NUMERICAL SIMULATION OF WELDING HIGH CARBON STEEL AFTER SPD PROCESS

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Abstract

The methods of intensive plastic deformation SPD (Severe Plastic Deformation) belong to a group of very attractive means of increasing utility properties of metallic materials (strength and structural characteristics). The paper is focused on numerical simulation forming of high-carbon steel C55E processed by the SPD DRECE (Dual Rolling Equal Channel Extrusion) and GTAW-141 welding process by Simufact software. Numerical simulation of welding and forming process benefits allows much wider perform verification of the influence of individual technological parameters on the final properties. On the test welds were verified and compared results of numerical simulation. Last but not least, acquired information about the weldability, mechanical properties, structure, distribution of residual stresses allow an effective deployment of given materials in real industrial applications.

Keywords: Numerical simulation welding, high-carbon steel, residual stress, severe plastic deformation, Simufact.welding software

1. INTRODUCTION - CHARACTERISTIC OF THE PROBLEM

SPD processes enable to greatly improve properties of materials. At the Department of Mechanical Technology at VŠB-TU Ostrava we created a number of devices which enable processing various materials, such as alloys of aluminium, copper and steel. Successful industrial utilization of such materials requires, among other things, solving problems of connecting these materials with certain welding technologies, including welding, soldering and adhesive bonding. Earlier papers experimentally examined on a limited scale the weldability of steel processed through SPD DRECE process using 142-GTAW and 15-PAW welding technologies. The optimization of welding process requires a relatively extensive experiment. For this reason, we prepared in parallel a numerical model, which would enable continuous verification of other technological variations without the need for further demanding and extensive experiments. To create the numerical model, we used Simufact (Forming & Welding) program environment, which allows for an advanced numerical simulation of two technologies - forming and welding - in one environment at the same time.

2. EXPERIMENTAL MATERIAL

As an experimental material, we used steel strips made from high-carbon steel measuring 50 x 2 x 1000 mm, which were labelled C55E (12060 according to the Czech standard). Chemical composition and default mechanical properties are shown in **Tables 1** and **2**. Since the Simufact program database did not include the C55 material, we created a new equivalent material for the database based on C45 steel. **Figures 1** and **2** show reinforcement curves and CCT diagram used for structure simulation.

Table 1 Chemical composition of the high carbon steel C55E

Steel	C [wt. %]	Si [wt. %]	Mn [wt. %]	Al [wt. %]	P [wt. %]	S [wt. %]
C55E	0.53	0.03	0.43	0.02	0.030	0.035

Table 2 Mechanical properties of the high carbon steel C55E initial state (IS)

Steel C55E	Tensile Strength [MPa]	Yield Strength [MPa]	Elongation [%]	Hardness HV10
IS	549	373	21.1	176

