Lifelong modelling of properties for materials with technological memory

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Abstract. An investigation of real automobile parts produced from dual phase steel during standard periods of life cycle is presented, which considers such processes as stamping, exploitation, automobile accident, and further repair. The development of the phenomenological model of the mechanical properties of such parts was based on the two surface plastic theory of Chaboche. As a consequence of the composite structure of dual phase steel, it was shown that local mechanical properties of parts produced from this material change significantly their during their life cycle, depending on accumulated plastic deformations and thermal treatments. Such mechanical property changes have a considerable impact on the accuracy of the computer modelling of automobile behaviour. The most significant errors of modelling were obtained at the critical operating conditions, such as crashes and accidents. The model developed takes into account the kinematics (Bauschinger effect), isotropic hardening, non-linear elastic steel behaviour and changes caused by the thermal treatment. Using finite element analysis, the model allows the evaluation of the passive safety of a repaired car body, and enables increased restoration accuracy following an accident. The model was confirmed experimentally for parts produced from dual phase steel DP780.

1. Introduction

Numerical methods for engineering calculations, such as Finite Element Analyis, have become the most popular tool for engineering design; however, these methods can only give an adequate simulation of real processes where the material behaviour is adequately modelled. That is why it is so important to have an appropriate description of the properties of new materials, and it is for this reason that the implementation of new materials for designs using old calculation methods of or old models can lead to unpredictable results. Materials with technological memory are the most difficult type in respect of the implementation of their properties within a calculation, because the material characteristics change considerably at each step of the technological operation. Usually these changes of properties become apparent locally or are direction of loading dependent, so after a technological treatment the properties such of materials are anisotropic and heterogeneous. Complex phase steels, widely used as the basic metal for automotive vehicle body manufacture, are representative examples of such materials.

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Dual phase steel has a composite microstructure that consists of grains of martensitic phase and perlite phase, and demonstrates significant work hardening under plastic deformation. This structure is formed by quenching of steel at the temperature range of the critical temperatures of austenite transformation. The main drawback of this microstructure is that it can be inadvertently altered during the repair, as a result of heating, leading to reduced performance properties. Such heating or changing of the operational temperature during restoration, as is typical of various repair methods, has a significant influence on the microstructure of different kinds of high strength steels [1-5]. The great benefit of such metals is the capacity to dissipate large amounts of energy through plastic deformation during impact, which is a consequence of the high level of hardening. At any given point in the life of a dual phase steel component, the mechanical properties depend on all plastic deformations accumulated during previous operations.

A phenomenological approach is the most common tool for simulating the properties of dual-phase steels. The Chaboche kinematic hardening model is widely used to describe the behaviour of steel [4]. This approach combines isotropic hardening and non-linear models that take into account the Bauschinger effect [5, 6]. The calculation of mechanical behaviour after technological operations is a necessary and most difficult task. The degradation of dual-phase steel properties during repair procedures requiring heating are studied in papers [7, 8]. Research into the alteration of dual-phase steel hardness in the heat affected zone during welding is presented in [9], where the reduction of strength following cooling is attributed to the partial release or martensite; however the majority of research interest is in the influence of thermal effects on the dual phase steel during new material stamping. During the life of a real engineering component, it accumulates a lot of technological operation influences involving plastic deformation, repair, welding, heating, or straightening. One such example is a side member of car body, initially manufactured by stamping and welding, subsequently plastically deformed during an accident, and then repaired by pre-heating then stretching the pre-heated dent. The problem is to predict the real mechanical properties of this part, and how to simulate its behaviour under subsequent plastic deformation.

2. The aim and strategy of the investigation

The aim of this article is to develop algorithms, models and equations for calculating the mechanical properties of materials with technological memory following technological treatments, as in the example of the side member of a car body made from dual phase steel, following the consecutive processes of production, plastic deformation, repair and further new plastic deformation.

The most critical technological factors causing microstructural changes, and therefore changes in mechanical properties as it is composite structure with nonstable microstructure, are: accumulated plastic deformation, taking account of the history of the deformation directions; deformation rate; current temperature of the metal; history of thermal treatment and relaxation period.

The strategy of this work is to develop:

1. A phenomenological model for the mechanical properties of dual phase steel, based on Chaboche two surface plasticity, by adding
2. Empirical relations for the stretch behaviour of pre-compressed heated metal,
3. Empirical relations for the evolution of mechanical properties of dual phase steel after heating, holding at temperature for a period of time, and then cooling to the normal temperature after this (these relations were investigated in previous studies [7-9]), and
4. Finite Element Analysis (FEA) of the reconstruction of the behaviour of the car body side member under the three consecutive thermo-mechanical operations, dynamic plastic compressed deformation, restoration by heating, and then dynamic compressed deformation again. In these analyses, every subsequent FEA iteration must use the output data from the previous calculation as input data for next operation.

