DESIGN OF PIECES TO BE SUBMITTED TO HEAT TREATMENT: CONCEPTS, PRINCIPLES AND RECOMMENDATIONS.

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Abstract: This paper describes technological aspects regarding the design of pieces to be heat treated. Brief concepts are described relating to the importance, application, typology and stages of the process. The focus of the paper is to present check lists and directories, principles and recommendations to be considered regarding pieces submitted to heat treatment, such as, the selection of the right heat treatment, geometry and finishing care and the control of the heat treatment stages. This information was collected through interviews with professionals and specialists in the area and through bibliographical research. By means of case studies it was verified that these principles and recommendations help to prevent the occurrence of flaws in pieces that require heat treatment, increasing the quality and reliability of the systems.

Keywords: production design, heat treatment, principles and recommendations.

1. Introduction

Although there is a great diversity of construction materials, in the area of mechanical engineering, with infinite properties, the fabrication process does not always give us the desired conditions, that is, no residual stress and some resistance. Thus, in order to increase the field of application of the materials, the process of heat treatment is used to modify mechanical and structural properties.

According to Chiaverini (1988), heat treatment is the group of heating and cooling operations that materials are submitted to, under controlled conditions of temperature, time, atmosphere and cooling velocity, with the objective of modifying their properties or rendering them certain characteristics.

The main objective of any heat treatment is to modify the mechanical and structural characteristics of materials according to their applications. Chiaverini (1988) and Colpaert (1974) cite the following specific objectives of heat treatment:

- Remove internal stress;
- Increase or decrease hardness, and consequently mechanical resistance;
- Improve ductility and heat resistance;
- Improve machinability and formability;
- Improve corrosion and wear and tear resistance;
- Improve cutting properties;
- Modify electrical and magnetic properties.

However, for these objectives to be attained, the crystalline structure of the material needs to be modified by means of a heat process. Heat treatment consists of three stages: **heating, temperature hold time and cooling.**

Heating consists of increasing the temperature of a material to the point that there is a change in its crystalline structure. This can be carried out in ovens, by induction, by flames or using other specific processes. The **temperature hold time** is the homogenization of the temperature at which the crystalline structure changes. The **cooling** stage consists of reducing the temperature of the heated material to the environmental temperature. The cooling stage is extremely important because it defines the final characteristics of the material. Lots of means are used for cooling the material, such as: water, oil, cast salts, air, ovens, salt solutions and polymers, among several others. The cooling and heating rates have a great influence on the final characteristics of the crystalline structure of the material.

All of the stages of any heat treatment vary according to the kind of treatment to be employed, the chemical composition and microstructure of the material, the shape and dimensions of the piece and the technical objectives to be achieved. Figure 1 shows the behavior of the microstructure of a material during the three stages of a certain heat treatment, under controlled conditions of time and temperature.

