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# ANALYSIS OF SOME STEEL BEHAVIOUR AT HIGH OPERATING TEMPERATURES

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**ABSTRACT**: An important consideration at high temperatures is that creep strength is usually the primary dimensioning factor. This means that by choosing the right material, we not only extend the lifetime of steel's application, but can also specify a thinner material for overall savings in cost.High temperature austenitic steels are commonly employed in a number of applications where the temperature exceeds 550°C. Moreover, ferritic steel grades are best suited for temperatures between 550°C and 850°C, but the higher alloyed grades can be applied at temperatures up to 1150°C too. Due to their structure, the ferritic steels show lower strength at temperatures exceeding 600°C, but are more resistant to thermal shocks than high temperature austenitic stainless steels.The paper deals with some steel grades intended for machine parts which work at high operating temperatures. It has been found that, for operating temperatures higher than 800ºC, the best results are obtained for austenitic stainless steel grades containing more than 18% Chromium and 8-10% Nickel. Also, we are making clarifications regarding their structure.

**Keywords**: high operating temperatures, steel grades, operating requirements

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## 1. INTRODUCTION

The name "high operating temperatures" is involved in many types of operations in numerous industries. Some of the most common examples of machines operating at high temperatures are the steam boilers, gas and steam turbines, tanks for crude oil and tar distillation, containers for oils hydrogenation, heat treatment furnaces and parts for diesel engines, or other internal combustion machines.

For using under unusual conditions, we can make a change in the chemical composition for a better adaptation to the operating conditions. However, in some cases, certain combinations of alloys must be developed to meet the operating requirements. For example, the aviation and aerospace industries encountered design problems of greater complexity, requiring high temperature resistant alloys either for installations or strength constructions.To meet these requirements, new types of steel have been developed and are currently made. [1, 2]

The steel grades for valves, the hot work die steel and some alloy steel grades for tools are used at high temperature, but these ones are included in special categories.High-alloyed austenitic stainless steels differ substantially from more conventional grades with regard to resistance to corrosion and, in some cases, also mechanical and physical properties. This is mainly due to the high contents of chromium, nickel and molybdenum. High-performance austenitic grades are available for a wide range of process conditions, providing the right protection against corrosion, material deterioration or maintenance need. They have good weldability and excellent formability. High temperature ferritic stainless steels have broadly the same mechanical properties as their austenitic counterparts at room temperature. However, when subjected to high temperatures (>600°C), it is possible for the creep strength to drop to just a quarter of the value an austenitic heat resistant steel would show in the same environment.

Materials are selected on the basis of service requirements, notably strength, so corrosion resistance (stability) may not be the primary design consideration. Assemblies need to be strong and resilient to the unique loads and stresses imparted on them, which can include significant temperature changes and thermal gradients for many high-temperature applications. Moreover, it is necessary to know what materials are available and to what extent they are suited to the specific application. The decision is quite involved and the choice is significantly affected by the environment and the intended use. The user or designer needs to properly understand that the environment dictates the materials selection process at all stages of the process or application.To provide as optimum performance as possible, it is necessary for a supplier to be aware of the application, and for the user to be aware of the general range of available materials. Otherwise, severe problems can result.

## 2. ANALYSIS AND EXPERIMENTS

The steel grades included in the above mentioned category are used in large quantities for the construction of machinery able to operate under high temperature stress, in which the creep property interferes. Although the plain carbon steel has a creep limit below the alloy steels used at high operating temperatures, it is largely used in case of operating conditions up to temperatures of about 550°C, after which the rapid oxidation begins; therefore, it is still necessary to use a chromium steel grade. The low-alloy steel grades containing small percentages of chromium and molybdenum have a creep limit higher than the carbon steel, and that's why they are used to obtain more resistant materials.

At temperatures above 550°C, the percentage of chromium necessary to provide adequate oxidation resistance to the steel increases rapidly. The steel grades containing 2% Cr and addition of molybdenum are used up to temperatures of 620°C, and those containing 10-14% Cr can be used up to about 700-760°C. The austenitic stainless steel grades with 18% Cr and 8% Ni are usually used at higher temperatures, their resistance to oxidation being considered appropriate up to about 820°C. The steel grades containing 25% Cr and 20% Ni or 27% Cr are used for operating temperatures of 820-1100°C.