3. Methods of experimental studies

The mechanical properties of DP 780 steel samples were determined on a universal tensile testing machine. The chemical composition of the investigated steel DP780 is: 0.18 C; 0.5 Si; 2.0 Mn; 0.025 P; 0.8 Cr; 0.015 S.

Table 1. Mechanical properties of steel.

Material	Yield strength, MPa	Tensile strength, MPa	Maximum elongation, %
DP780	490	780	14

Monotonic tension and reverse loading (compression-tension) was executed on a universal tensile testing machine MTS 810, while fixing the sample to prevent buckling under compression and heating during the test. Elongation was recorded by laser extensometer LE-05. To prevent loss of stability of the test sample, it was supported by applying 3.35 kN lateral force by applying pneumatic cylinders on both sides. The stabilizing lateral force was applied to the sample through a set of rollers and Teflon coated plates in order to reduce friction.

When using the stabilizing lateral force it is necessary to perform a correction of output readings, taking into account the friction forces between the sample and the support plate and complex stress status of the test sample [10]. The coefficient of friction was determined by dividing the axial force during the normal loading. The average value in the series of similar experiments was 0.165.

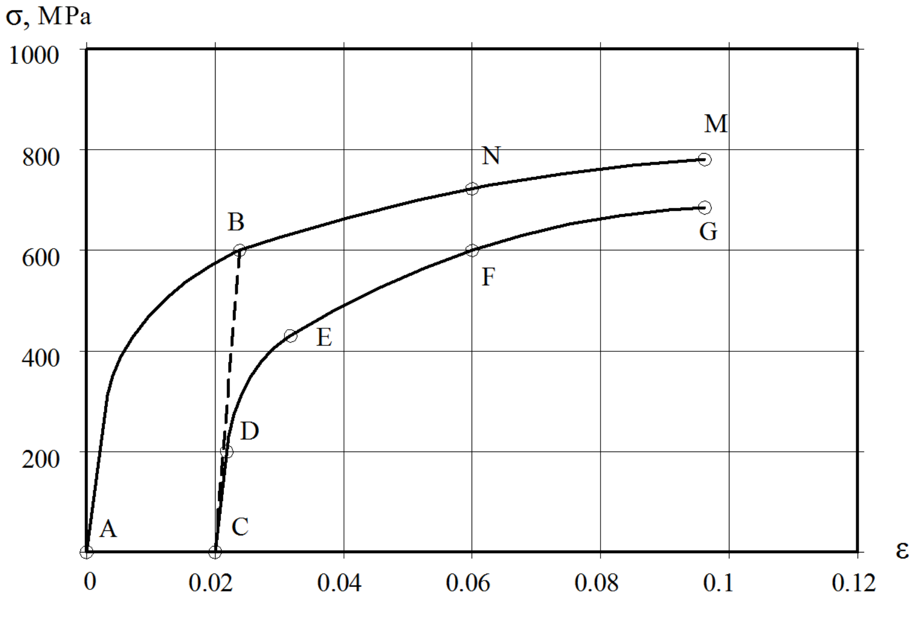

Figure 1. Compression-tension of DP780 dual-phase steel.

Specimen heating occurs as a result of heat exchange with the heating element via a plate with a Teflon coating. Oak spacers were used to isolate all the mechanisms of the testing machine. Temperature control was ensured by means of a calibrated thermocouple installed in the centre of the heating clamping plates. During stretching, the pre-compressed metal is heated to 150 °C, 300 °C, and 450 °C. These are the same conditions that the vehicle body undergoes during heated drawing.

The true behaviour of dual-phase steels is shown in figure 1. Samples of steel were pre-compressed to a value of effective residual strain of 0.02 (section A-B), the load was removed (section

B-C), and then the samples were stretched (section CG). Compression and tension are shown in the first positive quadrant of the graph (figure 1). While analysing the behaviour of the DP 780 dual-phase steel (figure 1), the following states can be singled out: the Bauschinger effect (point D), transition near the onset of hardening plasticity (point E), and softening in the area (F-G). In order to construct a model of the behaviour of such steel it is proposed to use a two-dimensional rheological Chaboche theory [4].

