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APPLICATION OF VIRTUAL REALITY AND HIGH PERFORMANCE COMPUTING IN DESIGNING ROTARY FORMING PROCESSES

This paper presents an innovative solution in the form of a virtual reality (VR) and high performance computing (HPC) system dedicated to aid designing rotary forming processes with laser beam reheating the material formed. The invented method allowing a virtual machine copy to be coupled with its actual counterpart and a computing engine utilizing GPU processors of graphic NVidia cards to accelerate computing are discussed. The completed experiments and simulations of the 316L stainless steel semi-product spinning process showed that the developed VR-HPC system solution allows the manufacturing process to be effectively engineered and controlled in industrial conditions.

Keywords: rotary forming; virtual reality; finite element; computer simulation; high performance computing

1. Introduction

The aerospace and defence industry is amongst the most innovative industries, where the continuous progress is determined by the necessity to ensure as high reliability of manufactured products subjected to extreme operation conditions as possible. To maintain market competitiveness it is necessary to invest in new solutions or to develop processes applied. In manufacturing processes using common materials, the selection of a forming process is relatively simple. The situation is entirely different when non-conventional materials are used in the manufacturing process, in particular in the context of high quality requirements [1]. In this case, the problem is significant, and involves the need to carry out tests in order to optimize the manufacturing process. Then, it is necessary to conduct a series of fabrication, experimental and industrial tests, aided by numerical simulations. On the other hand, the minimization of costs and manufacturing time while maintaining the product top quality and repeatability is an additional factor considered in the industrial practice. The conventional rotary forming process is a plastic forming process, applied on an industrial scale for a very long time. Now it is used primarily when forming thin-walled products with axially symmetrical shape (high plasticity and low strength materials). However, taking into account high mechanical parameters of materials applied in aerospace and defence applications, it is necessary to introduce modifications to enable them to be worked. The design concept of rotary forming with material preheating during forming was developed in 2001 in the Fraunhofer Institute [2]. A laser beam reheats a small fragment of the area (in front of the forming roll), thanks to the coordinated movement of the forming roll, the material can be formed on a rotating spinning die. The material formed, subjected to the laser impact, heats up to high temperatures, where its mechanical properties rapidly decline. Rotary forming aided by laser heating can meet all the above mentioned requirements, and furthermore, it can improve the mechanical properties of the final product and reduce the cost of a small-scale production, which is characteristic of the aerospace and defence industries [1,2]. The process of rotary forming with laser beam reheating of the material [3-8] has a number of advantages, including:

- possibility of hot forming almost unworkable materials such as nickel and titanium alloys,
- good surface quality of final products with a low roughness,
- no need to use inter-operational heating processes,
- favourable stress distribution in the material formed,
- possibility of forming complicated axially symmetrical shapes in a single cycle, which vastly reduces the manufacturing time and cost.

Introducing a new (or modifying the existing) manufacturing process involves the need to conduct a series of tests, which

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allow new engineering guidelines to be prepared. This objective involves high financial outlays, and a long implementation time. In addition, for new solutions, the process should be adjusted to the specificity of the production plant, and the characteristics of the finished products obtained. Numerical simulations, allowing the manufacturing process to be virtually designed and operationally controlled, can be very helpful in designing these processes. Numerical simulations of processes of rotary forming with laser beam reheating of the material have not been commonly used so far due to limitations related to simulation times. The emergence of software using GPU processors to accelerate computing in the market, common access to new interactive engineering technologies using virtual reality (VR) systems [9,10], and the construction of cyber-physical systems in line with the Industry 4.0 concept, create new possibilities for designing new techniques for the aerospace and defence industry. Bearing this in mind, the main objective of the project was to develop a new approach to engineering using advanced numerical modelling of rotary forming processes with laser (GPU aided computing), and capabilities of virtual reality systems (VR).

2. System of virtual reality (VR) and high performance computing (HPC)

The developed solution is based on commercial simulation software Impetus Afea [12] coupled with a virtual reality environment (VR). The software is integrated at the level of graphic interfaces of both modules. Fig. 1 shows a diagram of the designed VR-HPC system. Coupling of the VR-HPC system with an actual machine for rotary forming is executed by generating a program code in a computer numerical control programming language. Numerical simulations of processes of rotary forming with laser beam reheating of the material have not been commonly used so far due to limitations related to simulation times (simulation times exceeded ten weeks). The high performance computing (HPC) module performs numerical computing using NVidia GPU (graphic processing unit) processors of graphic cards to accelerate numerical computing. Use of standard workstations available in the market, furnished with a few graphic cards allows parallel and multivariant simulations to be completed in acceptable time (a few days). The final effect is a set of design-engineering guidelines of the process designed, including the number of forming passes, and their trajectory, roll/configuration of a few rolls (radius and tool rake angle), rotary speed and roll/rolls feed, heating parameters (heating strategy, laser power, time).