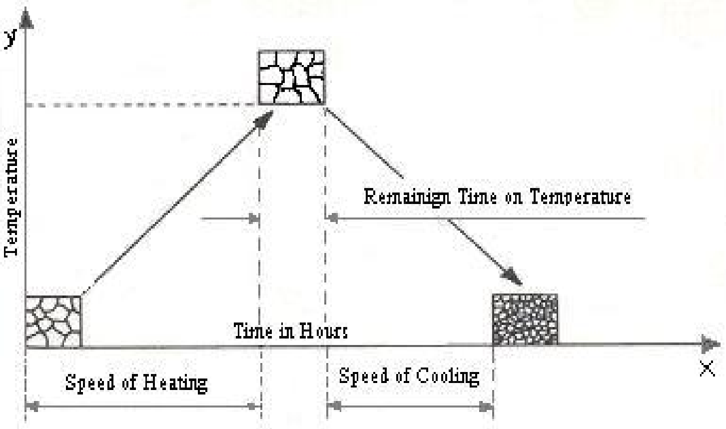
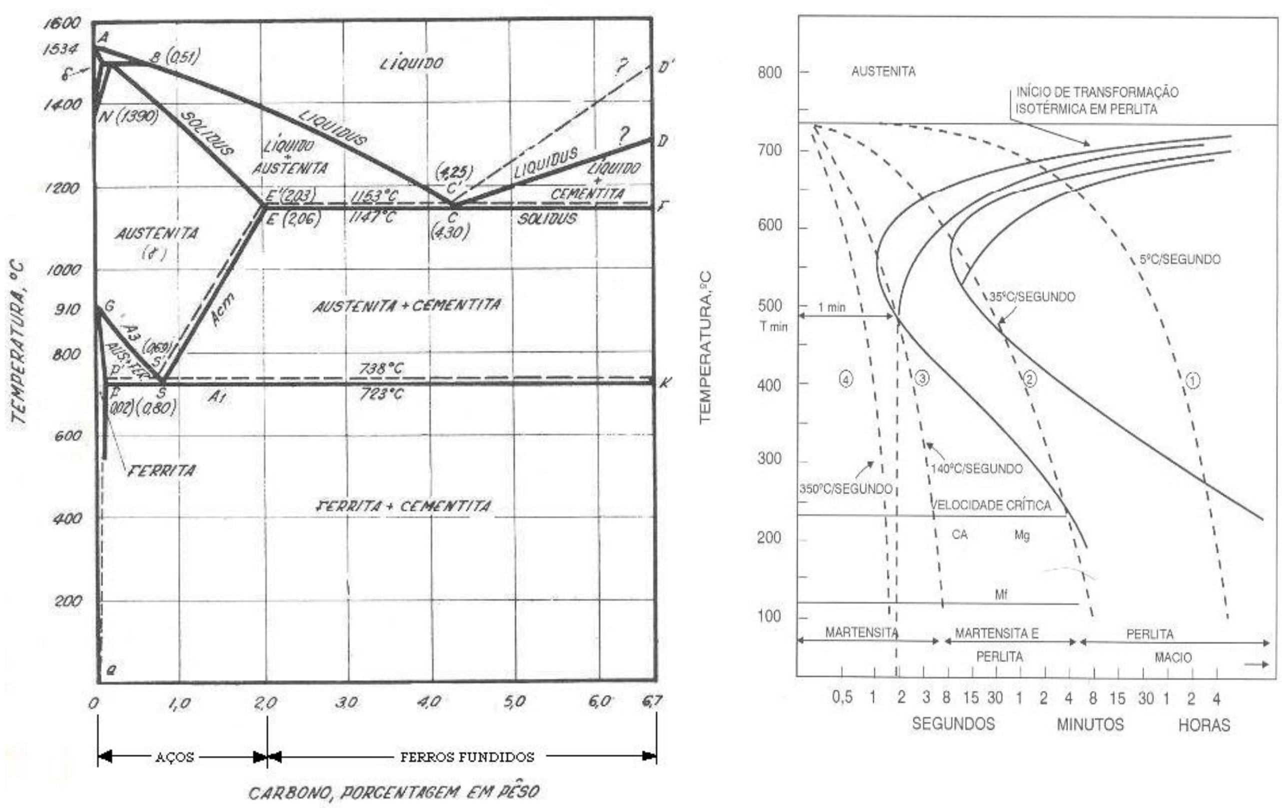


Fig. 1 - Stages of Heat Treatment (CHIAVERINI, 1988).

The characteristics and microstructural changes of steel and cast irons, as a function of time, temperature and carbon percentage, are illustrated in the Carbon-Iron Phase Diagram, Figure 2(a), and in the TTT Diagram (Temperature, Time, Transformation), Figure 2 (b).

The Carbon-Iron Phase Diagram (Fe-Fe_3C) indicates the type and the behavior of the crystalline structure of a steel or cast iron, as a function of the temperature and the carbon percentage of the material. For example, if a steel with 0.45%C is heated from 25ºC to 900ºC, the crystalline structure is transformed from ferrite + pearlite to austenite.

The TTT Diagram indicates the effects of cooling rate on the transformation of the crystalline structure of a metal, with a logarithmic scale for time. For the same example (steel with 0.45%C), when cooled from 900ºC to 25ºC, in a time period of 10 seconds, its structure will be transformed from austenite to martensite. However, if the cooling process takes a few hours, its structure will revert to ferrite + pearlite.