4. Main relations of the model accounting for technological material memory

4.1. Two surface plasticity model

According to theory, it is assumed that the stress tensor can be used to define both a surface of elasticity (limit of proportionality), f, and a surface of plasticity (yield strength of the material of the surface), F. Inside surface f the material behaves linearly elastic and obeys Hooke's law. Outside of F the material behaves plastically. The distance between the surface of plasticity and the surface of the elasticity is a continuous function, which describes the type of non-linear elastic deformation, *i.e.* variable elastic modulus.

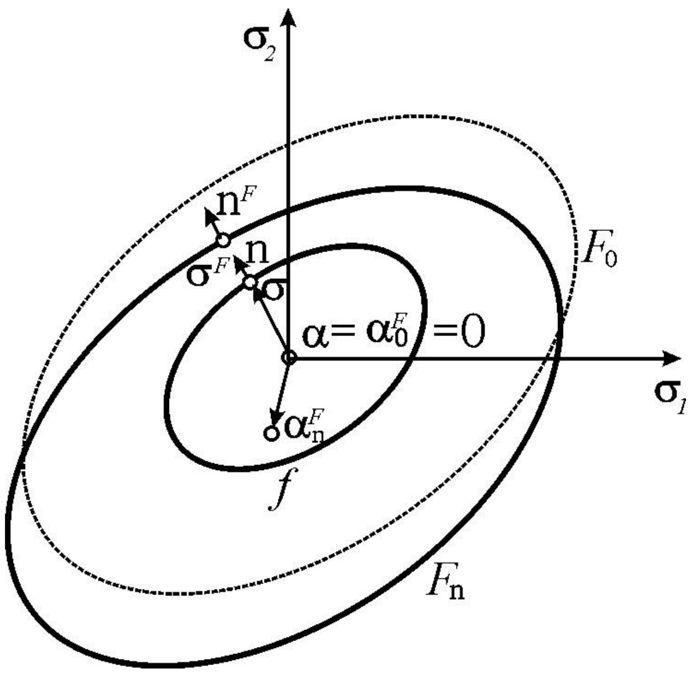

Figure 2. Graphic interpretation of the two-dimensional plasticity model.

Figure 2 shows the behaviour of the surface f, which represents the elastic state, and F, which determines the plastic state in the plane of the principal components of the stress tensor (for the two-dimensional case).

Surfaces f and F can be described by the equations:

$$f = \varphi(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - r(\varepsilon^P, \dot{\varepsilon}^P, T) = 0\,, \tag{1}$$

$$F = \Phi(\boldsymbol{\sigma}^F - \boldsymbol{\alpha}^F) - R(\varepsilon^P, \dot{\varepsilon}^P, T) = 0\,, \tag{2}$$

where r and R limit the dimensions of surfaces f and F respectively, and the location of their centres is determined by the tensors of residual microstrain $\boldsymbol{\alpha}$ and $\boldsymbol{\alpha}^F$ respectively. The dimensions and coordinates of the centres of surfaces f and F do not change during the elastic deformation.

When stress tensor $\boldsymbol{\sigma}$ reaches a boundary of the surface f, the centre of the surface, $\boldsymbol{\alpha}$, begins to move along the surface in the direction of stress growth. When the inner surface, f, reaches the boundaries of the surface F, the material is then in the plastic state. According to the conditions of the surface translations, the contact occurs at the point congruent to the stress tensor. The increment of the stress tensor is directed outward from the surface f, $d\boldsymbol{\sigma} :: d\mathbf{n} > 0$. Both types of deformation, described by this theory – plastic deformation $\boldsymbol{\varepsilon}^P$ and elastic deformation $\boldsymbol{\varepsilon}^e$ – are present at this moment.

During deformation, the dimensions of the surfaces f and F may be changed to reflect the isotropic hardening of the material [4].

The Bauschinger kinematic hardening effect is simulated by the residual microstrain tensor. Both kinematic and isotropic hardening is pronounced in modern automotive steels, reflecting the capacity for significant energy absorption during deformation. The tensor of residual microstrain $\boldsymbol{\alpha}^F$ is described in accordance with the Chaboche model:

$$\boldsymbol{\alpha}^F = \boldsymbol{\alpha}_1^F + \boldsymbol{\alpha}_2^F \tag{3}$$

$$d\boldsymbol{\alpha}_1^F = \frac{2}{3}C_1 d\boldsymbol{\varepsilon}^P - \gamma \boldsymbol{\alpha}_1^F d\bar{\boldsymbol{\varepsilon}}^P \tag{4}$$

$$d\boldsymbol{\alpha}_2^F = \frac{2}{3}C_2 d\boldsymbol{\varepsilon}^P \tag{5}$$

