Hyperplasticity effect under magnetic pulse straightening of dual phase steel

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Abstract. An investigation of the behaviour of dual phase steel parts during straightening operations, by means of magnetic pulse treatment, is presented. The mechanical analysis of magnetic-pulse treatment for the straightening of thin-walled sheet metal parts produced from dual phase steel was performed, taking into account the effect of hyperplasticity under the influence of the magnetic field. Taking account of the causes of the hyperplasticity and thus the increase of material plasticity, it has been shown that the magnetic impulse gravity can be adjusted by controlling the operation modes. The dependence of the generated magnetic impulse gravity force on the electrical current strength induced in this part was explored and used for analysis of the magnetic pulse straightening of dual phase steel part. Experimental results were obtained for thin-walled sheet metal part produced from dual phase steel DP 780. The results are used to demonstrate the material deformation under the influence of magnetic impulse gravity force considering the increase of material plasticity. The dependence of relative material deformation on the generated magnetic impulse gravity as well as on the current strength induced in this material was obtained and analyzed.

1. Introduction

Modern automotive industry is faced with various standards and requirements for safety, fuel efficiency and the atmospheric pollution. One possible solution of these problems is the improvement of the automobile body engineering. Such an improvement should take into account not only development and creation of new designs, but also the use of modern materials.

The traditional requirements of the vehicle body are high strength, in both static and dynamic terms; and impact stability of body shape, and stiffness, which is defined by elastic modulus of material. For a long time mild steel has met all these requirements and has been the main and basic material of the automobile industry. The main reason for this is that mild steel has advantageous properties such as drawability and work-hardening; parameters that characterize the material behaviour during production processes such as forming and stretching.

These better properties, as well as lower cost and well-developed production technologies, ensured the leader place for mild steel \cite{1}; however, modern developments in metallurgy and materials science have lead to the availability of a wide range of materials offering different sets of mechanical and physical properties. In some circumstances, the new plastics and composite materials can provide better properties than traditional steels, and, as a result of lower density, the usage of these materials in automobile construction can also enable a vehicle weight reduction. In turn, this can result in improved indices of fuel efficiency and atmospheric pollution. Various materials such as aluminium,
magnesium and titanium also offer potential weight reduction and improvement of mechanical properties of automobile body. Compared with plastics and composites, light alloys are much more preferable for application in mass-production vehicles due to the significant development of processing and manufacturing capabilities for products made from these alloys.

Despite the wide range of materials, the main choice of the automobile manufacturers is still steels. This preference can be explained by issues of production cost, passive safety, mass-production, and the simplicity of repair and restoration. The weight reduction in this case is achieved by the improvement of design and usage of Advanced High Strength Steels (AHSS), such as Complex Phase steels, Boron steels, Transformation Induced Plasticity (TRIP) and Dual Phase (DP) steels. Although these steels do not show a weight reduction relative to traditional mild steel, the high value of strength of these materials allows a pro rata reduction in thickness of automobile body elements that then leads to the weight reduction. The usage of AHSS enables the continued utilization of the existing production and manufacturing technologies [1].

Among the types of AHSS, the dual phase steel should be highlighted as the steel having the best formability and elongation compared with other high-strength steels of the same strength. The microstructure of dual-phase steels commonly consists of a ductile phase matrix (ferrite) with some amount (about 15%) of hard martensite phase induced by heat treatment and alloying processes. Control of the martensite concentration enables the strength of the material to be determined at any value from 350 to 1000 MPa, while the presence of ferrite in the microstructure is responsible for material ductility [2, 3]. As a result, the dual-phase steel combines both high strength and high relative elongation properties, resulting in high energy absorption, as well as good formability and the possibility of processing by the cold forming method.

