The influence of heat treatment on properties of cold rolled alloyed steel and nickel superalloys sheets used in aircraft industry

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Abstract. Superalloys based on nickel and selected steels are widely used in the aerospace industry, because of their excellent mechanical properties, heat resistance and creep resistance. Metal sheets of these materials are plastically deformed and applied, inter alia, to critical components of aircraft engines. Due to their chemical composition these materials are hardly deformable. There are various methods to improve the formability of these materials, including plastic deformation at an elevated or high temperature, or a suitable heat treatment before forming process. The paper presents results of the metal sheets testing after heat treatment. For the research, sheets of two types of nickel superalloys type Inconel and of three types of steel were chosen. The materials were subjected to multivariate heat treatment at different temperature range and time. After this step, mechanical properties were examined according to the metal sheet rolling direction. The results were compared and the optimal type of pre-trial softening heat treatment for each of the materials was determined.

1 Introduction
Heat treatment is the main factor constituting alloys microstructure, and consequently, their end properties. In the case of nickel superalloys and high alloyed steels, where applications require particularly high properties of the product, each stage of product forming should be monitored, and the result should be controlled in details. Heat treatment in a technological line of producing critical parts of jet engines is an example of special processes, that is, they cannot be controlled directly. The results are known after the process. Heat treatment processes give materials initial and interoperational technological characteristics, indicative of their ability to process and final properties defining the usefulness of the product. About their result decide all phases of the process – heating, holding time and cooling.

Nickel superalloys and high alloyed steels are materials used in the aerospace industry because of their properties, which include very good resistance to high-temperature oxidation and good mechanical properties at elevated temperature. Demanding components for the aerospace industry are produced from sheets made of these alloys formed in the processes of metal forming [1].

Due to the complex chemical composition, sheet made of nickel superalloys and of high alloyed steel have a large capacity for strain hardening. During the plastic deformation at a temperature lower than the recrystallization temperature of the material, there is the phenomenon of strain hardening. Not only the mechanical properties are changing but also magnetic, electric or corrosion resistance. Authors [2] investigated effects of solution and intermediate heat treatments on the properties of
Inconel 718. Material was subjected to solution heat treated in the range 917-1038°C and subsequently given intermediate and/or aging heat treatments. The studies on the alloyed steel formability of at high temperatures were carried out by [3-4]. The authors proposed a simulation method of metals deformation on the Gleeble® 3800 simulator. The aim of the study was to recreate the course of changes in temperature and strain, which is subject to the material during high temperature metal forming.

Materials for the plastic forming may be heat treated either before forming them to obtain the required technological properties, during shaping to renew the technological properties, and after plastic forming processes, in particular in order to achieve the desired operating characteristics.

In the case of nickel superalloys, short-term heat treatment was predominantly used prior to final aging step with a view to obtaining the phase γ' of a fine dispersion. One of the main objectives of the heat treatment of nickel superalloys for plastic processing is to obtain adequate dispersion of carbides and their types. It is generally a multi-stage treatment carried out in the temperature range 1040-1100°C, depending on the alloy [5-7].

Heat treatment of stainless steel is usually performed based on the type of steel and the reasons for carrying out the procedure. Heat treatment such as annealing, quenching and tempering, increased ductility and corrosion resistance of the material. The properties can be modified during the manufacture of the alloy, or during heat treatment after the manufacturing process. Heat treatment of stainless steel is carried out under controlled conditions to avoid carburizing, decarburization and coating surfaces with scale.

The essence of the research presented in the publication was to seek opportunities to improve the technological properties of the material being processed, and above all, to improve the plastic properties of batch sheets. The search for methods to improve the properties of deformed material is fully justified by the results of preliminary tests of experimental industrial process of rotary forming, which showed that the loss of plastic properties is a serious limitation of the efficiency and effectiveness of the process.

2 Methodology
For research samples from sheets made of the following materials were chosen:
1. AMS 5599
2. AMS 5596
3. AMS 5510
4. AMS 5604
5. AMS 5536

The shape, size and direction of sampling for testing the mechanical properties are shown in figure 2.1.

In the first stage of the study, the mechanical properties of metal sheets in the initial conditions were identified. For this purpose, a static tension test on machine Zwick/Roell Z050 was conducted. The machine was operated and controlled by program testXpert® 2, which was also used to collect data from the tensile test. Rockwell hardness measurements were also performed.
Afterwards, a study on the impact of heat treatment on the mechanical properties of the metal sheets were made. Studies were realized in 2 bars vacuum furnaces used for aviation production with cylindrical molybdenum or graphite chamber and horizontal loading. Furnaces had gas mixer and a heat exchanger located within the housing. The dimensions of the working chamber was 900x780x1800 mm. The operating range of the furnace was 500-1180°C. The required temperature uniformity is defined by ranges:
1. (500÷720) +/- 8°C
2. (721÷1180) +/- 14°C

Figure 2.2 shows the patterns of heating and cooling for the heat treatment.