(a) (b)

Figure 2. Carbon-Iron Phase Diagram (a) and TTT Diagram (b) for eutectoid Steel (CHIAVERINI, 1988).

More information on the behavior of the crystalline structure of steel and cast iron, along with concepts regarding the diverse types of crystalline structures, can be found in Smith (1993), Chiaverini (1986) and Colpaert (1974).

In Chiaverini (1986), Colpaert (1974), Senai (2000) and Villares (1993), the heat treatments are divided into two groups: thermophysical treatments and thermochemical treatments. The thermophysical treatments modify the crystalline structure of a material, and consequently its mechanical properties, only through variations in its temperature. The most common thermophysical treatments used are: normalizing, annealing, hardening and tempering. The thermochemical treatments modify the structure of the materials by means of heat variation combined with the addition of chemical elements on the superficial layer of the materials, for example, nitration and carburizing.

Nowadays, the increasing need to improve the physical, chemical and structural properties of materials has encouraged the development of new technologies and types of heat treatment. These include: Carbonitriding, Austempering, Austenitizing, Patenting, Cyaniding, Artificial Aging, Martempering, Laser Beam Hardening, Electron Beam Hardening and Induction Hardening. Further details about these technologies and the heat treatments cited above can be found on the CIMM and Brasimet sites and in the literature cited herein.

However, to reach the objectives of the different types of heat treatment and consequently guarantee the quality and reliability of the heat-treated pieces, and also a reduction in the costs of the process, a few precautions are necessary and technical specifications on the design of the pieces need to be detailed. In compiling specific information relating to these processes, the focus will be the principles and recommendations to be considered in the designing of pieces to be submitted to heat treatment. Cases studies on changes in the design of pieces submitted to heat treatment will then be demonstrated.

2. Principles and recommendations for design of pieces submitted to heat treatment

Drawing on Callister (2000), Chiaverini (1986), Colpaert (1974), Mangonon (1999) and Villares (1993), along with interviews carried out through specially prepared questionnaires and with professionals from a few companies which provide heat treatment services, a few principles and general recommendations were proposed for the design of pieces to be submitted to heat treatment. These will be presented in check lists and directories on which to base the selection of the most appropriate heat treatment, and the precautions necessary regarding the geometry and finishing of the pieces and the control of the heat treatments stages.

2.1. Basis for the selection of the right heat treatment

The selection of an inappropriate heat treatment for the design of a certain piece can cause incalculable damage to a company. This adverse consequences may occur at any stage from the fabrication (processing and material waste) to the use the piece (functional reliability and safety). Therefore, for the selection of an adequate heat treatment it is suggested that the following questionnaires are answered and analyzed:

a) What kind of mechanical solicitation is applied to the piece?
- Static, dynamic or combined.

b) What are the required mechanical, chemical, physical and/or fabrication properties of the piece?
- Tensile strength, compression resistance, impact resistance, shear resistance, flexibility, strength, among others;
- Machinability, conformability and weldability.

c) In which kind of physical or chemical environment will the piece work?
- Abrasive, corrosive, erosive, high or low temperatures, among others.

d) What are the goals to be obtained with the heat treatment?
- Value of the required resistance or final hardness of the piece.

OBS: a higher hardness value indicates greater mechanical resistance of the pieces, but less resistance to impact. Lower hardness values indicate greater malleability, making conformation and machining easier .

e) In which part of the piece is it desirable to have this level of resistance and hardness?
- The whole section, only on the solicited surface.

f) What material is or will the piece be made of? What is it's commercial class, name and chemical composition?
- The chemical composition of the material influences the kind of heat treatment to be applied, based on the stages of the process;
- The quality of the material of the piece must be controlled. For an example, the presence of a alloying elements such as phosphorus or sulfur in the steel above normal standards, causes non-uniform heat treatment of the piece.

OBS: The adequate selection of materials in the product design stage is of great importance to the performance of a product.

g) How many heat treatments will be necessary?

The number of heat treatments depends on the material, the fabrication process and the geometry of the piece. For example, for the manufacture of razorblades made out of ABNT H13 steel, three heat treatments are required, in the following order: annealing (before and after being machined, to relieve stress), hardening (to increase hardness, appropriate for the cutting capacity of the razors) and tempering (to relieve superficial stress resulting from the hardening and increased impact resistance).