The term, $d\bar{\boldsymbol{\varepsilon}}^P$, here is the equivalent increment of plastic strain

$$d\bar{\boldsymbol{\varepsilon}}^P = \left(\frac{2}{3} d\boldsymbol{\varepsilon}^P : d\boldsymbol{\varepsilon}^P\right)^{1/2} \tag{6}$$

Evaluation of the size of the surfaces of elasticity and plasticity is a major theoretical problem in the phenomenological approach, as it determines the start of the plasticity and residual deformation. The dimensions of the surfaces r and R are determined experimentally based on the elongation diagram of the metal. Evaluation of mechanical properties will lead to changes in size of R surface.

4.2. Empirical study of the influence of temperature on pre-compressed metal

The feasibility of repair of body parts has not yet been the subject of significant research, nor has the impact of local changes in strength, as a result of local heating, on the behaviour of the entire structure. Experimental studies to simulate the process of heated drawing of the deformed parts (including pre-compression and following drawing with heating) were carried out. Such a loading sequence is typical during the repair of a deformed vehicle.

Compression-tension diagrams were recorded during testing of the DP780 dual-phase steel (figure 1). A decrease in strength, ductility and a change in hardening rate, with increasing temperature, is demonstrated.

Empirical dependency is used to describe the behaviour of steel in the heated state. Dependency is represented as a result of multiplying the isotropic hardening h_1 and the heat evolution h_2.

$$\sigma = \sigma(\varepsilon, T_H) = h_1(\varepsilon, T_H) \cdot h_2(T_H) . \tag{7}$$

The function h_1 reflects the impact of plastic deformation degree, taking into account the nature of hardening change under the influence of temperature. The term h_1 is a combined function of $g_1(\varepsilon)$ and $g_2(\varepsilon)$.

$$h_1(\varepsilon, T_H) = \beta(T_H)g_1 + (1 - \beta(T_H))g_2 \, , \tag{8}$$

where T_H – heating temperature of steel; ε – accumulated plastic deformation of the metal. Function $g_1(\varepsilon)$ reflects the behaviour of the hardening curve at a temperature of 20 °C, while under the influence of heating, the function of ductility takes the form of $g_2(\varepsilon)$. The transition from one form to another is performed in accordance with the function $\beta(T_H)$. The function $\beta(T_H)$ changes from 0, at 20 °C, to 1, at 450 °C. For $\beta(T_H)$=0, h_1 degenerates to $g_2(\varepsilon)$, and for $\beta(T_H)$. = 1 – to $g_1(\varepsilon)$. The Zener-Hollomon parameter [11] was used to describe the work hardening of metal in normal conditions $g_1(\varepsilon)$ while Voce's function [12] was utilized to describe heated metal $g_2(\varepsilon)$.

$$g_1(\varepsilon) = K \cdot \varepsilon^n \, , \tag{9}$$

$$g_2(\varepsilon) = \sigma_0(1 - A\exp(-B\varepsilon)) \, . \tag{10}$$

We can transform (8) into

$$h_1(\varepsilon, T_H) = \beta(T_H)K \cdot (\varepsilon)^n + (1 - \beta(T_H))\sigma_0(1 - A \cdot e^{-B \cdot \varepsilon}) \, . \tag{11}$$

For the $\beta(T)$ function it is convenient to use simple linear law:

$$\beta(T_H) = \beta_1 - \beta_2(T_H - T_0) \, , \tag{12}$$

where β_1, β_2 – constants derived from the experimental data; T_H – heating temperature of steel; and T_0 – base temperature (20^{0}C).

The need to develop this function arises from the diagram of dual-phase steel for stretching at various temperatures (Figure 3). The graph shows that the hardening rate depends on the temperature and decreases with temperature increase. This behaviour is not considered in the traditional phenomenological models.

A simple linear function will be used for the function $h_2(T_H)$. Heating during the repair cannot be controlled with high precision because of the large volumes of heated metal, the thermal conductivity and the specific heat of the material. Therefore, during the repair, the accuracy of linear dependence (even with the certain error) will be higher than the accuracy of the temperature control methods:

$$h_2(T) = \sigma(1 - \beta_3(T_H - T_0)) \, , \tag{13}$$

where β_3 – experimental constant.