On the one hand, the virtual reality (VR) module can play a role of a tool for executing the training process of future machine operators and also, provides tools to enable an interactive set-up of the manufacturing process (Fig. 2A-D).

The most important functionalities of the VR module include:

- generating a complete numerical code for the actual machine (record and reading),
- generating a start script with process parameters for the high performance computing module (HPC),
- interactive engineering module allowing the number of passes of the forming roll and their trajectory with a virtual test (Fig. 2B) to be designed,
- virtual inspection of the product geometry after the virtual forming process (HPC module) (Fig. 2D).

The presented capabilities of the VR module allow the engineering and process data to be effectively and quickly

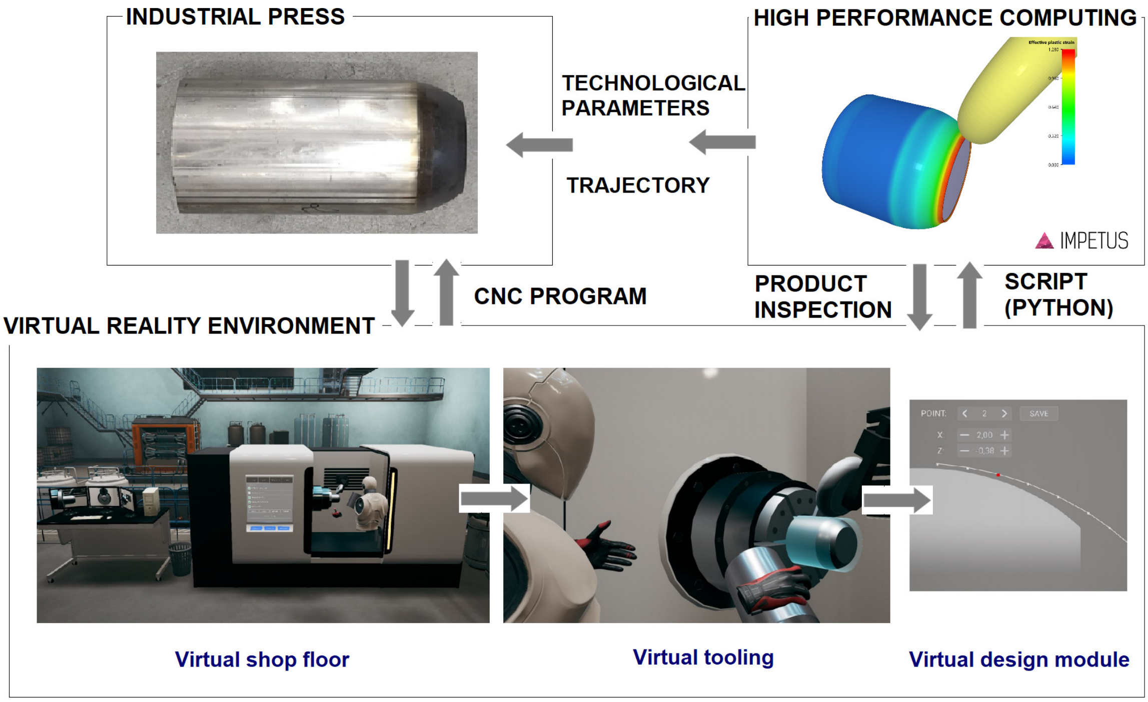


Fig. 1. Diagram of the VR-HPC system (coupling at the level of user interfaces)