One of the main causes of flaws in heat treated pieces is the lack of a complementary heat treatment, for example, tempering after the hardening. Further information on the number of heat treatments necessary for each material can be found in the specifications of the material manufacturers.

h) Based on the quality and the cost limit for the process.

2.2. Precautions with the geometry and finishing of the pieces

The precautions with the geometry and finishing are essential for the fabrication of pieces with quality and reliability, because they prevent the development of flaws like trines, breaks and deformations. The main precautions are:

- Avoid sharp edges since they generate accumulative stress points. Rounded edges are recommended with a minimum radius of 1 mm;
- Avoid having holes near each other or near edges;
- The hole diameter must be larger than the depth;
- For pieces which need slots, the width of the slot must correspond to at least three times the depth;
- The pieces dimensions must be above the nominal dimensions, for the following cases:
  - ✓ In cases where the final finishing of the piece is necessary (e.g. rectified or polished);
  - ✓ To compensate for thermal deformations;

OBS: Avoid dimensions greatly above the nominal dimensions, because this can result in damages to the heat-treated surface, mainly when the final finishing is executed.

Figure 3 illustrates some precautions which must be considered in the geometric conception of the piece.

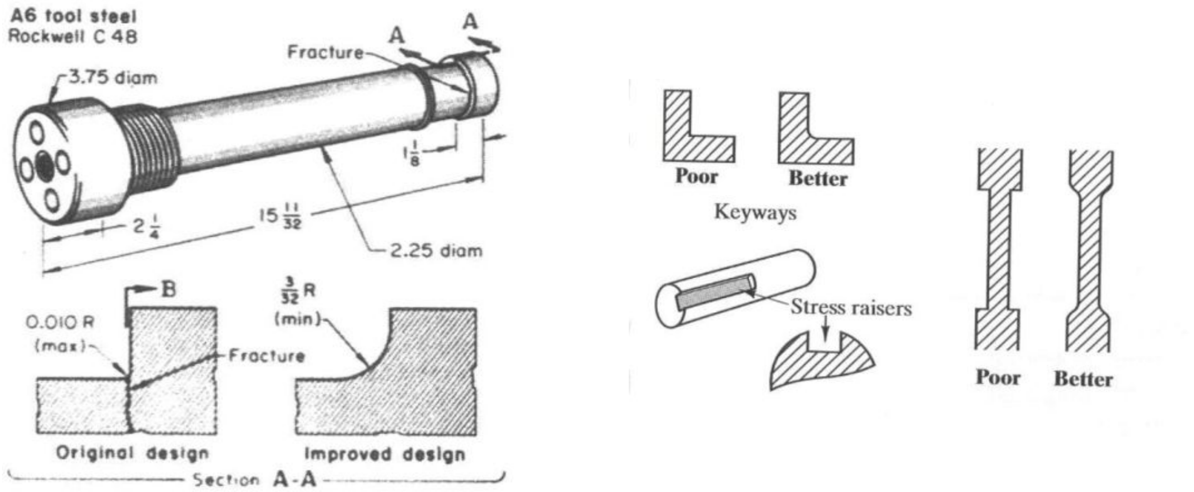


Figure 3. Defects and improvements in the piece geometry submitted to heat treatment (MANGONON, 1999).

- The roughness also greatly influences the quality of the pieces to be heat treated. A medium roughness (Ra) greater than 2.0 µm provokes accumulation of superficial stresses in pieces submitted to heat treatments like hardening or cementation.

2.3. Control of the of heat treatment stages

The good performance of a piece doesn't only depend on the selection of the appropriate heat treatment and of the precautions taken with regard to the geometry and finishing of the piece, but also on the control of the heat treatment stages. The good control of all the stages is the best way to guarantee the goals of the selected process. Some precautions regarding the stages of the heat treatments are described below.

a) Precautions with the heating:

- The pieces must be free of, for example, dirt, oils, greases, cutting flaws originating from the machining. Such residues adhering to the piece hinder the proper functioning of the heat treatment stages, mainly that of cooling;
- The heating must be gradual rather than fast. If the heating is excessively fast, fissures or deformations can appear in the pieces, due to the residual stresses resulting from previous processes;
- The piece must be heated in a uniform way;
- The heating temperature doesn't depend exclusively of the type of heat treatment, but also of the chemical composition of the material.

b) Precautions with temperature hold time.

