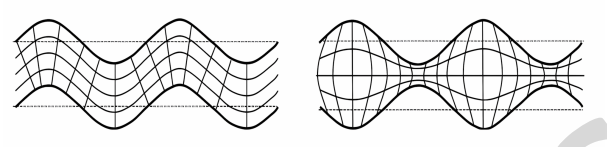

Figure 97: Lamb Waves

8.2.1 Propagation Velocity of a Wave Within a Medium

Depending on the physical characteristics of the material under consideration, ultrasonic waves will propagate within it at different velocities.

Note

Indeed, the mechanical properties of a component are closely linked to its respective crystalline structure, making them a direct measure of this characteristic.

Since we are dealing with vibrations of an elastic nature, in the case of longitudinal waves, we can define the **propagation velocity of a wave** (time of flight) using the following expression:

$$v = \sqrt{\frac{E\,(1-\nu)}{\rho\,(1+\nu)\,(1-2\nu)}}$$

where E and ν correspond, respectively, to the Young's modulus and Poisson's ratio of the material, while ρ is its density.

Naturally, this parameter depends not only on the material considered but also on its state of aggregation. Liquids and solids, in fact, exhibit significant diversity concerning the introduced parameter.

8.2.2 Ultrasound Sources and Probe Materials

The primary sources of ultrasound are **piezoelectric materials** and **magnetostrictive materials**, both defined by their ability to deform in the presence of an electric field and a magnetic field.
Generally, there are two possible working methodologies associated with these materials:

- Induction of a magnetic dipole moment in the medium to which an alternating current with a certain frequency is applied. This current is transmitted as a sound wave with a wavelength comparable to that of ultrasound
- Use of ultrasound to induce a magnetic dipole moment within the material. This corresponds to the opposite case of the previous methodology. In this case, it is as if considering an

electrical circuit with a current generator, where the material serves as a component through which the current passes

Due to these characteristics, these materials are also employed in the fabrication of **probes**, which can operate differently depending on the number of crystals they contain:

- **Transmitting-receiving probes** → These probes contain two crystals that operate independently, where the first generates the signal, and the second receives it. Due to this fact, these instruments are used to detect defects beneath the surface of a component and often have a characteristic inclination

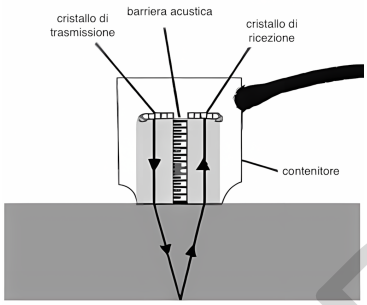

Figure 98

- **Focused probes** → These probes have a single crystal and are used for more specific cases, where the size of their focus varies based on the analysis for which they are intended

Additionally, since these probes must come into direct contact with the material, the so-called **"couplant mediums"** are used to optimize the analysis process.

> These couplant mediums consist of liquids or viscous materials, such as water, oil, gels, or special pastes. They ensure the best possible contact between the probe and the material to be analyzed so that the examination can provide as precise information as possible. The presence of external elements can be highly detrimental to the described analysis.

Therefore, two working methodologies have been devised to ensure the reliability of the results:

- **Immersion Testing** ▸ In this method, both the component and the probe are immersed in the couplant, which often corresponds to water. This ensures optimal contact between the probe and the material
- **Dynamic Application Testing** ▸ This method involves a probe providing a constant supply of the couplant during the analysis, allowing for localized dispersion of this element

8.2.3 Effect of Frequency

The **frequency** is also an extremely important parameter in this context.

Note

Indeed, as the frequency of an ultrasonic wave increases, its sensitivity and, consequently, the resolution of the data derived from it will also increase.

However, this concept is valid only in theory, as in practical applications, secondary signals are often perceived due to metallurgical elements, such as the presence of secondary phases, inclusions, and grain boundary segregations. For this reason, it is advisable to operate at lower frequencies

to reduce the likelihood of encountering these secondary signals that could compromise the quality of the obtained information.

Note

Additionally, it is commonly stated that the minimum observable size by an ultrasonic wave is approximately half of its wavelength.

8.3 Representation of Data for a Component

Now that we have understood the experimental procedure of this technique, let's explore how the data obtained from the conducted analysis can be represented.
There are four types of scans, each defined by a specific resolution regarding the analyzed component:

- **A-scan System (Amplitude):** This is a point-by-point scanning methodology, primarily used for manual analyses. It represents a graph of the wave amplitude over time. The measured parameter depends on the signal intensity, which is closely related to the distance the wave has traveled. This analysis allows determining the presence or absence of a defect at the studied point
- **B-scan System (Brightness):** In this case, the probe is not fixed at a point but is mobile. It is possible to obtain multiple A-scan results and convert them into a single contribution representing a section of the studied component. In this case, time is converted into distance, providing information on both the presence and size of defects within the material
- **C-scan System (Contrast):** This is a B-scan supported by a simultaneous representation of the cross-section studied by the wave. It allows identifying the dimensional depth of the observed defects
- **D-scan System (Depth):** It is a C-scan where the propagation velocity of the wave in the medium is also evaluated. This provides information about the distance at which various defects are positioned relative to the surface of the component

8.3.1 Configurations

Similar to the previous section, let's explore the possible configurations for conducting this type of analysis.
The following options are available:

- **Transmission Method:** Two probes are used, located on opposite sides of the component to be analyzed
- **Reflection Method:** A single probe is employed and placed on the surface of the medium
- **Echo-Pulse Method:** This method uses a single probe on the surface of the component, measuring the intensity of the reflected ultrasonic wave
- **Multiple-Echo Method:** Similar to the previous method, with the only difference being that, in this case, the propagation velocity of the wave is evaluated over a more extended path