Figure 1 shows the creep limit of several industrial stainless steel grades, compared with that of the carbon steel. We can see that the creep limit of the austenitic stainless steel grades is higher than the creep limit of the ferritic ones, and that this property is not influenced by the additions of chromium and silicon. However, the molybdenum, niobium and tungsten have a pronounced effect.

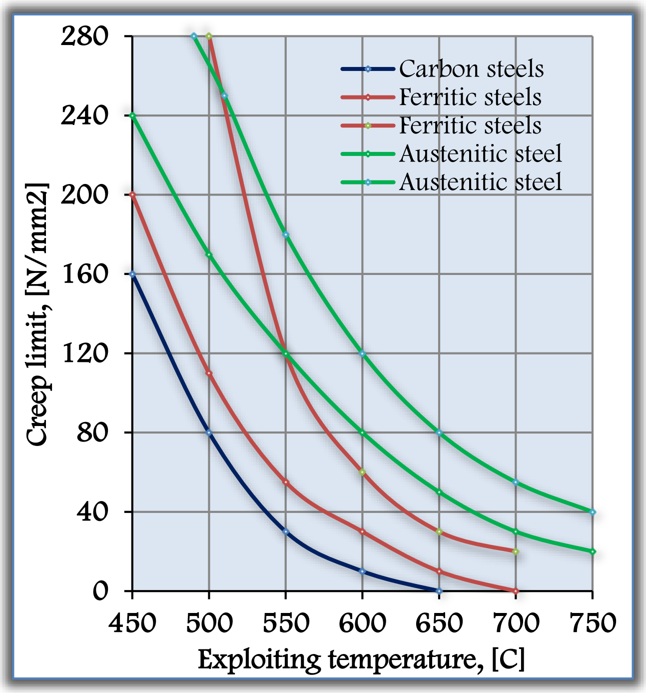


**Figure 1**. Creep limit of several industrial stainless steel grades, compared with that of the carbon steel, at different exploiting temperatures

### 2.1. Analyses and experiments on ferritic steel grades

The most common and widely used type of steel is the ferritic steel grade with 0.12% C and 14-18% Cr, which can be used in operation up to temperatures of about 850°C. The higher chromium content provides to this steel grade a corrosion resistance higher than that of the martensitic ones and, in addition, this material can be drawn, formed and even welded by using appropriate methods. It is widely used for decorative items in architecture and automotive manufacturing industry. Due to its resistance to nitric acid, this type of steel is used for the manufacture and transportation of this acid. Its creep limit is not very high, but the steel is adequate for some applications in operating conditions up to 820°C, such as manufacture of combustion chambers for household ovens.

The high chromium content of the steel (23-27% Cr) provides to this alloy excellent thermal stability properties. It is used as metal sheets and strips, at temperatures up to 1150°C. This type of steel is not suitable for drawing, as the above one, but it can be formed. Consequently, it is widely used in the manufacture of furnace parts, such as: plugs, sleeves for burners and annealing funnels. Due to its resistance to nitric acid and other oxidising agents, this type of steel is suitable for many chemical processing facilities. [5, 6, 9]

### 2.2. Analyses and experiments on austenitic steel grades

The basic type and the most widely used steel grade of this category contain maximum 0.15% C, 8-10% Ni and 17-19% Cr. This steel grade has an excellent corrosion resistance and, thanks to its austenitic structure, it has a very good plasticity. It can be easily deep drawn and formed. It can be easily welded but, as we could see, the welding temperature can cause a precipitation of carbides in the weld area and in the vicinity of the weld, in the case where cooling is not achieved fast enough, which makes these areas to be sensitive to inter-crystalline corrosion. This can be corrected by annealing the welded part at a temperature higher than 1040°C to re-dissolve the carbides, followed by a rapid cooling for keeping the carbides in solution.

The applications of this type of steel are vast and varied, including kitchenware, transport equipment, oil, chemicals, paper and food processing machinery.