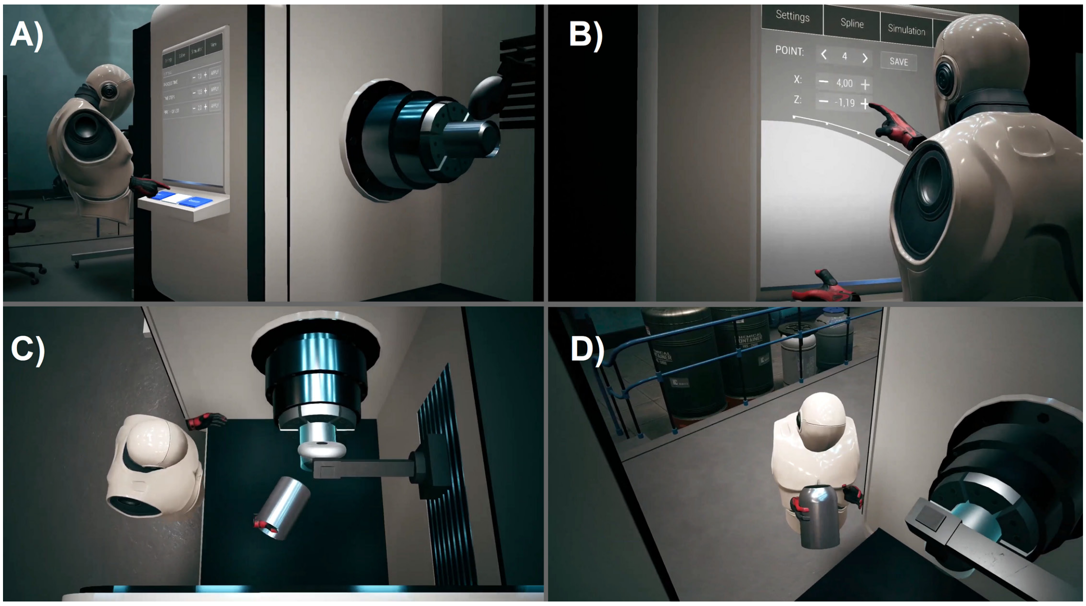


Fig. 2. Virtual reality environment: A) machine control and code generation, B) engineering modules, C) process set-up, D) final product inspection

prepared for the needs of high performance simulations (HPC module), and the execution of the rotary forming process in actual conditions.

3. Computer aid in designing the rotary forming process – example of the VR-HPC system application

3.1. Main assumptions of the numerical model

Fig. 3 presents a diagram of the numerical model (thermo-mechanical solution) of the process of rotary forming with the local reheating of the deformation zone by a laser beam. The model comprises three main solution domains, identified as ID:1 (spinning die), ID:2 (forming roll), ID:3 (input material), respectively. In numerical computing, the ID:1 (spinning die) solution domain and ID:2 (roll) are considered a rigid material, not deformable. The both solution domains were discretized with "shell" type shell elements. The area of input material (solution domain ID:3) was discretized with six-wall 8-nodes elements within the area where the semi-product is not formed. 64-node elements were used for the area that would be subjected to large deformations (conical part of the material formed). The application of 64-node elements significantly extends computing times, but at the same time, it allows more precise results to be achieved. In the numerical solution, a constitutive model was assumed to include the stress variation as a function of strain, and temperature [11,12].

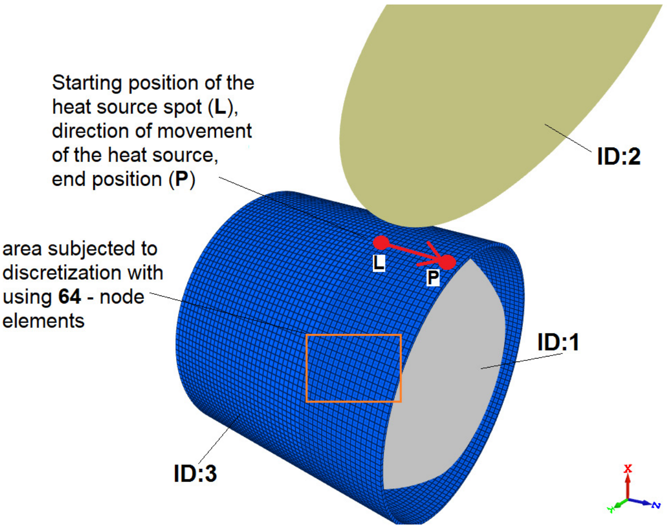


Fig. 3. The numerical model of the process of rotary forming with the local laser beam reheating of the material

Necessary thermo-mechanical data, including high temperature stress-strain curves was taken from paper [13]. The stress-strain curve was described by equation:

$$\sigma_p = K\varepsilon^n \tag{1}$$

TABLES 1 and 2 summarize the stress-strain curve coefficients and thermo-physical data, respectively.