As described, it is no surprise that a wide range of grades of dual-phase steel is used for automotive industry such as DP500, DP600, DP780 and DP980; however, the parts made from dual phase steel or AHSS have some limitations and problems in the stages of production and manufacturing. These problems are related to the dependence of the strength and the plastic behaviour of these materials on the strain and heat treatment history. The technological memory leads to significant hardening of the material and thus to complications during restoration or forming. For example, Hansen [4] showed that a relatively small increase of plastic strain from 3 to 5% leads to an increase of the yield strength of dual-phase steel from 70 to 80 ksi (from 482 to 552 MPa). This hardening presents a need to increase manufacturing operation pressure forces and significantly increase operation time during the straightening process of automobile body, after damage or traffic accidents. The presence of some residual strain is also related to the pre-strain effect incurred during the manufacturing stages. It is well known that the amount of pre-strain, and as result, the plastic behaviour, depends on the loading path [5, 6]. Most parts of automobile body elements are fabricated using sheet metal forming processes that very often include changes in the loading path. For example, the material flowing through the die corner moving to die, bending and unbending in different directions, complex deformation due to the complicated configuration of die and other impact during multi-stage fabrication processes such as deep-drawing and blanking. The result the need for complex loading paths during manufacture processing leads directly to the presence of some pre-strain [7, 2].

Huh et al. [2] show that the some amount of pre-strain effects the dynamic tensile properties, the initial yield stress and the flow stress. According to the presented results the yield strength and tensile strength of DP600 steel, with pre-strain of about 10%, increased by 22.6 MPa and 32.8 MPa respectively at the strain rate of 100 s\(^{-1}\).

Morestin and Boivin [8] describe a decrease in elastic modulus during the unloading of dual-phase sheets, leading to non-linear strain recovery, which has an undesirable effect during forming processes. According to their results, an increase in plastic strain by 5% leads to a decrease of 10% in the unloading elastic modulus; moreover, the unloading modulus will degrade with increasing plastic pre-strain [9, 10].

Technology such as Superplastic Forming (SPF) provides an alternative approach to material forming. The superplasticity or hyperplasticity is characterized by elevated ductility, with such
materials displaying elongations of up to 200% (for some materials the elongation during SPF can reach the value 400% and higher). The benefits of SPF usage are a reduction in residual stresses and in springback. The mandatory conditions for SPF process conditions are [11]:

- The presence of two or more fractions in the microstructure
- The presence of a fine stable grain size, usually between 5 – 15 μm
- Deformation being made at a relatively slow strain rate, normally in the range from $10^{-4}$ s$^{-1}$ to $10^{-2}$ s$^{-1}$
- An operation temperature higher or equal to 0.5 $T_m$, where $T_m$ is the melting temperature of processed material, measured in Kelvin

On the other hand, SPF is a slow process compared with the traditional processes of metal sheet forming [11].

Unfortunately, not all materials are suitable for this type of forming. Commonly, the SPF process is used for processing of various aluminium, magnesium, and titanium alloys [11-14]; however, in the work [15] it has been established that ultrafine grained ferrite/martensite dual phase steel, produced by an equal channel angular pressing (ECAP) process, can also be processed as a superplastic material.

Another way to obtain the superplasticity during the forming process is to use a magnetic field, and an increase in material plasticity and a reduction in residual stresses has been demonstrated [16, 17]. It has been shown, [18], that the elongation of HS 37/23 steel can be increased by between 4.95% and 7.50% under the influence of a magnetic field with magnetic inductions of 0.4 T and 1.07 T respectively. Golovashchenco et al. [19] demonstrated a method for elimination of springback by applying an electromagnetic force on a workpiece that is fixed in the die. According to their results, about 90% of internal stresses can be eliminated by applying this method. These results were confirmed by Iriondo et al. [20] by testing the sheet samples made from DP600 and TRIP700 high strength steels and applying electromagnetic discharges of from 8 to 24 kJ. The changes in observed sizes of U-channels samples was about 8 mm compared with samples formed without applying an electromagnetic field.

Among the technologies of magnetic forming of metal sheets, there is the method that can be used for straightening of automobile body [21, 22]. This method is based on Ampere’s law and the interaction between two conductors with the current flow, while placed in a magnetic field. The main purpose of this article is to study the behaviour of dual-phase DP780 steel during this forming process, and to examine the presence of the superplasticity/hyperplasticity.