The stability of these types of steel by operating at high temperatures is assessed based on the structural changes and corrosion. For example, at the steel grade containing 9% Ni, the changes in structure after 30,000 and, respectively, 100,000 operation hours, at a temperature of 550°C and an operating pressure of 140daN/$cm^2$, is obvious (Figure 2).

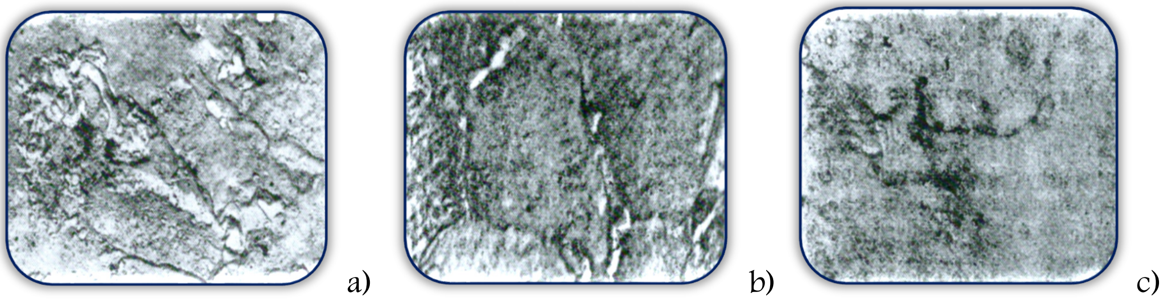

a) b) c)

**Figure 2.**Changes in the structure of steel with 9% Ni
a –unexploit (initial structure, MEx3000); b – exploait 30.000 h at 550°C and p = 140 daN/$cm^2$ (MEx3000); c – exploit100.000 h at550°Candp = 140 daN/$cm^2$ (MEx3000)

If the Ni content in composition is specified to be close to its lower limit (max. 8%), then this type of steel is hardening faster during the plastic processing due to the lower stability of the basic phase in the structure – the austenite.

The austenitic steel grades have good resistance to high temperatures and, therefore, they are in high demand for use at high temperatures. But, quite frequently in practical situations, when heating austenitic stainless steel for machining, a percentage of ferrite content appears in the structure, worsening considerably the plasticity of that steel and affecting partly or totally the integrity of that product.In order to elucidate this phenomenon, certain laboratory and industrial researches have been conducted. [7, 8, 10]

### 3. LABORATORY AND INDUSTRIAL RESEARCHES

The laboratory researches have been conducted by using two billets weighing 100 kg each, cast from industrial steel heats.

In order to provide to the experimental billets solidification conditions similar to the industrial ones, we heated the semi-finished products to a temperature of about 300-400°C and the cooling was made in the vicinity of the oven.

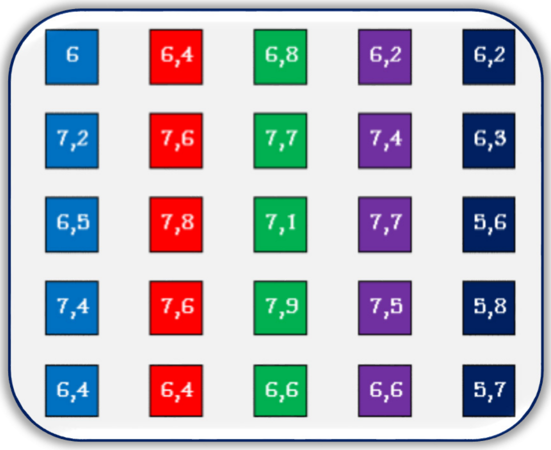
The results of chemical analyses carried out for the industrial heats and the experimental billets had only deviations of hundredths, falling within the limits prescribed by standards.

The experimentally cast billets have been used in laboratory research to determine the deformability and the correlation of this property with the technological solutions for dissolution or diminution of the secondary phases from the basic structure, for improving the plasticity during the machining process.

Thus, we started with the study of ferrite dispersion in the basic structure of the cast steel, by cutting flat samples of 120 x 120 x 20 mm from the cross section of the billets.