The final iteration of the plasticity evolution equation for dual-phase steel, taking into account the isotropic hardening and heating:

$$R(\varepsilon, T_H) = [\beta_1 - \beta_2(T_H - T_0)K \cdot (\varepsilon)^n + (1 - \beta_1 - \beta_2(T_H - T_0))\sigma_0(1 - A \cdot e^{-B \cdot \varepsilon})][1 - \beta_3(T_H - T_0)] \, . \tag{14}$$

The empirical coefficients of the model were obtained by the method of least squares and are presented in table 2.

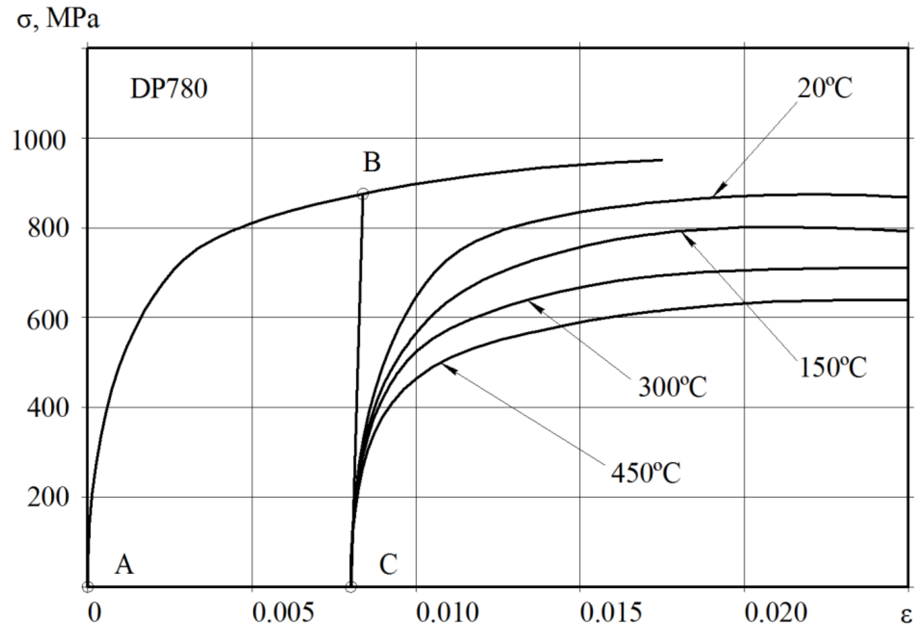

Figure 3. Compression-tension diagram of DP780 steel at 20 ^{0}C, 150 ^{0}C, 300 ^{0}C and 450 ^{0}C.

Table 2. Empirical model coefficients.

Steel	K, n	σ_0	A	B	β_1 β_2	β_3	R^2 $\sqrt{D}$, MPa
DP780	1655 0.213	752.1	0.265	30.31	0.507 0.00187	$5.8\cdot10^{-4}$	0.998 2.5

4.3. Empirical study of the mechanical properties evolution after cooling, depending on heating temperature and hold duration

These studies were performed in previous investigations [7-9] and underpin the use of the final relations reflecting considerable degradation of the mechanical properties of dual phase steels following technological heating to the temperature more than 600 ^{0}C and for durations of more than 20 minutes. The lower temperatures and shorter durations did not affect mechanical properties so much; otherwise, the maximum temperature and hold duration, taking into consideration the simulation of the evolution of the plasticity limit during the repair, with non-isothermal heating, are proposed.

$$R(\varepsilon,T,t)=\left[(1-\alpha(T,t))K_2\cdot\varepsilon^{n_2}+\alpha(T,t)(\sigma_0-(\sigma_0-B_6)\exp(-a_1\cdot\varepsilon))\right]\cdot\left[1+\frac{C_1\cdot t^{n_5}\left(\dfrac{T}{C_3}+C_2\right)^{n_6}}{\sigma_0}\right], \tag{15}$$

where

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$$\alpha(T,t)=\left(1-\frac{\sigma_{B0}-B_1\cdot t^{n_3}\left(\frac{T}{T_{AC1}}+B_2\right)^{n_4}}{\sigma_{B0}}\right), \quad (16)$$

T – heating temperature, ^{0}C; T_{AC1} – temperature of phase transition critical point AC_1; ε – accumulated plastic strain; σ_{BO} – tensile strength of the base metal MPa; t – holding time at the maximum temperature, s; $R(\varepsilon,T,t)$ – function of the limit of plasticity evolution after the cooling; and the following are empirical coefficients:

$K_2, n_2, \sigma_0, B_6, a_1, C_1, C_2, C_3, B_1, B_2, n_3, n_4$

Table 3. Empirical coefficients of evolution model of temperature degradation.