- The length of time for which a piece remains at a treatment temperature is determined according to the type of heat treatment, the piece geometry and the material;
- If the temperature hold time is higher or lower than designated, the goals of the heat treatment, and consequently those of the design, won't be reached with success. Thus, problems appear, such as the continued presence of austenite, and the non-uniformity of the hardness of the piece;

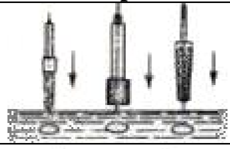
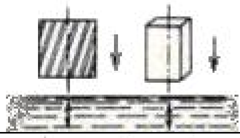
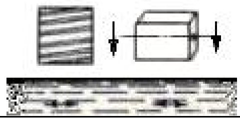
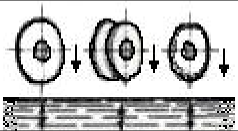
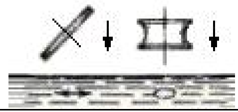
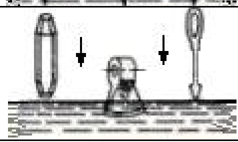
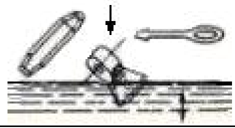
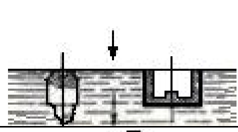
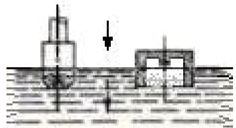
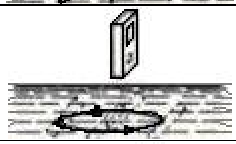
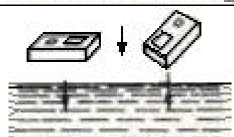
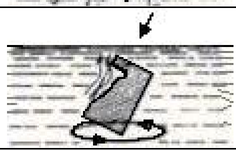
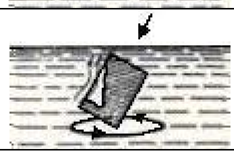
• Whenever possible, a protecting atmosphere for the pieces must be used when a temperature hold time greater than 1 hour is required. The purpose of this protection is to minimize or even eliminate the action of oxygen on the piece, in other words, to avoid the occurrence of phenomena such as decarburization and oxidation.

c) Cooling Precautions.

- The amount of cooling fluid must be sufficient to guarantee a uniform cooling of the pieces;
- The type of cooling fluid must be selected according to the material of the piece;
- The pieces must be agitated when submerged in the cooling fluid, to ensure a uniform cooling;
- The temperature of the cooling fluid must be defined and controlled during the process;
- The piece must be gradually, rather than suddenly, submerged in the fluid;
- The cooling must be carried out according to the type of heat treatment, material and geometric form of the piece.

In the Table 1, the correct forms of submersion of the pieces in the cooling fluid are illustrated.

Table 1. Precautions for the cooling of pieces during the heat treatment process (YOSHIDA, 1985).

Types of Pieces	Correct position	Incorrect position
Long pieces, like drills and machining tools.		
Cylindrical pieces or blocks		
Pieces in th3 form of disks, like gears.		
Punches, nails or keys.		
Stamping punctures.		
Small stamping tools.		
Matrixes		

• The instruments used for the control of the heat treatment stages, such as thermometers and hard-meters, they must be regularly calibrated.

3. Cases Studies of the alteration in the design of pieces submitted to heat treatments

In this section two cases studies of pieces submitted to heat treatment will be presented . The first case considers a gear with helical teeth used in a speed reduction system. The second case considers a cutting tool used in a motorized manual weeder. Both pieces presented flaws when used to carry out their main functions.

The case study problems were presented by companies in the mid-west of Santa Catarina. At the request of these companies, and for legal reasons, their names are not mentioned here.