The results are shown in Figures 3-18, and represent either the ferrite dispersion in the basic mass, or the arrangement of the points in which the ferrite content was measured in the cross sections of the samples.

From the below analysis, it is noted that the ferrite distribution either in the same cross section or at different levels along the height of the cast billet is non-uniform. This phenomenon can be caused by the segregation of the alloying elements in the mass of the initial billet, which occurs during the solidification and cooling processes. Thus, the content of ferrite formed during the solidification process, as well as the distribution of this phase per cross section, depend on either the chemical composition or the parameters of the steel-making and casting processes (casting temperature, solidification speed, cooling speed after solidification), especially at high temperatures – above 1000-1100°C.



| | | | | |
|---|---|---|---|---|
| 6 | 6,4 | 6,8 | 6,2 | 6,2 |
| 7,2 | 7,6 | 7,7 | 7,4 | 6,3 |
| 6,5 | 7,8 | 7,1 | 7,7 | 5,6 |
| 7,4 | 7,6 | 7,9 | 7,5 | 5,8 |
| 6,4 | 6,4 | 6,6 | 6,6 | 5,7 |

**Figure 3**. Arrangement of points for the ferrite content measured in the cross sections of sample 1

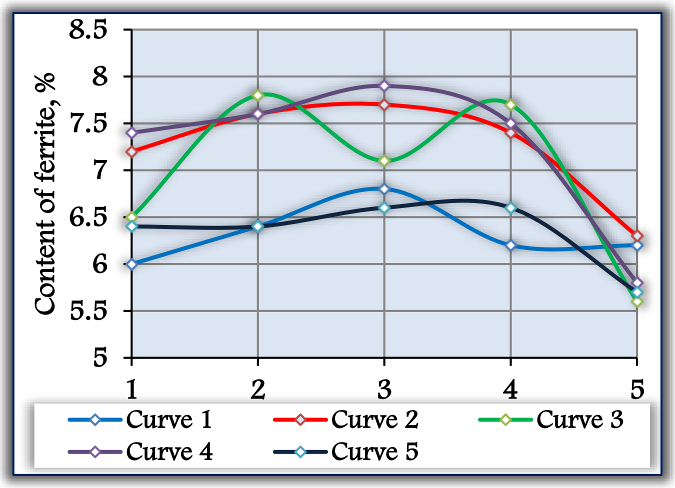
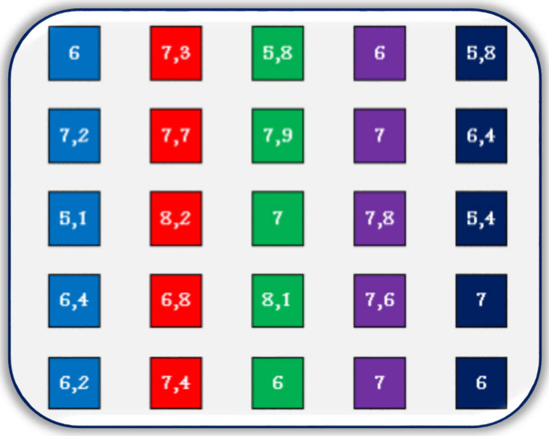


**Figure 4**. The ferrite dispersion in the basic mass for sample 1



| | | | | |
|---|---|---|---|---|
| 6 | 7,3 | 5,8 | 6 | 5,8 |
| 7,2 | 7,7 | 7,9 | 7 | 6,4 |
| 5,1 | 8,2 | 7 | 7,8 | 5,4 |
| 6,4 | 6,8 | 8,1 | 7,6 | 7 |
| 6,2 | 7,4 | 6 | 7 | 6 |