2. Experimental method

2.1. Materials parameters

The material investigated in this study was dual phase DP780 Y450 steel sheet, from which samples were taken. The experimental measurements were carried out three times. The thickness of each sample tested was 0.001 m. The chemical composition and mechanical properties of each dual phase steel studied are shown in Tables 1 and 2. The microstructure of the material comprises ferrite (about 85%) and martensite fractions. The samples were tested without pre-strain or heat treatment preparations.

2.2 Experimental parameters

Figure 1 represents schematically the experimental setup used for this particular study. Eddy currents are induced in the sheet metal blank, as well as in the accessory attracting screen, by the discharge of an electromagnetic impulse generated by the coil inductor [22]. The induction of current in the conductive material placed in the variable electromagnetic field leads to the appearance of attracting and repelling forces. It has been established [21] that the frequency of electromagnetic field has
significant influence on the summation action of these two forces. According to the results obtained, the repelling force is slight and can be neglected at the frequency ≤ 2 kHz.

For the study of the behaviour of dual-phase steel, for applications such as repair and maintenance of sheet metal constructions (straightening process, dent removing, etc.), the test frequency chosen was 2 kHz. The single turn induction coil radii were \( R_1 = 0.07 \) m and \( R_2 = 0.075 \) m. The experiment was carried out with discharge times of 0.1, 2.5 and 5 μs, and maximum current \( I_{\text{max}} = 70 \) to 82 kA. The values of the current induced on the surface of the sheet metal blank and on the accessory attracting screen are measured using an Ammeter. The attractive force acting on the sheet metal blank can be calculated by equation (1) [21, 22]:

\[
F_{\text{attr}} = \mu_0 \cdot J_{\text{ind}}^b \cdot J_{\text{ind}}^s \cdot \frac{r}{(2h)}, \text{ N (1)}
\]

where \( J_{\text{ind}}^b, J_{\text{ind}}^s \) (A) is the current induced in the sheet metal blank and in the accessory attracting screen, respectively; \( r \) is the radius of the operation area (in the range from 0 to \( R_1 = 0.07 \) m); and \( h \) is the distance between the coil inductor, the accessory attracting screen and the sheet metal blank. In this particular study, the distance \( h \) is 0.15 mm. \( \mu_0 = 1.26 \times 10^{-6} \) N A\(^{-2}\) is the permeability of free space.

**Table 1.** Chemical composition of the dual-phase DP780 Y450 steel (wt.%).

| Steel grade | C  | Mn | P  | S  | Si | Cr  | Mo  | Cu  | W  |
|-------------|----|----|----|----|----|-----|-----|-----|----|
| DP780 Y450  | 0.17 | 2.2 | 0.007 | 0.6 | 0.010 | 0.399 | 0.270 | 0.001 | 0.005 |

**Table 2.** Mechanical properties of dual-phase DP780 steel.

| Steel grade | Tensile strength (MPa) | Yield strength (MPa) | Strain rate (s\(^{-1}\)) | Elongation (%) |
|-------------|------------------------|----------------------|------------------------|---------------|
| DP780 Y450  | 842                    | 450                  | 0.63                   | 18.5          |