Steel	K_2, n_2	n_3, n_4, n_5, n_6	C_1, C_2	B_1, B_2, B_4, B_6	σ_0, σ_{BO}	a_1, T_{AC1}	R^2, $\sqrt{D}$, MPa
DP780	1655 0.213	0.66 6.5 0.66 3.44	2.38 0.4	0.034 0.024 2.21 300	260 780	8.56 724	0.999 0.7

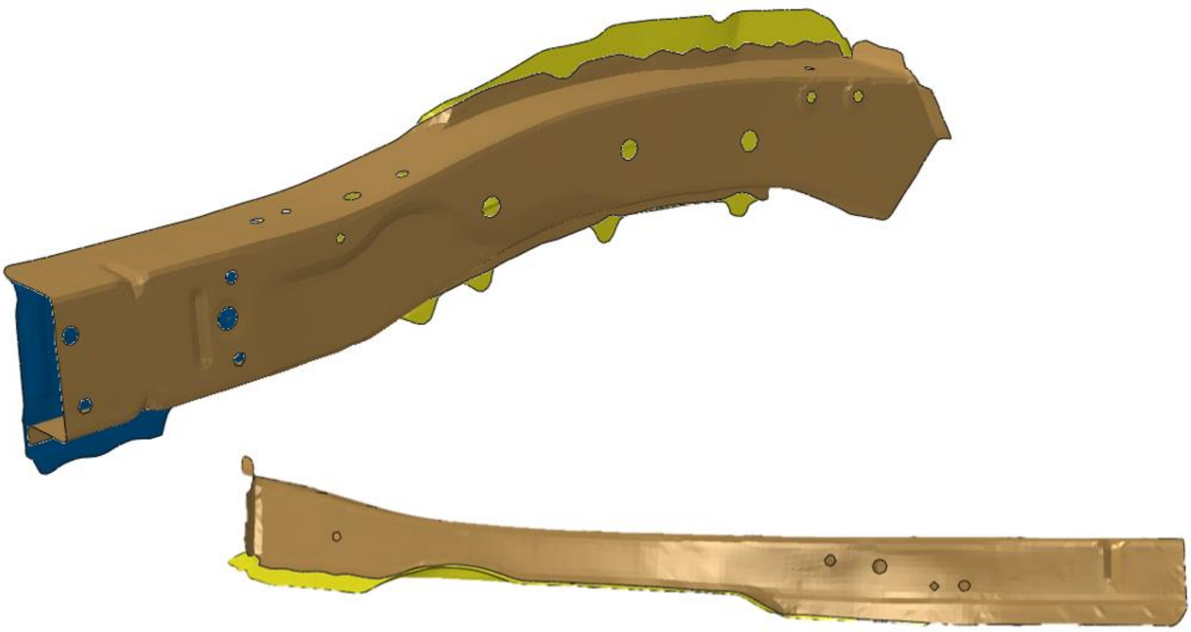

Figure 4. Shape of the side member under investigation.

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5. FEA modelling of consecutive technological operations on side members

To evaluate the feasibility of dual-phase steel side member repair by drawing under heating, an computational experiment was conducted with a finite element model of the side member, using ABAQUS 6.11-3 Standard. Side member material properties were calculated in accordance with the UMAT procedure. To communicate with the ABAQUS pre-processor through the UMAT interface a program was developed that allows input of material properties with the help of the `INPUT FILE` file and `* USER MATERIAL` command.

Dual-phase steel DP780, with wall thickness of 1.5 mm, was chosen as the material of the detail. A curved shape was specified for the side member (figure 4), and was used to obtain strains that are typical for repairs using drawing techniques.

At the first stage of trial, the new side member was deformed by an impact with a flat rigid plate of mass 500 kg, travelling in axial direction at a speed of 16 m/s (figure 5).