**Figure 5**. Arrangement of points for the ferrite content measured in the cross sections of sample 2

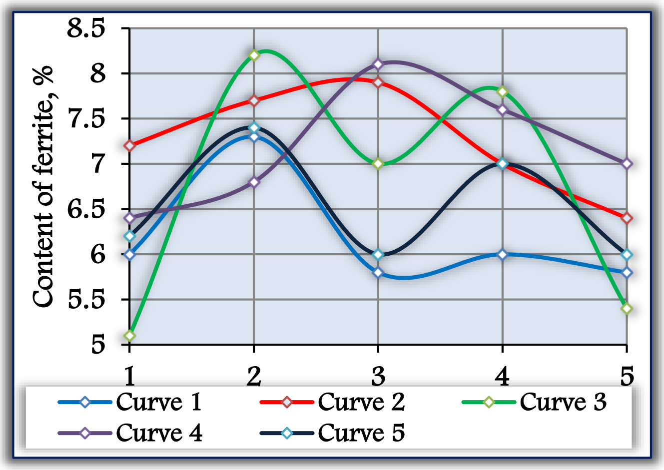
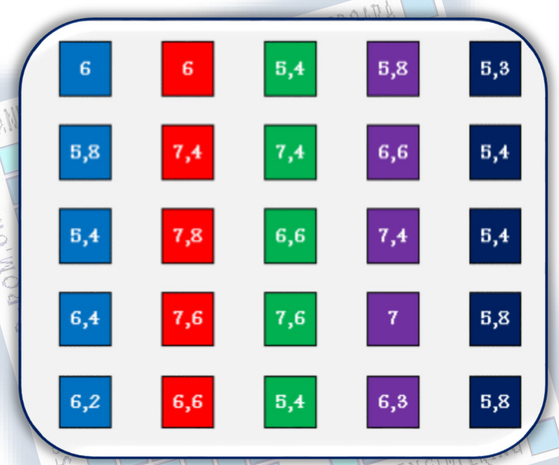


**Figure 6**. The ferrite dispersion in the basic mass for sample 2



| | | | | |
|---|---|---|---|---|
| 6 | 6 | 5,4 | 5,8 | 5,3 |
| 5,8 | 7,4 | 7,4 | 6,6 | 5,4 |
| 5,4 | 7,8 | 6,6 | 7,4 | 5,4 |
| 6,4 | 7,6 | 7,6 | 7 | 5,8 |
| 6,2 | 6,6 | 5,4 | 6,3 | 5,8 |

**Figure 7**. Arrangement of points for the ferrite content measured in the cross sections of sample 3

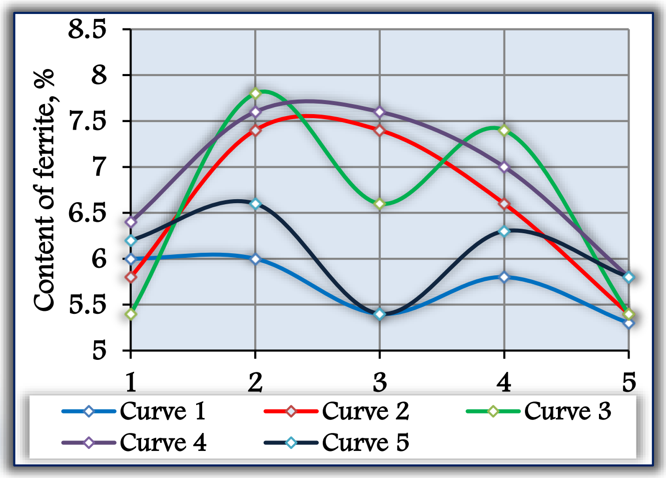
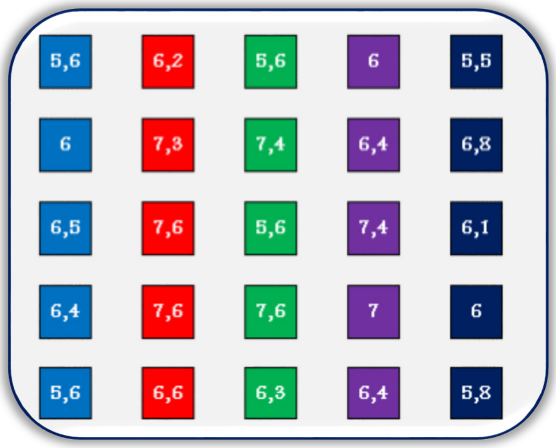