The proposals for improvements in the design of the pieces considered in Case 1 and Case 2 were based on the principles and recommendations for the design of pieces to be submitted to heat treatment presented in Item 3 of this paper. Some of the goals mentioned in the cases studies were taken from Chiaverini (1988), Colpaert (1974) and Villares (1993).

3.1. CASE 1: Gear of helical teeth:

Situation presented:

- **Failure type:** trine in the longitudinal section that propagated obliquely from the cotter channel to the extremity of the tooth, according to Figure 4.
- **Material of the gear:** Steel SAE 8620.
- **Type of heat treatment**: Solid cementation in box, for 4 hours and cooling in oil.
- **Superficial hardness:** 65 HRC.

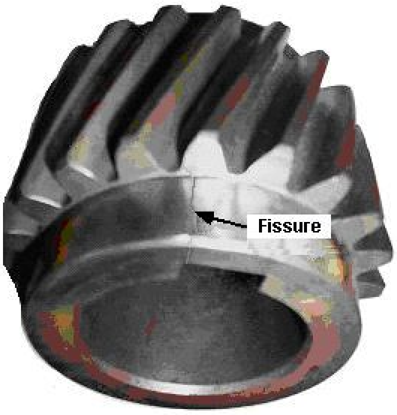


Figure 4. Gear with helical teeth showing failure (collected in the field).

Analysis of the design and proposals for improvements: some parameters to be considered in the gear design were defined.

- **Solicitations and applied forces:**
  - ✓Combined solicitations - static and dynamic;
  - ✓High torque, flexing and impact forces;
  - ✓Effect of sliding between the gear teeth surfaces, resulting in high levels of friction and subsequent wear.
- **Environment:**
  - ✓Environmental factors do not affect the gear functioning.
- **Objectives to be reached:**
  - ✓Torque and flexing resistance;
  - ✓Resistance to wear. The superficial hardness of the gear should ideally be between 55 and 60 HRC. A hardness of 65 HRC provoked the accumulation of stresses in the gear, thus facilitating the formation of trines;
  - ✓Impact resistance: thus the nucleus of the gear must be strong. Ideally, the gear nucleus hardness should be between 35 and 40 HRC.
- **Material of the gear:**
  - ✓According to the steel manufacturers, the steel SAE 8620 is considered ideal for such applications. Therefore, the material won't be modified.
- **Heat treatment required:** according to the catalog of the material (GERDAU, 2003), and given the tool type and material, the following heat treatments are recommended:

1º Solid cementation at 900 ºC for 4 hours with cooling in a protected atmosphere.
2º Hardening at 850 ºC, temperature hold time according to the thickness of the gear and cooling in oil.
3º Tempering at 250 ºC, according to Figure 5, to reach the ideal superficial hardness (55 to 60 HRC) and to relieve the superficial stresses due to the hardening. The temperature hold time must be 15 hours, with cooling in a protected atmosphere.

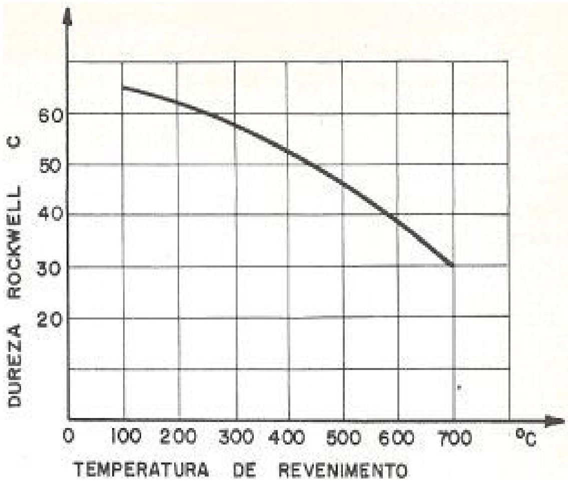


Figure 5. Diagram of Tempering for the Steel SAE 8620 (VILLARES, 1993).

- **Precautions regarding the geometry and finishing of the gear:**

It can be observed in Figure 4 that the gear has some accumulated stress points, such as, the acute chant and the high roughness in the cotter channel. With the objective of inhibiting the formation trines in the gear, the roughness must be reduced and the acute chant in the cotter channel eliminated.