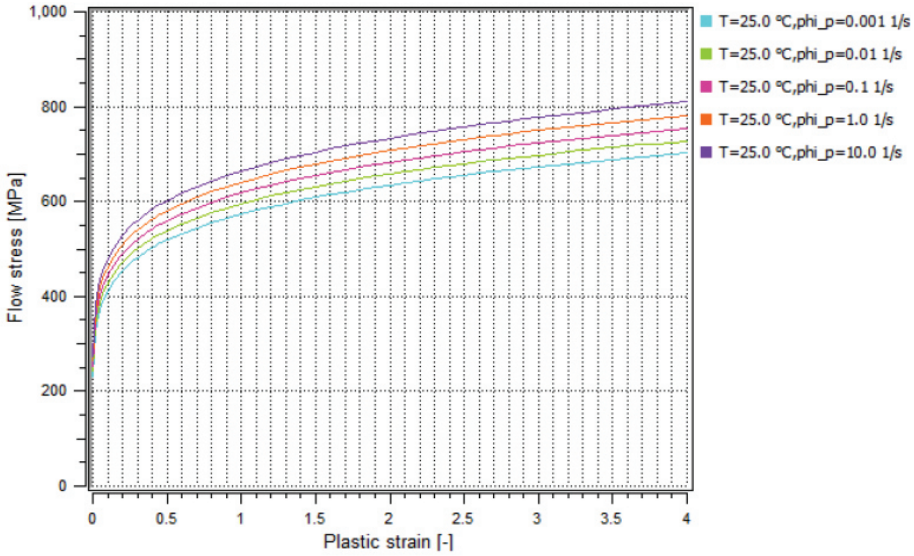

Figure 1 Flow stress curves for used steel

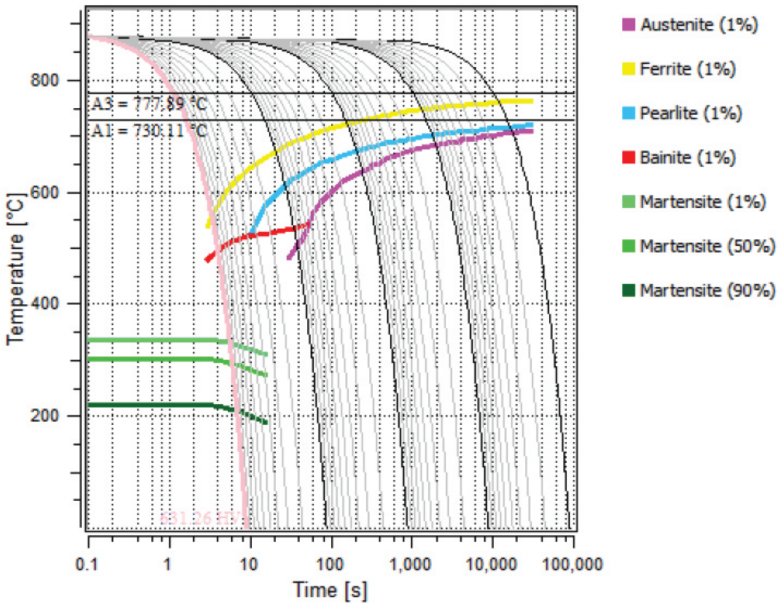

Figure 2 CCT diagram used steel

3. NUMERICAL SIMULATION OF SPD DRECE PROCESS

For numerical simulation of DRECE process, we created a modular model of the technology, which comprised a main cylinder, two pressure cylinders and a wedge between upper and lower pressure cylinder. (see **Figures 3, 4**) [1, 2]. We chose parts of the processed sheet's retainer as optional elements. In case of a change in the geometry of each tool, it is possible to modify the respective geometry in the model and simulate a new state or alternatively, based on a calculation, to modify the geometry of real models. With respect to the geometry of tools and network parameters, it is possible to change the width of the intermediate product. When using a 5 mm element size, it was necessary to increase the width of processed sheet from 48 mm (used in experiment) to 50 mm in order to create elements of the same measures across the sheet. With the original width of 48 mm the outer elements of the sheet had measures of 4 x 5 mm and this irregularity had influence on non-homogeneity of stress in the main axes. Sheet length was decreased to lower calculation time from 1000 mm to 500 mm. The sheet processed had therefore measures of 50 x 2 x 500 mm. In order to avoid misalignment of the sample and to keep its width, which was supposed to remain constant during the process, we included in the process geometries for more accurate conduit of the sheet in direction of movement.

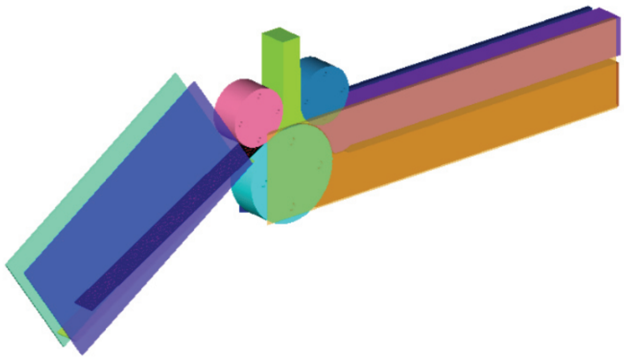

Figure 3 Model of DRECE equipment

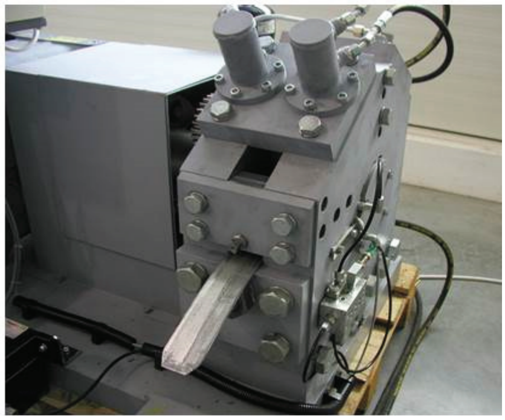

Figure 4 Prototype of the DRECE equipment [1]