**Figure 8**. The ferrite dispersion in the basic mass for sample 3



| | | | | |
|---|---|---|---|---|
| 5,6 | 6,2 | 5,6 | 6 | 5,5 |
| 6 | 7,3 | 7,4 | 6,4 | 6,8 |
| 6,5 | 7,6 | 5,6 | 7,4 | 6,1 |
| 6,4 | 7,6 | 7,6 | 7 | 6 |
| 5,6 | 6,6 | 6,3 | 6,4 | 5,8 |

**Figure 9**. Arrangement of points for the ferrite content measured in the cross sections of sample 4

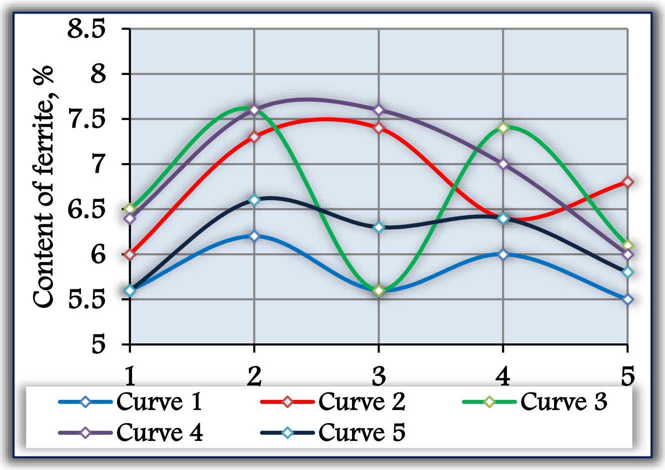
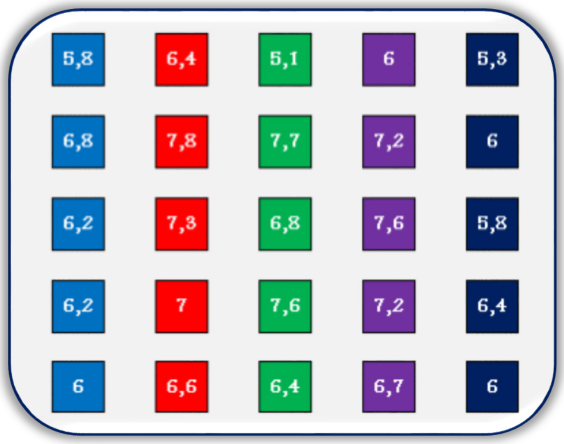


**Figure 10**. The ferrite dispersion in the basic mass for sample 4



| | | | | |
|---|---|---|---|---|
| 5,8 | 6,4 | 5,1 | 6 | 5,3 |
| 6,8 | 7,8 | 7,7 | 7,2 | 6 |
| 6,2 | 7,3 | 6,8 | 7,6 | 5,8 |
| 6,2 | 7 | 7,6 | 7,2 | 6,4 |
| 6 | 6,6 | 6,4 | 6,7 | 6 |

**Figure 11**. Arrangement of points for the ferrite content measured in the cross sections of sample 5

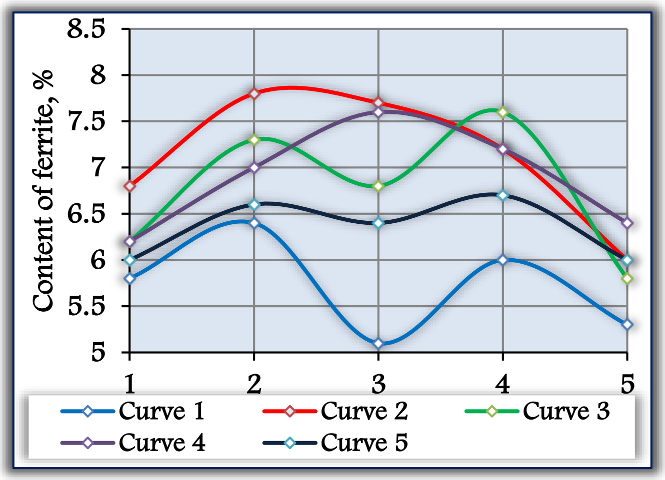


**Figure 12**. The ferrite dispersion in the basic mass for sample 5

| | | | | |
|---|---|---|---|---|
| 5,9 | 6 | 5,1 | 5,8 | 5,3 |
| 6,8 | 7,8 | 8 | 6,8 | 6,3 |
| 6,8 | 7,9 | 6,7 | 7,8 | 5,7 |
| 6,5 | 7,1 | 7,8 | 6,8 | 6,2 |
| 5,8 | 6,6 | 5,7 | 6,4 | 5,4 |

