Evolution of mechanical properties of boron/manganese 22MnB5 steel under magnetic pulse influences

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Abstract. The boron/manganese 22MnB5 steel can be noted as the widely used material for creation of details, which must withstand high amount of load and impact influences. The complexity and high labor input of restoration of boron steel parts leads to growing interest in the new forming technologies such as magnetic pulse forming. There is the investigation of the evolution of mechanical properties of 22MnB5 steel during the restoration by means of magnetic pulse influence and induction heating. The heating of 22MnB5 blanks to the temperature above 900°C was examined. The forming processes at various temperatures (800, 900 and 950°C) were performed during the experiments. The test measurements allowed to obtain the relationships between the strain and the operation parameters such as induced current, pulse discharge time and the operation temperature. Based on these results the assumption about usage of these parameters for control of deformation process was made. Taking into account the load distribution and the plasticity evolution during the heating process, the computer simulation was performed in order to obtain more clear strain distribution through the processed area. The measurement of hardness and the comparison with the properties evolution during hot stamping processes confirmed the obtained results.

1. Introduction

Improvements of manufacturing and production process allow non ferrous alloys such as aluminum, magnesium and titanium alloys, to occupy a significant niche among the construction materials. The high strength, good wear and corrosion resistances, as well as lower density comparing with the steel made these alloys a good option for aeronautical, nautical, and automotive purposes.

In order to keep their part of market, steel manufacturers had to improve their products and provide better relation between costs, weight, and properties. The advanced high strength steels (AHSS) came as the material that capable to provide these requirements. The cost issue is solved by saving of available manufacturing powers for casting, forming, and machining, since the creation of parts from AHSS use the existing production and manufacturing technologies. Although AHSS has density commensurate to the traditional mild steels, the weight reduction can be achieved by decrease of part thickness due to significant values of material strength. Despite the fact that AHSS have different structures, hardening and strengthening mechanisms, they were grouped together due to their considerable strength parameters. Values of yield and ultimate strengths for these materials are varied in the range from 550 MPa and 650 MPa for High-Strength Low-Alloy (HSLA) steels to 1250 MPa and 1500 MPa for Martensitic (MS) steels respectively.
Among the AHSS the boron steel should be highlighted, as the steel that has the highest strength-to-weight ratio that makes this steel is cost effective choice for strong and critical constructions. The hardening and strengthening mechanisms for boron steel are strongly associated with heat treatment and bake hardening that allows to obtain an almost full martensite structure, which provide the highest strength properties. [1]

Parts made from boron steels as well as from other types of advanced high-strength steels have some limitations during the production and restoration operations, since the applying of the colossal strength is required for forming parts made from this steel or restoration these parts after their deformation. However, this problem is solved by use of the correct sequence, and precision control of forming and heat treatment. The well-known and wide used manufacturing technology is hot stamping process also known as press hardening. The traditional hot stamping process includes:

- Heating of the blank in a furnace to temperatures above AC₃-temperature point in order to transform ferrite-bainite structure into austenite;
- Commonly the heating rate is higher than 10⁶°C/s and after reaching the temperature, material is kept at this temperature at least 3-5 min;
- After preprocessing the heated blank is transferred to high speed hydraulic press. The cooling and forming process are going simultaneously with the cooling rate higher than 29°C/s in order to achieve the complete transformation of ductile austenite into hard and brittle martensite. [2]

The production and manufacturing processes are well studied and developed. However, the restoration of elements made from boron steels is time-consuming process and demanding to the compliance of heat and cooling rate requirements. One of the possible ways is the usage of magnetic technologies such as induction heating and usage of magnetic field for material forming. According to [3] the induction heating allows to obtain high heating rates that necessary to avoid grain coarsening during heating process. This method was successfully approved in works of Bariani et. al. [4] [2]

The usage of magnetic field allows to improve the material plasticity and as result increase the productivity operation process. [5] [6] The some articles demonstrate the increase of material plasticity and reduce of residual stresses. In the work [7] it was shown that the elongation of HS 37/23 steel increase by 4.95% and 7.50% under influence of magnetic field with magnetic induction 0.4 T and 1.07 T respectively.

In this particular study, the main object is to analyze the properties of boron/manganese 22MnB5 steel during the forming operation performed by means of induction heating and magnetic forming. The method used for pulsed magnetic forming process is described in the articles [8] [9].