**Table 3.** The results of experimental measurements.

| \( J_{\text{ind}}^b \) (kA) | \( t = 0.1 \) (μs) | \( t = 2.5 \) (μs) | \( t = 5 \) (μs) |
|-----------------------------|-------------------|-------------------|-------------------|
| \( \varepsilon_1 \), %     | \( \varepsilon_2 \), % | \( \varepsilon_3 \), % | \( \varepsilon_1 \), % | \( \varepsilon_2 \), % | \( \varepsilon_3 \), % | \( \varepsilon_1 \), % | \( \varepsilon_2 \), % | \( \varepsilon_3 \), % |
| 70                         | 0.50              | 0.54              | 0.48              | 0.58            | 0.63              | 0.60              | 0.71            | 0.80              | 0.68              |
| 72                         | 0.54              | 0.56              | 0.53              | 0.66            | 0.67              | 0.64              | 0.79            | 0.77              | 0.76              |
| 74                         | 0.61              | 0.61              | 0.59              | 0.74            | 0.75              | 0.74              | 0.85            | 0.85              | 0.83              |
| 76                         | 0.72              | 0.70              | 0.75              | 0.89            | 0.84              | 0.77              | 0.97            | 1.04              | 0.92              |
| 78                         | 0.98              | 0.96              | 0.98              | 1.05            | 1.10              | 1.07              | 1.20            | 1.15              | 1.17              |
| 80                         | 1.21              | 1.25              | 1.22              | 1.30            | 1.30              | 1.27              | 1.44            | 1.42              | 1.41              |
| 82                         | 1.53              | 1.52              | 1.50              | 1.62            | 1.70              | 1.58              | 1.70            | 1.72              | 1.72              |

The tensometric linear displacement sensor is used to define and measure the strain related to appropriate current induced in the system being studied. This sensor has a sensitivity of about 0.001 mm, which enables precise control of the material deformations.
The temperature measurements during magnetic pulse straightening are performed by means of a laser pyrometer, “MLG 36.6 Double”. The range of its measurement is from -50 to +250 °C and the measurement error is less than 1.5%.

The hardness of the tested samples was measured using the Vickers hardness test, as is consistent with the ISO 6507-1 standard.

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

1 – Multi-turn induction coil; 2 – Accessory attracting screen; 3 – Sheet metal blank; 4 – Dielectric intermediate piece; 5 – Spacer with the tensometric linear displacement sensor; 6 – Measuring unit; 7 – Control block.

![Figure 2. The strain – current relationship curves for t = 0.1, 2.5 and 5 μs.](image)

**Figure 2.** The strain – current relationship curves for $t = 0.1$, 2.5 and 5 μs.

### 3. Result and Discussion
During the experimental measurements the relations of relative deformation from the induced current strength in sheet metal blank were obtained. The strain results, for each of the three tests for the three pulse durations, are presented in Table 3.
The experiment was carried out three times for each value of the discharge time \( t \) in order to take into account any inaccuracy in measurements. The relation between strain and current for each value of the discharge time is presented in figure 2.

It is also worth noting that the value of induced current in the sheet metal blank and in the accessory attracting screen is non-uniform through the operation area. The current distribution through the operation area is presented in the figure 3.

![Figure 3. The current distribution through the operation area.](image)

The results show the maximum obtained strain for the maximum current. According to figure 3, the current induced in the blank increases with distance from the centre of the operating area, and reaches a maximum when the distance \( r \) is equal to the \( R_1 \) parameter. In order to simplify the further calculation, the measured strain is assigned to the narrow section from \( r_1 = 0.8R_2 \) to \( r_2 = 0.93R_2 \). The attractive force on this area is the average value between force at the distances \( r_1 \) and \( r_2 \), which can be calculated by using equation (1).

The stress applied on this area by attractive force is given by:

\[
\sigma = \frac{F_{\text{attr}}}{A}, \text{ MPa}
\]

(2)

where \( F_{\text{attr}} \) (N) is the average attractive force between tested sample and the accessory attracting screen, and \( A \) is the surface area of the sample part, which is exposed to the influence of the attractive force \( F_{\text{attr}} \). Considering the simplification made earlier, the surface area is:

\[
A = \pi \cdot R_2(0.93 - 0.8), \text{ m}^2
\]

(3)

The results of calculations are presented in Table 4 and the stress – strain curve is presented in figure 4.

The stress-strain curves obtained represent the plastic deformation region. The plastic deformation is more important for straightening operations and dent removal, therefore the elastic region was neglected during these experimental measurements. From the results it can be seen that the strength of
the samples straightened with a pulse with a discharge time of about 5 μs is lower compared with that of the other samples. The ductility did not change significantly.