**Figure 13**. Arrangement of points for the ferrite content measured in the cross sections of sample 6

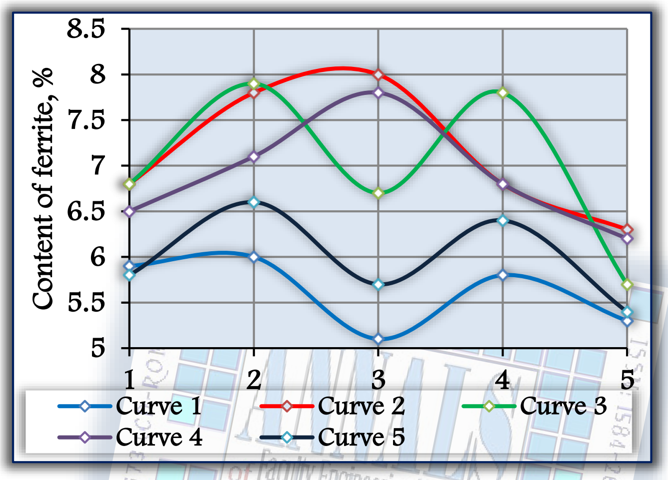


**Figure 14**. The ferrite dispersion in the basic mass for sample 6

The subsequent transformation of ferrite is realised through the diffusion phenomenon that occurs at high temperatures (generally above 1000ºC). The decrease of distances among the ferrite islands and their elongation during the plastic deformation lead to the acceleration of diffusion processes. If the heating for further processing is realised within the temperature range of minimum stability of ferrite, then its solubilisation can occur. However, if the temperature is too high, the ferrite content could increase. [8]

The analysis of points arrangement on the cross sectional surface of the slices obtained from the experimental billets cast from industrial steel heats (Figures 3-18) reveals that the lower ferrite content appears towards the exterior. Towards the centre, the content is constantly increasing, showing in some cases a slight decrease along the meridian axis.

| | | | | |
|---|---|---|---|---|
| 5,7 | 6 | 5,4 | 6 | 5,5 |
| 6,6 | 7,2 | 8,2 | 6,8 | 6,2 |
| 6,3 | 7,6 | 6,8 | 7,5 | 5,6 |
| 6,2 | 7 | 7,4 | 7,4 | 5,7 |
| 5,5 | 6,5 | 6,2 | 7 | 5,6 |

**Figure 15**. Arrangement of points for the ferrite content measured in the cross sections of sample 7

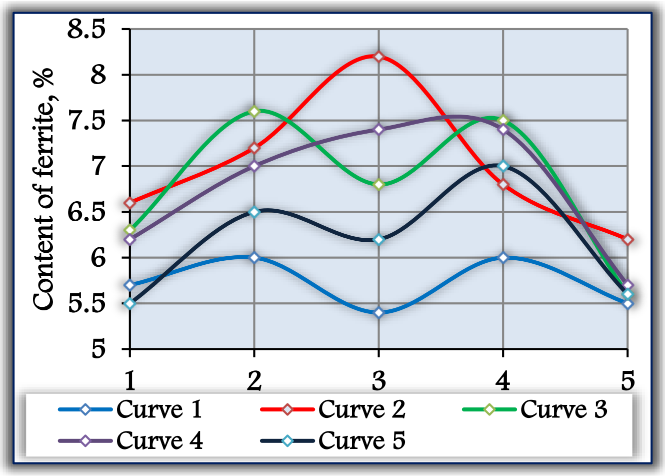
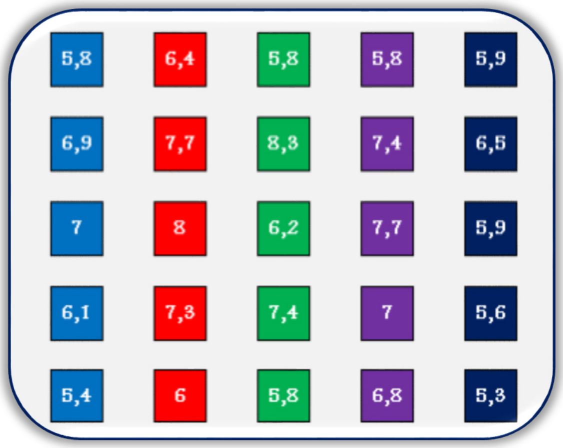