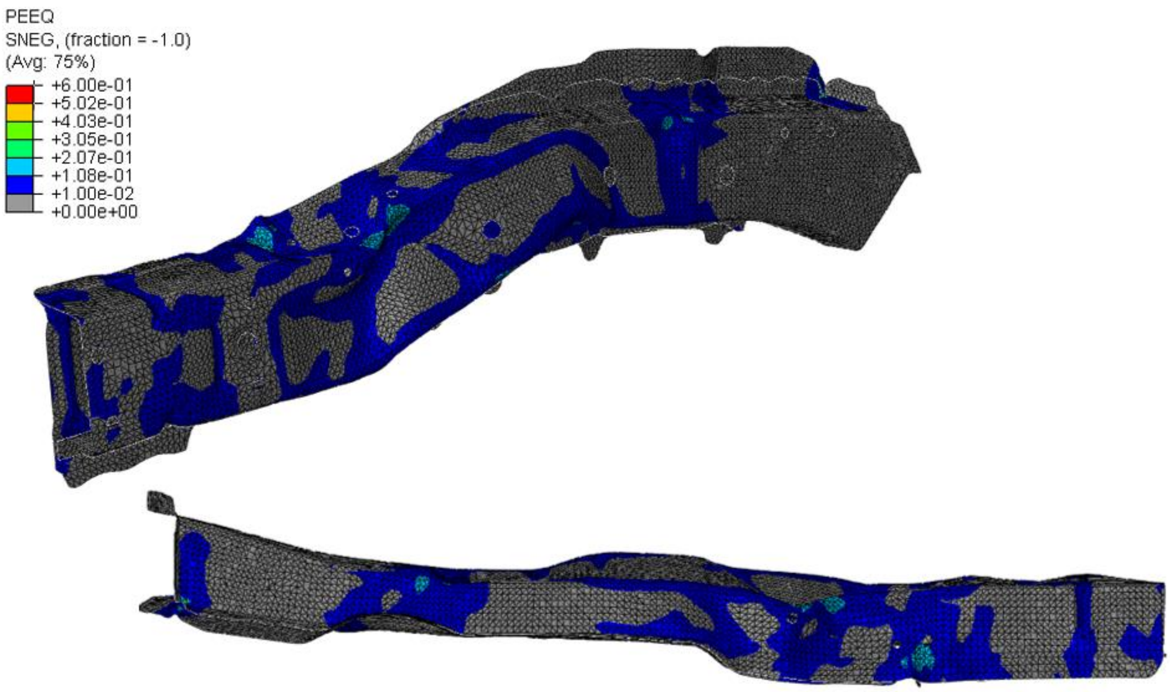

Figure 5. Deformation and stress in the side member after collision.

The analysis results of the new deformation of the side member (figure 5) show damage typical of frontal impact. The side member lost stability and bent at the base, where it is mounted, and at the tip, which is the point of force application. The most significant deformation occurred in the middle, as this is the site of application of the largest forces. The plastic strain energy in this case was equal to 10.5 kJ.

During the second phase of testing, the pre-deformed side member (figure 5) was subjected to a tensile load to simulate the process of repair. The data output file (Output Database) from ABAQUS has been exported to the original file (Input File), making it possible to transfer information about the accumulated strain in each element. Deformed elements were heated to reduce their limit of plasticity to the values of non-deformed metal in order to compensate for the strain hardening and equalize the strength characteristics of all elements. The heating temperature of each deformed element was calculated individually depending on the degree of deformation according to equation (14).

By substituting the value of the accumulated plastic deformation we determine the amount of heat required for each finite element. The same value of plasticity is achieved for all the elements of the detail by assigning the heating temperature to each of the elements.

Elements of the side member that used to have a strain now demonstrate a degradation of the ductility properties: this can be seen as a reduction of the hardening curve. The magnitude of degradation is in direct correlation with the degree of plastic deformation. Degradation is calculated according to equation (15).

The same distorted side member was subjected to drawing with overheating to investigate the effect of a non-optimal method of repair on the behaviour of steel. The side member was heated to a temperature of 700 °C. Optimally heated and overheated side members returned to the same shape after drawing, therefore completely restoring an original geometry.

The optimally heated and overheated repaired side members were deformed again at the next stage of the research. The numerical experimental conditions of load and speed were kept the same (figure 4). In the collision results (figure 6), both components exhibit an increase in deformation compared to a new side member. Note that all deformations arising from the three sequential numerical experiments was taken into account as part of the experimental methodology, therefore both the repaired parts have a significant number of elements which have modified properties, shown in the colour scheme of figure 5. The side member component repaired with minimal heating (figure 6 a) shows only a slight deviation of the shape compared to the new sample, with the strain concentration in the middle.