The probable reason of this effect can be ascribed to the influence of the magnetic field on the material microstructure, leading to a change in the amount and distribution of the microstructural defects that take part in work hardening process. During plastic deformation of crystalline material the microstructural defects, such as vacancy defects, itinerant electrons, etc., deform the crystal lattice of the material and prevent the dislocation movements that lead to material hardening, and the increase of internal stresses. Under the influence of the magnetic field, the number of internal defects decreases as a result of their self-elimination under the action of the Lorentz force. These changes lead to a reduction in the barriers to dislocation movement and thereby increase the material plasticity.

Table 4. Stress-strain relation for tested material.

| $F_{\text{attr}}$ (kN) | $\sigma$ (MPa) | $t = 0.1$ (μs) | $t = 2.5$ (μs) | $t = 5$ (μs) |
|------------------------|---------------|----------------|----------------|----------------|
|                        | $\varepsilon_1$ (%) | $\varepsilon_2$ (%) | $\varepsilon_3$ (%) | $\varepsilon_1$ (%) | $\varepsilon_2$ (%) | $\varepsilon_3$ (%) | $\varepsilon_1$ (%) | $\varepsilon_2$ (%) | $\varepsilon_3$ (%) |
| 1926.3                 | 481.57        | 0.50           | 0.54           | 0.48           | 0.58           | 0.63           | 0.60           | 0.71           | 0.80           | 0.68           |
| 2037.9                 | 509.48        | 0.54           | 0.56           | 0.53           | 0.66           | 0.67           | 0.64           | 0.79           | 0.77           | 0.76           |
| 2152.7                 | 538.18        | 0.61           | 0.61           | 0.59           | 0.74           | 0.75           | 0.74           | 0.85           | 0.85           | 0.83           |
| 2270.7                 | 567.67        | 0.72           | 0.70           | 0.75           | 0.89           | 0.84           | 0.77           | 0.97           | 1.04           | 0.92           |
| 2391.7                 | 597.94        | 0.98           | 0.96           | 0.98           | 1.05           | 1.10           | 1.07           | 1.20           | 1.15           | 1.17           |
| 2515.9                 | 629.00        | 1.21           | 1.25           | 1.22           | 1.30           | 1.30           | 1.27           | 1.44           | 1.42           | 1.41           |
| 2643.3                 | 660.84        | 1.53           | 1.52           | 1.50           | 1.62           | 1.70           | 1.58           | 1.70           | 1.72           | 1.72           |

Figure 4. Stress-strain curves of DP780 steel under pulsed action during discharge times 0.1, 2.5 and 5 μs.

Note that there is some concave area on the stress-strain curves for discharge times of about 0.1 μs and 2.5 μs. For a discharge time of 5 μs this area is poorly expressed. This concave area is
characterized by a decrease in the material strength and an increase in elongation. The non-typical part of curve detects the improvement in sample plasticity, in the loading range between about 561 and 600 MPa.

Knowing the relationship between the values of induced current and applied loading (equations 1 and 2), it is possible to find the current range responsible for the change in material properties. Calculations showed that, for a current density of about 1071 $\text{A} \cdot \text{mm}^{-2}$, the onset of the concave area is observed. This result is in agreement with previous works [17, 23], where the authors noted that the increase of material plasticity is more noticeable for a pulse duration of about $10^{-4}$ s and current density of between about $10^3$ to $10^4$ $\text{A} \cdot \text{mm}^{-2}$; however, this variation of curve shape might also indicate material hardening and accumulation of some internal stresses.

In order to find the reason for these results, the hardness of DP780 steel samples was measured. The hardness not only demonstrates the properties of material surface, but also provides an evaluation of the ability of material to resist plastic deformation. Measurements of sample hardness by the Vickers method gave results within the range 245 to 250 Hv, while the typical hardness of DP780 is about 250 Hv. The hardness of samples straightened under a discharge time of $t = 0.1 \mu\text{s}$ and current density of about 1071 $\text{A} \cdot \text{mm}^{-2}$ does not exceed the normal value of DP780 steel hardness, and is 246 Hv. Based on the results obtained, it can be assumed that there is no hardening process or stress accumulation, thus, the concave area indicates the presence of superplasticity under the influence of pulsed magnetic field.