2. Experimental method

2.1. Materials parameters

As it is mentioned above, the material investigated in this study is the boron/manganese 22MnB5 steel as the most widely used and well-known grade of boron steels. The experimental measurements are carried out few times with metal blanks that have thickness about 0.001 m. The chemical composition and mechanical properties of studied boron steel are shown in table 1 and table 2.

Table 1. Chemical composition of the boron/manganese 22MnB5 steel (wt.%).

| Steel grade | C  | Mn  | P   | S   | Si  | Cr  | N   | Ti  | B   | Al  |
|-------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 22MnB5      | 0.22 | 1.25 | 0.013 | 0.004 | 0.25 | 0.14 | 0.004 | 0.03 | 0.003 | 0.040 |

Table 2. Mechanical properties of boron/manganese 22MnB5 steel.

| Steel grade | Ultimate Tensile strength (MPa) | Yield strength (MPa) | Elongation(%) |
|-------------|---------------------------------|----------------------|--------------|
| 22MnB5      | 1500                            | 1000                 | 8            |
2.2. Experimental parameters
The schematic representation of the experimental setup for this research is presented on the figure 1. It is well known that the discharge of electromagnetic impulse produced by the coil inductor leads to induction of eddy currents in both the metal blank and accessory screen. Since two parts with codirectional current flow are located in a variable electromagnetic field, then it is possible to assume the appearance of attracting and repelling forces between them. However, the researches performed in works [9] and [8] demonstrates that the relation between these force is strongly depended on the electromagnetic field frequency. The obtained results show that at the frequency $\leq 2$ kHz, the repelling force is much more lower and can be neglected comparing with attractive action.

![Figure 1. Schematic of experimental setup:](image)

For purpose of investigation of boron steel behavior during forming process by means of pulse electromagnetic attraction, the test frequency is 2 kHz. In order to generate magnetic pulses, the experimental setup includes induction coil with the inner and outer radii equal $R_1 = 0.07$ m and $R_2 = 0.075$ m, respectively. The used experimental setup allows to generate pulses with times equaled 1, 2.5 and 5 $\mu$s and to induce the currents $I_{ind}$ in the blank at the range 40...75 kA.

However, to provide the material deformation and simplify the samples forming, the blanks must be heated above the $AC_3$ – temperature in order to obtain complete transformation of already existing microstructure into austenite phase. In most cases, the boron/manganese 22MnB5 steel is heated above 900 $^\circ$C and kept at this temperature at least 3 min. [3] [10] [1] The test measurements are performed at operation temperatures 950, 900 and 800 $^\circ$C due to the low strength and high plasticity of material at these temperatures.

It is important to control the temperature during forming operation as well as during heat/cooling processes. For this purpose, the laser pyrometer Pyrometer IMPAC IGA 15 plus is used that can provide the accurate and digital noncontact measurements of sample temperature. The range of its measurement is 250...1800 $^\circ$C and the measurement error is less than 1.5%.

The presence of some difference in mechanical properties of tested samples can be established by measurements of material hardness. This measurement is performed by using Vickers hardness test as consistent with ISO 6507-1 standard.

3. Experimental method
During the experimental measurements, the relationship between current induced in the blank and relation deformation of material was obtained. In some cases, the induced current was not sufficient for plastic deformation of tested blanks. These results are represented on the figure 2 as the graphical interpretations of obtained results.

According to the obtained results, the relative strain obtained after pulse magnetic impact strongly depends on the operation parameters such as time of pulse discharge, operation temperature and induced in blank current. While the current and its distribution determines the value of attracting interaction, the operation temperature influences on the plasticity evolution of processed material. According to obtained results, with the temperature increase the significant reduction of flow stress as well as the decrease of work hardening is observed. The main reason of this is the tempering of microstructure, softening of material and the removing of its residual stresses.
The results of experimental measurements: (a), (b), (c) – the dependence of relative strain from the current induced in the blank at 800, 900 and 950 °C respectively; (d) – influence of temperature on the forming process.

The discharge time is also has some influence on the plastic deformation of processed material. During operation process, the duration of pulse is responsible for the duration of magnetic field treatment as well as for the duration of forming operation that leads to variation of strain rate. From the obtained results it can be seen that during the operation by pulses with duration of 5 μs, the boron steel demonstrates less strength and better formability. One of the possible reason is more prolonged influence of magnetic field on the material microstructure that leads to changing of amount and distribution of various structural defects such as vacancy, itinerant electron etc. These defects are the reason of the material crystal lattice deformation that interrupts the movement of dislocations during the loading process. The influence of magnetic field leads to self elimination of these defects that allows to improve material plasticity.