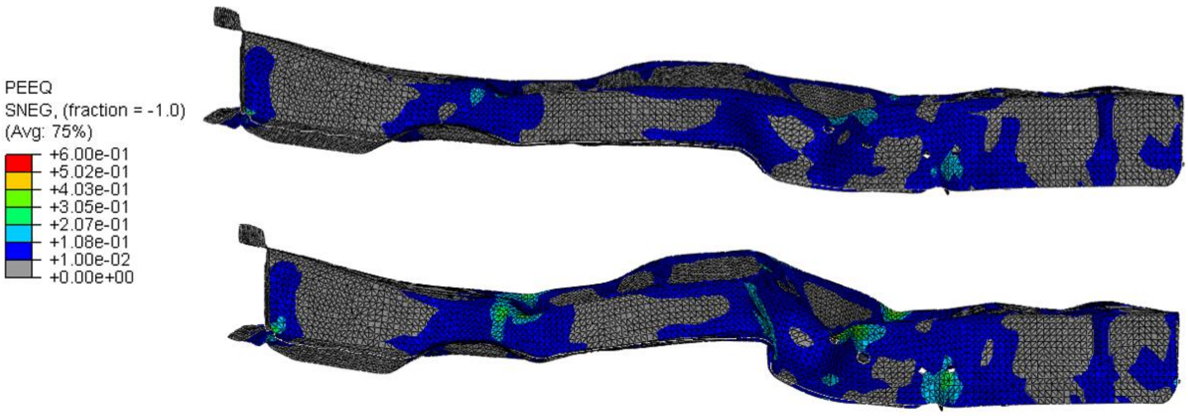

Figure 6. Deformation and stress in the repaired side members after repeated impact: (a) the optimally heated; (b) overheated.

6. Results and discussion

Simple visual evaluation (figure 6b) reveals differences in the shape of the overheated detail and demonstrates the presence of considerable strain along the length of the side member. The increased deformation of the part under load is presented in figure 7. The results for the model of the new side member reached the point of maximum deformation at 0.06 ms. Beyond that point it demonstrated some elastic unloading behaviour. The repaired, optimally heated side member finished the stage of energy absorption after 0.08 ms, while the repaired, overheated part continues deformation until past the 0.1 ms mark, showing no sign of elastic unloading. Comparison of the energy absorption graphs

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allows for a quantitative evaluation of changes in performance properties as a result of repair (figure 8).

The experiment conducted demonstrates that for a repair carried out with optimally heated drawing is able to sustain the level of passive safety of heat-treated steel car body in frontal impact. Energy absorption capability reduction of only 3% was observed in comparison with that of a new part. On the other hand, uncontrolled heating of the part during a repair can lead to a significant 18% drop in energy absorption and an increase in residual strain of 100%, which could be unacceptable for the purpose of providing body passive safety.

7. Conclusion

This series of studies has verified a methodology for the restoration of the material properties of passive safety components manufactured from heat-treated steels. Recovery technology and temperature conditions should be developed taking into account the evolution equations (14) and (15). The heating temperature must be strictly monitored during the repair, in accordance with the designed conditions. Adherence to the method of recovery could enable a significant reduction in body repair cost by allowing restoration of parts that are currently being replaced.

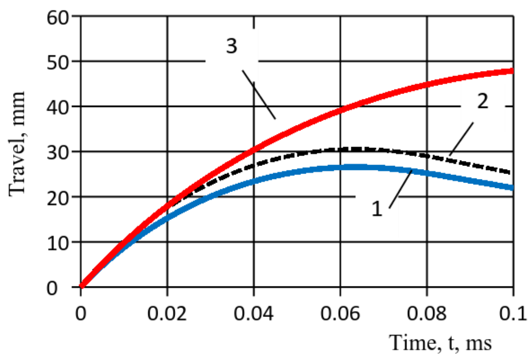

Figure 7. Side member travel during impact.

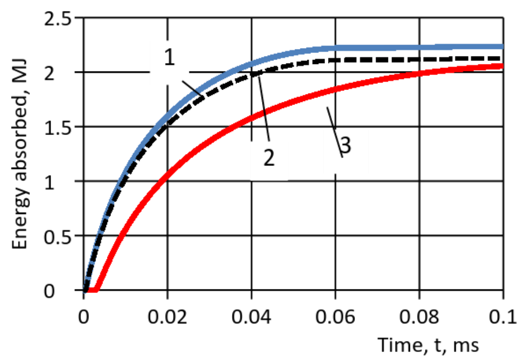

Figure 8. Collision energy absorption.

1 – a new side member; 2 – optimally heated during the repair; 3 – overheated during the repair.

The investigation confirms that the algorithm developed for the calculation and modelling of mechanical properties, which are then used in consecutive FEA iterations, can be used to predict the long term life behaviour of engineering machine components. The numerical calculation procedure consists of repeated numerical simulations of real technological operations on a real component. Such an approach is time resuming, but enables the acquisition of numerical results showing mechanical properties that reflect real anisotropic, and heterogeneous distortion, behaviour. Additionally this provides the opportunity for optimisation of future planned technological operations, such as the temperature control performed during this experimental study.

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