One of the main purposes of this article is to define the parameters that have an influence on the results of the magnetic pulse straightening and can be used as control and operation parameters. It is well known that temperature changes lead to vibrations of crystal lattice, thus the operation of temperature is one of the possible parameters. Measurement of the temperature of samples during the experiment was attempted; however, the thermal inertia of the dual-phase DP780 steel did not allow for effective direct temperature measurement. It must be noted that extra heating was not used during the experiment: any material heating is restricted only to that generated locally by the flow of the induced current through the conductive material. Since the range of induced current for each test was the same (from 70 to 82 kA), the temperature conditions were similar for all test measurements; however, the values of strain obtained differ for each duration of the discharge time. Based on this, it is possible to assume that the operation of temperature has less of an effect on the dual-phase material deformation compared with the other control parameters under magnetic pulse action. Additional research is required in order to evaluate the role of the operation of temperature during this kind of material forming.

It was observed that the discharge time has some influence on the material strength and deformation. The discharge time is responsible for both the strain rate and the duration of magnetic field treatment. Since the strain rate did not show a significant effect on the material deformation, the variations in results can be attributed to the difference in the duration of the magnetic field influence. It can be assumed that the increase of the discharge time and magnetic field impact can lead to weakening and relaxation of DP780 steel material. This assumption agrees with the results obtained in works [19, 20, 24].

4. Conclusion
Magnetic pulse technology is a potentially available method for straightening and repair of automobile body elements. The results obtained show the ability of the proposed system to apply magnetic force and form the sheet metal elements; moreover, the application of magnetic field during the straightening process has some influence on the structure of dual-phase steel materials. This influence provides the necessary decrease in material strength during the forming process to circumvent the effects related with internal stresses, pre-strain history, and work hardening during loading – unloading cycles. This effect is similar to the effect of hyperplasticity, which is observed during Superplastic Forming (SPF) processes as well as during forming operations employing a magnetic field.
The relationship between relative deformation, induced current and magnetic force were obtained. According to these results, the induced current discharge time had the more significant influence on the material deformation. This parameter, as well as the strength of induced current, can be taken as the main operation parameters for the control of the straightening process. It was shown that the improvement of DP780 steel plasticity is more significant for pulse durations of between about 0.1 and 2.5 μs, and with a current density from 1071 A·mm⁻².

The other parameters, such as the strain rate and the operation temperature, did not show a significant effect; however, their real role for the magnetic pulse straightening of sheet metal elements should be evaluated on the basis of further researches.