These geometries were a feeder ensuring direct movement of the sheet when inserting the sheet between the main cylinder and the guiding cylinder and supporting sides preventing misalignment of the sheet after the passage through tools. All of these supporting geometries, which were not included in the real experiment, were assigned zero friction with the intermediate product. For the FEM model, we used two types of meshes - Sheetmesh and sIMesh Tetra. Sheetmesh is the default mesh for meshing of intermediate products in form of sheets for further processing for example through rolling, bending or stamping. SIMesh Tetra is used for extremely complicated intermediate products, which are subjected to large volumetric changes of shape such as forging, extrusion etc. With respect to the length of simulation calculations, we chose element measures of 5 mm in both samples and set remeshing to occur upon reaching intensity of deformation of 0.4. The first type of element used in simulation is HEXAHEDRAL, which is used in the final element mesh SHEETMESH with three elements in sheet depth. With this mesh setting, the intermediate product is defined by 6827 elements. The data obtained clearly show the influence of the passage of sheet through DRECE instrument on size and intensity of deformation achieved. The choice of a final elements mesh type has dominant influence on the properties achieved. Using SheetMesh with elements spread to form hexahedrons between them, we achieved deformation intensity ε_{max} = 2.2 after 6 passages through DRECE facility. Using sIMesh Tetra with elements spread to form tetrahedrons between them, deformation increased up to the level of intensity ε_{max} = 3.3. The maximal stress intensity in the last, sixth, passage increased to 670 MPa using SheetMesh and 710 MPa using sIMesh Tetra. Stress in the *x* and *z* axes with SheetMesh after six passages showed introduction of pressure stresses of values σ_x = - 120 ± 20 MPa a σ_z = - 45 ± 15 MPa. When using sIMesh Tetra, the stress in the axes during processing was very fluctuating. In that respect, use of sIMesh Tetra appears to be inappropriate for further use for welding. With regard to the voltage waveform we only transferred the processed sheet with SheetMesh to the Simufact.welding program. **Figures 5-8** depict results of stress intensity and deformations after first and sixth passage. **Figures 9-10** show residual stress in the *x* axis after first and sixth passage.

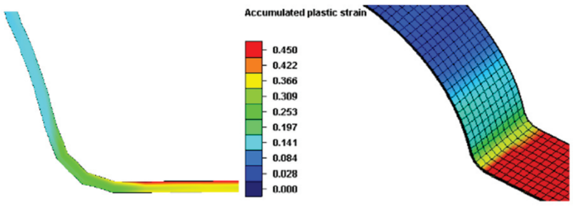

Figure 5 Accumulated plastic strain after 1st run DRECE, center plate

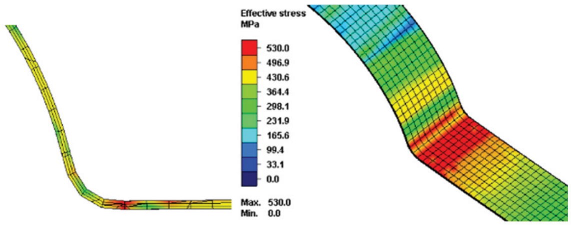

Figure 6 Effective stress after 1st run DRECE, center plate

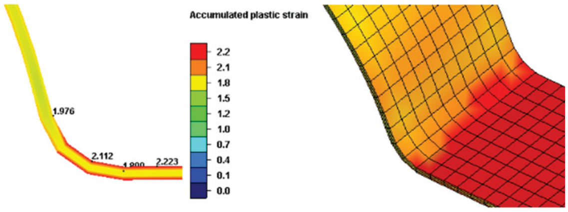

Figure 7 Accumulated plastic strain after 6x DRECE, center plate

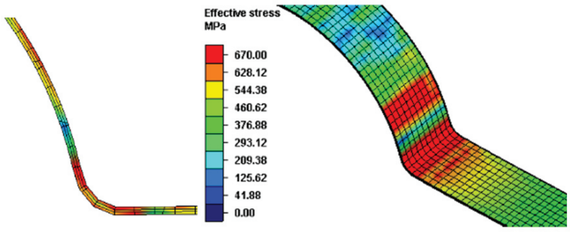

Figure 8 Effective stress after 6x DRECE, center plate

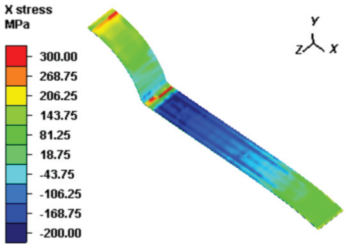

Figure 9 Residual stress in x direction after 6x DERECE

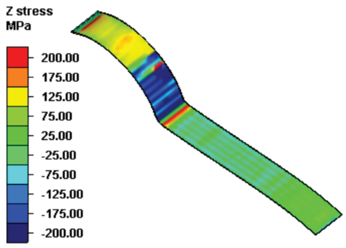

Figure 10 Residual stress in z direction after 6x DERECE

4. NUMERICAL SIMULATION OF WELDING

The DRECE process brings into materials a significantly different state in tightness values, properties and structure compared to default state. These findings are vital to respect while subsequently simulating welding technology. Use of a single software platform simplifies this requirement. We transferred the results through a file in SPR format and chose GTAW-141 as the primary welding technology. Welding parameters are shown in lit. [5, 6]. For the simulation, we selected a double ellipsoidal model of heat source (see **Figure 11**), which was calibrated to the size of melted area (see **Figure 12**).