TABLE 1

Strain-stress curve coefficients

Temperature, (°C)	*K*, (MPa)	*n*, (-)
50	1014,933	0,388308
100	1038,292	0,407563
200	1066,622	0,437705
300	1070,435	0,456692
400	1049,73	0,464523
500	1004,509	0,461199
600	934,7709	0,446718
650	890,7079	0,435295
800	721,7435	0,38429
900	578,4543	0,336342
1000	410,6481	0,277238

TABLE 2

Thermal-physical properties of the steel tested

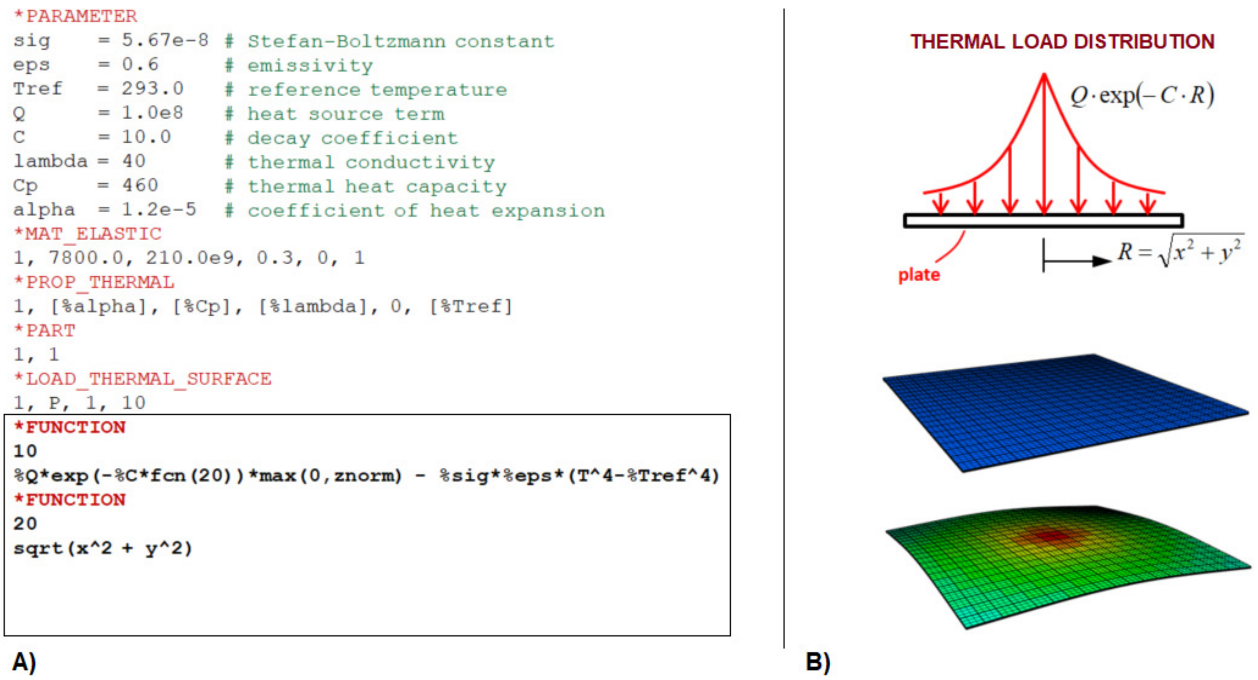
Temperature (ºC)	Specific heat (J/(kg*K))	Heat expansion (ºC^{-1})	Density (kg/m^3)	Conductivity (W/(m*K))
20	492	1.456e-05	7900	14.12
100	502	1.539e-05	7900	15.26
200	514	1.621e-05	7900	16.69
300	526	1.686e-05	7900	18.11
400	538	1.737e-05	7900	19.54
500	550	1.778e-05	7900	20.96
600	562	1.812e-05	7900	22.38
700	575	1.843e-05	7900	23.81
800	587	1.872e-05	7900	25.23
900	599	1.899e-05	7900	26.66
1000	611	1.927e-05	7900	28.08
1100	623	1.953e-05	7900	29.50
1200	635	1.979e-05	7900	30.93
1300	647	2.002e-05	7900	32.35
1400	659	2.021e-05	7900	33.78