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References
[1] Davies G 2012 “Materials for Automobile Bodies” (Oxford OX5 1GB, UK: Elsevier)
[2] Huh H, Kim SB, Song JH and Lim JH 2008 “Dynamic tensile characteristics of TRIP-type and DP-type steel sheets for an auto-body” International Journal of Mechanical Sciences 50 918–31
[3] Ishikawa N et al. 2015 “Microscopic deformation and strain hardening analysis of ferrite-bainite dual-phase steels using micro-grid method” Acta Materialia 97 257–68
[4] Hansen SS 1982 “The Formability of Dual-Phase Steels” Journal of Applied Metalworking 2(2) 107–18
[5] Tutyshkin N, Muller WH and Zapara M 2014 “Strain-induced damage of metals under large plastic deformation: Theoretical framework and experiments” International Journal of Plasticity 59 133–51
[6] Barlat F et al. 2014 “Enhancements of homogenous anisotropic hardening model and application to mild and dual-phase steels” International Journal of Plasticity 58 201–18
[7] Yu HY and Shen JY 2014 “Evolution of mechanical properties for a dual-phase steel subjected to different loading paths” Materials and Design 63 412–8
[8] Morestin F and Boivin M 1996 “On the necessity of taking into account the variation in the Young modulus with plastic strain in elastic-plastic software” Nuclear Engineering and Design 162(1) 107–16
[9] Govik A, Rentmeester R and Nilsson L 2014 “A study of the unloading behaviour of dual phase steel” Materials Science & Engineering A 602 119–26
[10] Ghaei A, Green DE and Aryanpour A 2015 “Springback simulation of advanced high strength steels considering nonlinear elastic unloading-reloading behavior” Materials and Design 88 461–70
[11] Ridley N 2011 “Superplastic forming of advanced metallic materials. Methods and applications.” (Cornwall, UK: Woodhead Publishing Limited) 1–31
[12] Wang CW, Zhao T, Wang G, Gao J and Fang H 2015 “Superplastic forming and diffusion bonding of Ti-22Al-24Nb alloy” Journal of Materials Processing Technology 222 122–127
[13] Guo ML, Liu J, Tan MJ and Chua BW 2014 “Microstructure evolution of Ti-6Al-4V during superplastic-like forming” Procedia Engineering 81 1090–95
[14] Kumaresan G and Kalaichelvan K 2014 “Experimental studies of a rectangular cup formation of A17075 Alloy in Superplastic Forming Process” Procedia Material Science 6 892–896
[15] Okayasu M, Sato M, Mizuno M, Hwang DY and Shin DH 2008 “Fatigue properties of ultra-fine grained dual phase ferrite/martensite low carbon steel” International Journal of Fatigue 30 1358–65
[16] Малюшевский ПП 1983 “Основы разрядно-импульсной технологии” (Кiev, СССР: Наукова Думка) Malyushewsky P P 1983 “Basics of the pulse technology” (Kiev, USSR:
Naukova Dumka) (in Russian)]

[17] Деляusto ЛГ 2005 “Основы прокатки металлов в постоянных магнитных полях” (Москва, Россия: Машиностроение) [Delyusto L G 2005 “Fundamentals of metal rolling in a constant magnetic fields” (Moscow, Russia: Mashinostroyeniye) (in Russian)]

[18] Гринкевич ВА, Шевченко ТН, Краев МВ, Краева ВС, Бондарев СВ 2013 “Экспериментальное исследование пластической деформации стали Ст3 во внешнем магнитном поле” Обработка металлов давлением 37(4) 79–82 [Grinkevich V A, Shevchenko T N, Krayev M V, Krayeva V S and Bondarev S V 2013 “Experimental Study of Plastic Deformation of St3 steel in a magnetic field” Obrabotka metallov davleniyem 37(4) 79–82 (in Russian)]

[19] Golovashchenko S 2005 “Springback calibration using pulsed electromagnetic field” AIP Conf. Proc. 778 284–5

[20] Iriondo E, Alcaraz JL, Daehn GS, Gutierrez MA and Jimbert P 2013 “Shape calibration of high strength metal sheets by electromagnetic forming” Journal of Manufacturing Processes 15 183–93

[21] Batygin YV, Golovashchenko SF, and Gnatov AV 2013 “Pulsed electromagnetic attraction of sheet metals – Fundamentals and perspective applications” Journal of Materials Processing Technology 213 444–52

[22] Batygin YV, Golovashchenko SF and Gnatov AV 2014 “Pulsed electromagnetic attraction of nonmagnetic sheet metals” Journal of Materials Processing Technology 214 390–401

[23] Троицкий ОА 2009 “Ультразвуковое электропластическое плющение металла” Вестник научно-технического развития 10(26) 42–9 [Troitskiy O A 2009 “Ultrasonic electroplastic flattening of metals” Vestnik nauchno-tekhnicheskogo razvitiya 10(26) 42–9 (in Russian)]

[24] Falaleev AP, Meshkov VV, Vetrogon AA and Shymchenko AV 2016 “Evolution of mechanical properties of boron/manganese 22MnB5 steel under magnetic pulse influences” IOP Conf. Ser.: Mater. Sci. Eng. 110 012107