- **Control of the heat treatment stages:**
  - ✓Precautions regarding the gear cooling , as seen in Table 1;
  - ✓Control of the temperature hold time.

3.2. CASE 2: Cutting tool for motorized manual weeder

Situation presented:

- **Failure type:** trines and breaks in the traverse section of the cutting tool, as shown in Figure 6.
- **Type of heat treatment**: Hardening with cooling in oil.
- **Material of the cutting tool:** Steel SAE S1 (steel chrome-tungsten-molybdenum).
- **Superficial hardness:** 60 HRC.

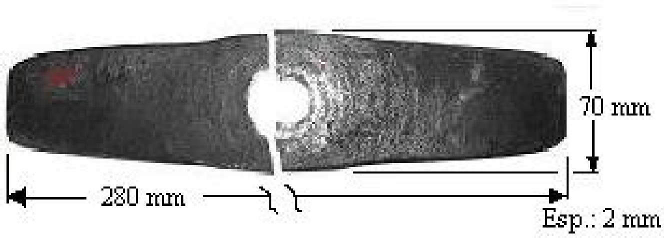


Figure. 6. Broken cut tool (collected in the field).

Analysis of the design and proposals for improvements: some parameters to be considered in the of the cutting tool design were defined.

- **Solicitations and applied forces:**
  - ✓Combined solicitations - static and dynamic;
  - ✓High impact for flexing forces.
- **Environment**:
  - ✓Suffers impact with several objects, such as stones and tree stubs.
- **Objectives to be reached:**
  - ✓Due to the impact for flexing, it must present strength and elasticity. Thus, the superficial hardness of the cutting tool must be between 45 and 55 HRC. At a hardness of 60 HRC the cutting tool became fragile when it was submitted to the impact forces.
- **Material of the cutting tool**:
  - ✓According to the steel manufacturers, Gerdau (2003), the steel SAE S1 is considered ideal for such an application. Therefore, the material won't be modified.
- **Heat treatment required:**

1º Hardening at 850 ºC with slow heating and cooling in oil in the position indicated in Table 1.

2º Tempering at 350 ºC, according to Figure 7, to reach the ideal superficial hardness (45 to 55 HRC) and to relieve the superficial stresses due to the hardening. The temperature hold time must be 1.5 hours, with cooling in a protected atmosphere.

- **Control of the heat treatments stage:**
  - ✓ Precautions regarding the cooling of the gear, as shown in Table 1;
  - ✓ Control of the temperature hold time.

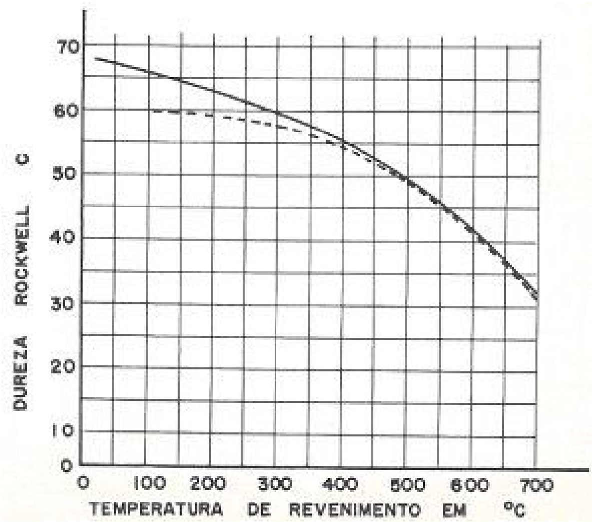


Figure 7. Diagram of tempering for the Steel SAE S1 (VILLARES, 1993).

4. Conclusions

The performance of a piece is directly related with the selection of the appropriate heat treatment, the functional and geometric analysis of the piece, the selection of the appropriate material and the control of the stages of the process applied.

This paper highlighted information on these aspects and thus, together with the case studies presented, it is expected that the principles and recommendations will lead to an increase in the quality assurance and reliability of the components that require heat treatment.

This study provides a concise and specific research source for engineers. It is recommended that more research be carried out on this theme, along with further validation tests, with the objective of developing a systematic or a method for the design of pieces to be submitted to heat treatment.

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