In the adopted numerical model, the problem of transient heat conduction was considered. A problem of this class is generally described by the Fourier-Kirchhoff differential equation. The accuracy of determination of the temperature field depends primarily on the correct determination of the boundary conditions necessary to solve the heat flow problem. It was assumed for the computing that the heat transfer to/from the environment (also between the roll, spinning die, and material formed) is modelled using overall heat transfer coefficient. In the model presented this condition was defined in the form of a heat flux q:

$$q = \alpha(T - T_0) \tag{2}$$

Where α is the overall heat transfer coefficient, T_0 is the ambient/tool temperature. The initial condition was assumed as the known temperature distribution $T = 20°C$ (material formed, roll, spinning die). In most studies related to the subject of heat transfer, contact effects are modelled with the heat transfer coefficient α. The main problem is related to the proper selection of this coefficient. The values provided in numerous publications considerably differ from each other, even by an order of magnitude [11]. In most papers, the values of coefficient α were determined by matching the temperature calculation results obtained with various methods to the results of measurements carried out during the process. For the purposes of the formulated numerical model and test simulations a constant value of the overall heat transfer coefficient of 10 W/m^{2}K was assumed. Also heat transfer to the roll and spinning die was included in the solution. The value of heat transfer coefficient in the area of contact roll-material formed, spinning die-material formed was 2000 W/m^{2}K. A functional model of deformation zone reheating with a moving heat source beam is an original element of the thermo-mechanical model presented. The solution is based on original scripts, using embedded eigenfunctions of computing engine Impetus Afea [12]. Fig. 4 shows a mathematical description of the moving heat source beam [11].

Function 10 defines the thermal loading. It is evaluated at each external element face. A face has its own center coordinate (x, y, z) and face normal direction $\{\text{xnorm } y\text{norm znorm}\}^T$. Function 10 is referring to function 20 through the call fcn(20). Function 20 calculates and returns the distance from the face center to the moving heat source. The model assumed that the heat source beam reheated the material zone by moving immediately in front of the forming roll (or stationary heating was performed at a specific width). The formulated numerical model is a fully parametrized model and its capabilities include any configuration of heat source movement (as a function of position and time).