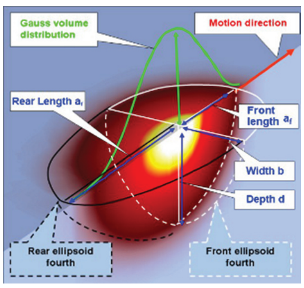

Figure 11 Heat source model [7, 8, 9]

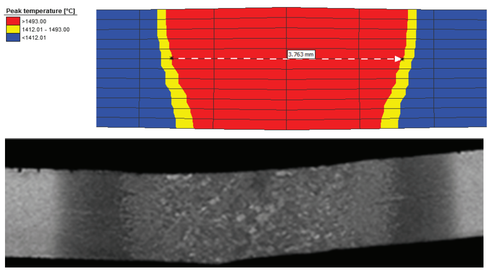

Figure 12 Heat source calibrations

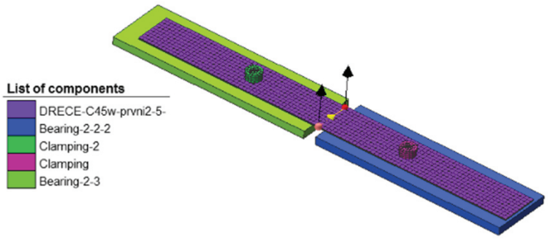

Figure 13 Clamping no treated steel strip

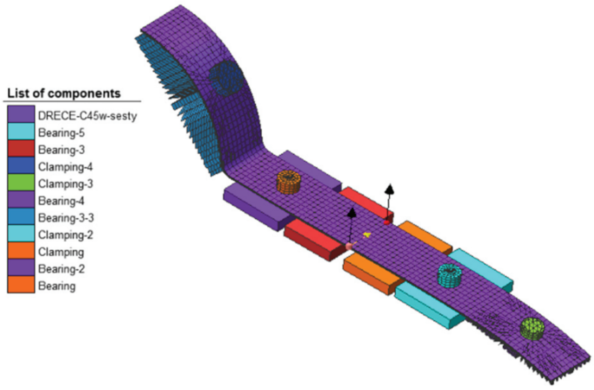

Figure 14 Clamping steel strip after DRECE

Figures 13 and 14 show welding process models without DRECE technology and after DRECE technology. The duration of movement delay at the start of trajectory was identical to the real experiment that is 2 s. Clamps were removed after 90 seconds from the beginning of welding. Total calculation time needed to be set accordingly in order to include the time required for cooling of the part. The total time of calculation was 150 seconds, with the welding process itself comprising 32 seconds. Temperatures that were achieved during welding of the sheet in default state and after processing were equal. Due to lower speed of heat removal form the weld joint, the weld pool at the end of the sheet widened. The highest temperature measured at the end of cooling after 150 s was 77 °C. Cooling time $\Delta t_{8/5}$ in the middle of the joint was 9.5 seconds. **Figure 15** shows the result of thermal analysis. Based on an inserted CCT diagram (see **Figure 2**), we conducted structural analysis concurrently with thermal calculation. The result after welding is shown in **Figure 16**.

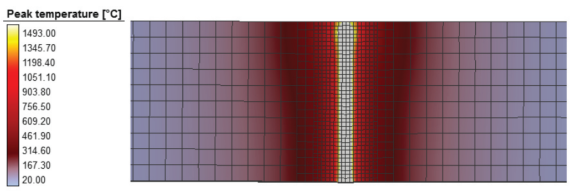

Figure 15 Thermal analysis

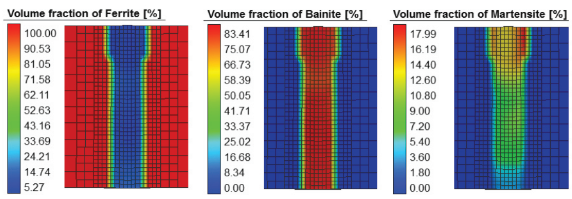

Figure 16 Structure analysis-6x DRECE weld

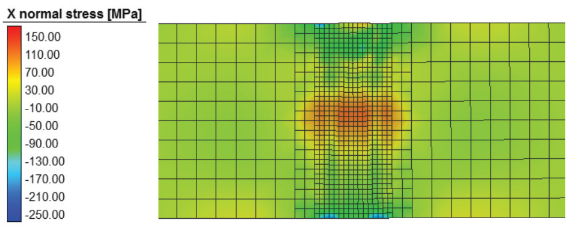

Figure 17 Residual stress in the x axis (perpendicular to the weld)-untreated plate