Summary plan of the heat treatment are shown in table 1.1.
Table 1.1 Plan of the heat treatment (HT = heat treatment).

| Material | HT a | HT a 2 | HT a 3 | HT a 4 | HT a 5 | HT a 6 |
|----------|------|--------|--------|--------|--------|--------|
| AMS 5599 | annealing | 900°C | annealing | 1000°C | vacuum 10⁻⁴ Tr | 982°C+Ar | 60min | vacuum 10⁻⁴ Tr | 1100°C+Ar | 60min | RCW b |
|          |      |        |        |        |        | RCW b |       |        | RCW b |       | RCW b |
| AMS 5596 | annealing | 900°C | annealing | 1000°C | vacuum 10⁻⁴ Tr | 982°C+Ar | 60min | vacuum 10⁻⁴ Tr | 1100°C+Ar | 60min | RCW b |
|          |      |        |        |        |        | RCW b |       |        | RCW b |       | RCW b |
| AMS 5510 | annealing | 900°C | annealing | 1000°C | vacuum 10⁻⁴ Tr | 982°C+Ar | 60min | vacuum 10⁻⁴ Tr | 1100°C+Ar | 60min | RCW b |
|          |      |        |        |        |        | RCW b |       |        | RCW b |       | RCW b |
| AMS 5604 | annealing | 900°C | annealing | 1000°C | vacuum 10⁻⁴ Tr | 982°C+Ar | 60min | vacuum 10⁻⁴ Tr | 1100°C+Ar | 60min | RCW b |
|          |      |        |        |        |        | RCW b |       |        | RCW b |       | RCW b |
| AMS 5536 | annealing | 900°C | annealing | 1000°C | vacuum 10⁻⁴ Tr | 982°C+Ar | 60min | vacuum 10⁻⁴ Tr | 1100°C+Ar | 60min | RCW b |
|          |      |        |        |        |        | RCW b |       |        | RCW b |       | RCW b |

a heat treatment
b rapid cooling water
c rapid cooling oil

Conditions for the heat treatment varied by temperature and cooling medium. After the heat treatment, a static tensile testing was carried out again, and Rockwell hardness was tested. The results are presented in the form of tables and figures.

3 Results and discussion
Table 3.1 shows the chemical composition of the alloy to be tested.

Table 3.1. The chemical composition of alloys intended for research.

| Material | Ni | Cr | Fe | Mo | Nb+Ta | C | Mg | Si | Al | Ti | Co | remaining |
|----------|----|----|----|----|-------|---|----|----|----|----|----|-----------|
| AMS 5599 | 58 | 23 | 5  | 10 | 4.14  | 0.1| 0.5| 0.5| 0.4| 0.4| b* | balance   |
| AMS 5596 | 55 | 21 | b* | 3.3| 5.5   | 0.08| 0.35| 0.35| 0.7| 1.0| b* |           |
| AMS 5510 | 12 | 19 | b* | 0.08| 0.7   | b* |           |
| AMS 5604 | 5.0| 17.5| b* | 0.45| 0.07 | 1.0| 1.0| b* |
| AMS 5536 | 50 | 21 | 18 | 9  |       | b* |           |
Figure 3.1 presents a summary of the stress-strain curves for the samples in initial conditions and after heat treatment. Due to slight differences between the tensile results of samples at a different direction relative to the rolling direction, results were averaged.

Figure 3.1. Summary diagrams of the stress-strain curves for the samples in initial conditions and after heat treatment
a) AMS 5599, b) AMS 5596, c) AMS 5510, d) AMS 5604, e) AMS 5536.
Analyzing the above results that the mechanical properties, it can be concluded that the use of the softening heat treatment bring the expected results, but not in every case the heat treatment significantly improved technological properties of the tested materials. The best results were obtained for alloys of AMS 5596, AMS 5510 and AMS 5536. Table 3.2 summarizes the optimum softening heat treatment and mechanical properties of the alloys in initial conditions and after heat treatment.

Table 3.2. Summary of the mechanical properties of the samples in initial conditions and after heat treatment.

| Material     | AMS 5599 | AMS 5596 | AMS 5510 | AMS 5604 | AMS 5536 |
|--------------|----------|----------|----------|----------|----------|
| Selected heat treatment | HT 2     | HT 6     | HT 6     | HT 6     | HT 4     |
| YTS [Mpa]    |          |          |          |          |          |
| E [%]        |          |          |          |          |          |
| YTS [Mpa]    |          |          |          |          |          |
| E [%]        |          |          |          |          |          |
| Mechanical properties in initial conditions | 946      | 50       | 932      | 51       | 610      | 52       | 1147     | 5        | 767      | 55       |
| Mechanical properties after heat treatment | 493      | 49       | 300      | 38,4     | 152      | 68       | 510      | 16       | 273      | 63       |

Based on the results of Rockwell hardness it can be concluded, as in the case of the tensile tests results, that the application of the softening heat treatment bring the expected results, but not in every case the heat treatment significantly improved technological properties of the tested materials. The best results were obtained for the AMS 5596 and AMS 5510. Table 3.3 summarises the optimum softening heat treatment and Rockwell hardness of the alloys in initial conditions and after heat treatment.

Table 3.3. Summary of the Rockwell hardness of the samples in initial conditions and after heat treatment.

| Material     | AMS 5599 | AMS 5596 | AMS 5510 | AMS 5604 | AMS 5536 |
|--------------|----------|----------|----------|----------|----------|
| Selected heat treatment | HT 6     | HT 6     | HT 6     | HT 3     | HT 6     |
| HRA          |          |          |          |          |          |
| Hardness in initial conditions | 60,3     | 58,5     | 46,7     | 64,0     | 48,1     |
| Hardness after heat treatment | 50,8     | 38,4     | 16,3     | 64       | 40,7     |
Summary
The results indicate the possibility of controlling the technological properties by prior heat treatment of metal batch. Type of heat treatment may be chosen based on the basic characteristics of alloys describing the evolution of the properties as a function of heat treatment parameters, namely temperature, cooling rate, and the sequence of treatments. Parameters are subject to optimization based on measurements of mechanical properties. The study is taking into account constraints resulting from the operational requirements and technical and technological possibilities.

Acknowledgment
The work carried out within the framework of agreement No. 11.11.180.004/2016.

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