In the works [9] [8] the authors present describe the attractive force as the function of currents induced in the processed blank and attractive screen. This relation can be expressed by equation (1):

\[ F_{\text{attr}} = \mu_0 \cdot J_{\text{ind}}^b \cdot J_{\text{ind}}^s \cdot \frac{r}{(2h)} \ N \]  

where \( J_{\text{ind}}^b \), \( J_{\text{ind}}^s \) – current inducted in the sheet metal blank and the accessory attracting screen, respectively, A;
\( r \) – the radius of the operation area (in the range from 0 to \( R_1 = 0.07 \) m);
\( h \) – the distance between the coil inductor, the accessory attracting screen and the sheet metal blank. In this particular study, the distance \( h \) is 0.00015 m;
\( \mu_0 \) – magnetic constant, which equals 1.26 \( \times \) 10\(^{-6}\) N\( \cdot \)A\(^{-2}\).

The hardening mechanism and mechanical properties of boron/manganese 22MnB5 steel after heat treatment is extensively studied due to frequent use of hot stamping operations for this particular material. According to works [11] the plasticity evolution during the heating process can be expressed by equation (2):

\[ \sigma_{22\text{MnB5}}(\varepsilon, T_H) = K_1 \cdot \exp \left( \frac{\beta_2}{T_H} \right) (\varepsilon_0 + \varepsilon)^{\gamma(T_H)} \]  

where \( T_H \) is the heat temperature, °C;
\( n(T_H) \) is the strain hardening exponent, that can be calculate as:

\[
n(T_H) = n_0 \cdot \exp(-c_n(T_H - T_0)),
\]

(3)

The other coefficients are empirical constants. According to the [11] the values of these coefficients for 22MnB5 steel are: \( K_1 = 34.48; \beta_4 = 2186.04; \varepsilon_0 = 0.0025; n_0 = 0.2034; c_n = 0.0024. \)

This equation allows to make computer simulation in order to establish the strain distribution during the forming process. The simulation was performed by means of ABAQUS 6.11-3 Standard. The material properties are calculated in accordance with the UMAT procedure. The results of the performed simulation are presented on the figure 3 as the distribution of strain across the deformed area of tested sample.

![Figure 3. The strain distribution during the magnetic pulse influences.](image)

It can be seen that the strain obtained during forming operation is mostly concentrated at the edge of operation area. However, the irregular strain distribution as well as the temperature heating can lead to the partial martensite transformation and decrease of strength properties of tested samples.

The measurements of the material hardness allow to analyze the changes in material microstructure after finishing of forming processes. According to obtained results the hardness of heated to 800, 900 and 950\(^\circ\)C samples are 450, 400 and 350 HV0.3 respectively. At the same time the hardness of 22MnB5 steel before heating is higher and equals to 500 HV0.3. It allows to assume that the material microstructure is non-uniform and includes other impurity phases in addition to the martensite.

![Figure 4. Optical microscopic images of the 22MnB5 steel before (a) and after (b) heating to 950 \(^\circ\)C](image)

The figure 4 demonstrates the martensite microstructure with some amount of ferrite phase. However, after heating the microstructure contains higher amount of ferrite and austenite that demonstrates degradation of martensite transformation. Moreover, the figure 4 (b) illustrate growth and enlargement of grains that leads to softening of 22MnB5 steel. These results well confirm the obtained hardness decrease mentioned earlier.
4. Conclusion
Within this paper, the new forming method based on the induction heating and action of the magnetic pulses is examined. This method is considered as the alternative way to restore and repair damaged details made from boron/manganese 22MnB5 steel. The experiment measurements demonstrate the influence of operation temperature, discharge time, and induced current on the degree of obtained plastic deformation. According to this results, the increase of temperature as well as the increase of discharge time leads to improvement of material plasticity. However, the usage of magnetic field for generation of processing load leads to non-uniform distribution of strain through the operation area. The presence of plastic strain localized in localized areas as well as heating process prevents full transformation of austenite into martensite phase. As the result repaired parts demonstrate the decrease of mechanical strength as well as the decrease of hardness. These results demonstrate that proposed method may be used for restoration of some parts. However, it is undesirable for the restoration of critical and vital components.

5. Acknowledgments
The research was funded by the Ministry of Education and Science of the Russian Federation according to base part of state tasks of the Sevastopol State University №2014/702 (Project 3867).

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