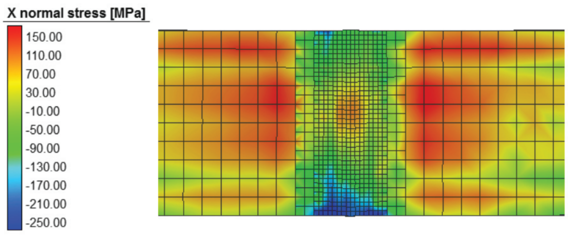

Figure 18 Residual stress in the x axis (perpendicular to the weld)-6x DRECE

The final structure in the joint after cooling contains, with configured parameters of the source, a high content of hard structures, primarily bainite (80%) and martensite and ferrite in smaller amounts (see **Figure 16**). This results in high hardness in welded metal of 480 HV, which corresponds to experimental results [3, 4, 5]. The configured heat source thermally influences source material to the width of 6.5 mm of weld axis. Simulation of multiple plastic deformation in DRECE facility confirmed the hypothesis of usability of only final elements mesh by SheetMesh, as its elements form a hexahedron. The result of SPD processing is a sheet with accumulated deformation of size 2.3. Stress in the *x* and *z* axes with use of SheetMesh meshing after six passages showed introduction of pressure stresses of the size of σ_x = - 120 ± 20 MPa a σ_z = - 45 ± 15 MPa (see **Figures 17, 18**).

5. CONCLUSION

The paper presents results of advanced FEM simulation of welding high-carbon steel after SPD process. The simulation itself contains a proposal of a DRECE technology model, a welding model proposal with and without SPD process. A modular numerical model system allows for quick modifications to both DRECE technology (including change to the geometry of instruments and change of material) and welding technology. The results acquired correlate well with the experiment [5]. Achieving compressive residual stresses during the process of DRECE technology inside the material has a positive influence on the weldability of the given material. The process of designing and optimization in processing new materials can be greatly accelerated by using advanced numerical simulation use of other welding technologies with minimal requirements on the experiment.

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REFERENCES

[1] RUSZ, S., MICHENKA, V., SALAJKA, M., TYLSAR, S., KEDRON, J. and JANCA,M. The forming of strip sheet of low carbon steel by DRECE process (Dual Rolls Equal Channel Extrusion), In *Metal 2012*, *21st International Conference on Metallurgy and Materials*, May 23rd - 25th 2012, Ostrava: Tanger, 2014,pp. 630-636.

[2] RUSZ, S., ČÍŽEK, L. Development of unconventional forming methods. In *Journal of Achievements in Materials and Manufacturing Engineering,* vol. 54, Issue 2, October 2012, pp. 194/201.

[3] VENGRINOVICH,V.L.,TSUKERMAN,V.L. Stress and Texture Measurement Using Barkhausen Noise and Angular Scanning of Driving Magnetic Field. In 6th WCNDT 2004-World Conference on NDT, Montreal, 2004, pp.175-182.

[4] TIITTO, S. Magnetic Methods. Handbook of Measurements of Residual Stresses; J. Lu (ed.) Society for Experimental Mechanics: The Fairmont Press Inc.: Lilburn, 1996, pp. 179-224.

[5] OCHODEK, Vl., HORÁK, P. Plasma welding of high carbon steel after SPD process. In *Metal* 2015, *24th International Conference on Metallurgy and Materials*, June 3rd-5th 2015, Ostrava: Tanger, 2015, pp. 804-809.

[6] SIMUFACT ENGENEERING GmbH. Simufact Welding 4.0.4, 2015.

[7] GOLDAK, J., CHAKRAVARTI, A., BIBBY, M. A New finite element model for welding heat source. In *Metallurgical transactions B*, vol. 15 B, June 1994, pp. 299-305.

[8] GOLDAK, J., BIBBY, M., MOORE, J., HOUSE, R., PATEL, B. Computer modelling of heat flow in welds. In *Metallurgical transaction B*, vol. 17 B, September 1986, pp. 587-600.

[9] SLOVACEK, M., DIVIS, V, JUNEK, L., OCHODEK, Vl. Numerical simulation of the welding process - distortion and residual stress prediction, heat source model determination. In *Welding in the World*, vol. 49, Issue 1-12, November 2005, pp. 15-29.