**Figure 16**. The ferrite dispersion in the basic mass for sample 7



| | | | | |
|---|---|---|---|---|
| 5,8 | 6,4 | 5,8 | 5,8 | 5,9 |
| 6,9 | 7,7 | 8,3 | 7,4 | 6,5 |
| 7 | 8 | 6,2 | 7,7 | 5,9 |
| 6,1 | 7,3 | 7,4 | 7 | 5,6 |
| 5,4 | 6 | 5,8 | 6,8 | 5,3 |

**Figure 17**. Arrangement of points for the ferrite content measured in the cross sections of sample 8

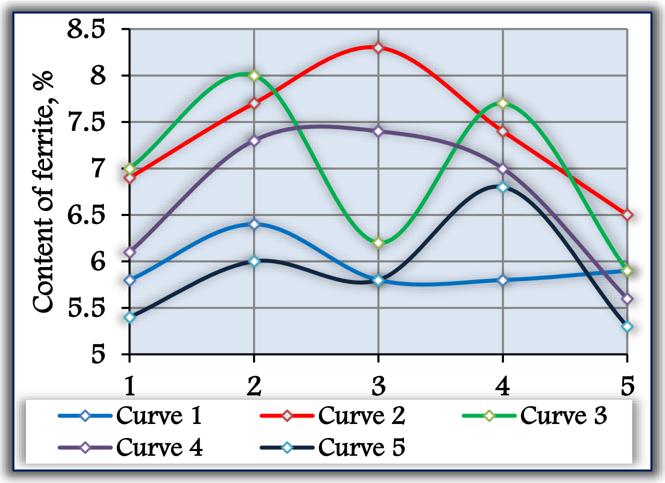


**Figure 18**. The ferrite dispersion in the basic mass for sample 8

In general, the maximum ferrite content in the cross section is located at about one third of the slice edge, on both sides of the centre line. In the manufacture of pipes, for example, the area with high content of ferrite is just the area subjected to the highest degree of deformation, the risk of cracking being the highest in this area. Therefore, it seems to be of major importance to ensure low ferrite content in the austenitic steel grades for improving the hot workability.

For practical operating conditions, it was revealed that the heats made of austenitic stainless steel, whose initial ferrite content was up to 5%, can be processed by hot rolling in good conditions (no occurrence of cracks), the heats whose ferrite content ranges between 5 and 9% are subsequently partially cracking, and the ones whose ferrite content is over 9% lead to a low yield due to the frequently found cracks.

## 4. CONCLUSIONS

The top fields of economy require new combinations of alloys for components able to work at high operating temperatures.It has been found that, for operating temperatures exceeding 800°C, the austenitic stainless steel grades containing more than 18% Cr and 8-10% Ni and stabilised with molybdenum and titanium give the best results but, when subjected to hot processing, these materials have low yield due to the difficulties caused by many technological problems.

Also, it has been found that, with respect to the resistance to oxidation and corrosion, the chromium increases significantly the steel resistance to corrosion thanks to the compounds of sulphur and other high-temperature corrosive substances (~1000°C).

A significant increase in the quality characteristics of the analysed steel grades was also obtained by adding various percentages of special alloying elements, but we should mention that these ones caused structural changes that worsened the plasticity and hot workability.

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