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*PARAMETER
sig    = 5.67e-8  # Stefan-Boltzmann constant
eps    = 0.6      # emissivity
Tref   = 293.0    # reference temperature
Q      = 1.0e8    # heat source term
C      = 10.0     # decay coefficient
lambda = 40       # thermal conductivity
Cp     = 460      # thermal heat capacity
alpha  = 1.2e-5   # coefficient of heat expansion
*MAT_ELASTIC
1, 7800.0, 210.0e9, 0.3, 0, 1
*PROP_THERMAL
1, [%alpha], [%Cp], [%lambda], 0, [%Tref]
*PART
1, 1
*LOAD_THERMAL_SURFACE
1, P, 1, 10
*FUNCTION
10
%Q*exp(-%C*fcn(20))*max(0,znorm) - %sig*%eps*(T^4-%Tref^4)
*FUNCTION
20
sqrt(x^2 + y^2)
```

Fig. 4. Mathematical description of the moving heat source beam: a) part of source code, b) scheme of thermal load distribution

3.2. Research methodology and objective

Experiments and simulations were performed for a third party interested in products with a similar shape, used in the electric-district heating industry. The input element for the tests comprised a steel pipe made of grade 316L, with a wall thickness of 2 mm, and an outer diameter of 154 mm. Based on experience, a forming roll with a radius of 50 mm was selected, set up at an angle of 45° to the spinning die axis. The rotary speed of the spinning die and the roll feed were determined in the range 120-280 rpm and 120-180 mm/min, respectively. A diode laser DL 036R (3.6 kW) was applied as the heat source, it had a capability of automatic power control depending on the set temperature (test range 850-1100°C). The distance from the laser optical system to the material formed was between 290 and 305 mm. During tests, stationary heating, and heating during movement was applied (see Fig. 1). Experiments were performed on a spinning-bending machine MZH-500, with an added laser head, pyrometer and a system to monitor the process (Fig. 5).

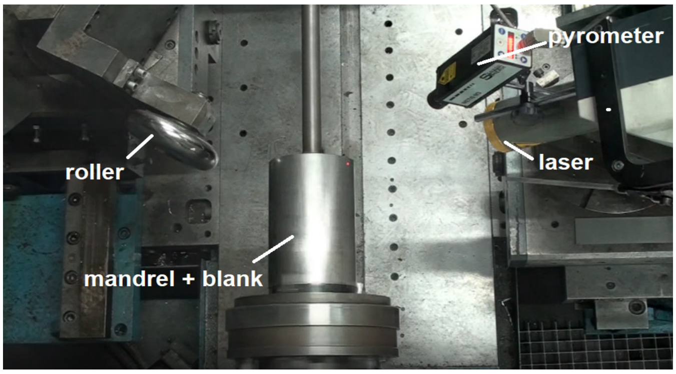

Fig. 5. Rotary forming test stand (a view from a monitoring camera)

Simulation tests were performed on a workstation fitted with a graphic card RTX 3060 (12 GB RAM), 64 GB RAM operation memory, and an 11 gen. Intel i7 processor. The main objective of the simulation and experimental test was to determine the optimum parameters of the manufacturing process to obtain a good quality product (without defects). An intermediate objective was to practically evaluate the developed VR-HPC system and to assess the possibilities for its application for operational control of an industrial process, and for effective design aid.

3.3. Example results

At the first stage of the research, experimental tests were performed without reheating the formed material (cold process). The roll movement trajectory comprising from 3 to 5 spinning passes was designed. In any case a product complying with the assumptions was not obtained, as it had a defect in the form of a longitudinal crack in the highest reforming place. Fig. 6 presents a view of an actual drawpiece, and a drawpiece after virtual cold forming (numerical simulation) in five passes with a visible defect in the form of a longitudinal crack.

In a subsequent test, the same roll movement trajectory was applied as for the cold forming (5 passes), but this time the surface deformed was additionally reheated to a temperature ensuring an enhanced material plasticity, i.e. approximately 950°C (heating of the deformation zone with a moving heat source). As we can see in Fig. 7, the product has no longitudinal

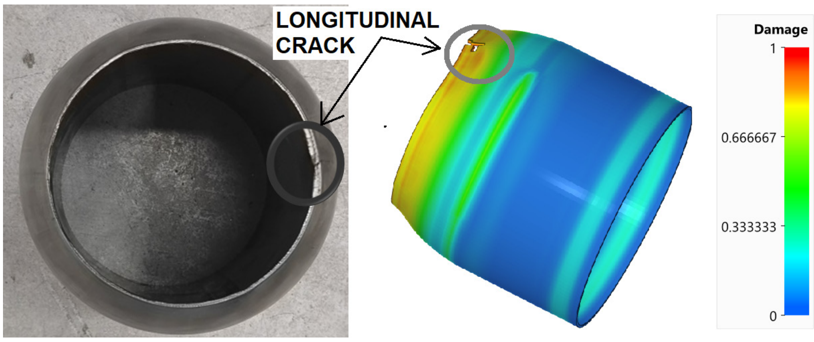

Fig. 6. Simulation and experiment (cold forming in five passes)

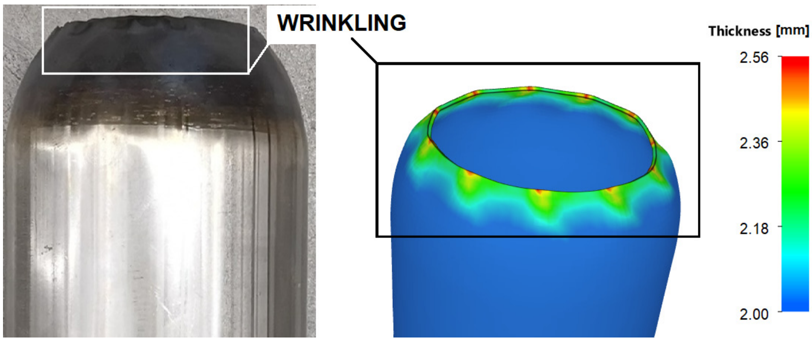

Fig. 7. Simulation and experiment (hot forming, faulty roll trajectory)

cracks as compared to the cold formed one. In the area of the highest reforming you can observe a tendency to wrinkling, resulting from compressive stress accumulation on the perimeter of the part formed.

The main cause of this situation was incorrectly designed roll trajectory, and an unstable heating process of the material formed. Therefore, further efforts focused on determining the conditions of stable heating of the material with a laser beam, and designing the process by minimizing the number of forming passes of the roll. A decision was made to use the stationary heating of the whole deformation zone (without the laser beam movement), which allowed the temperature field to be stabilized before starting the forming process. Fig. 8 presents the temperature field obtained after 70 seconds of heating the deformation zone (rotary speed of the spinning block 280 rpm). The temperature field was stabilized at about 1000°C along the whole perimeter. During the experiments, for the same rotary speed and heating time as in the simulation, the temperature field was stabilized at about 1050°C. The relative error between the both values was 4.76%.

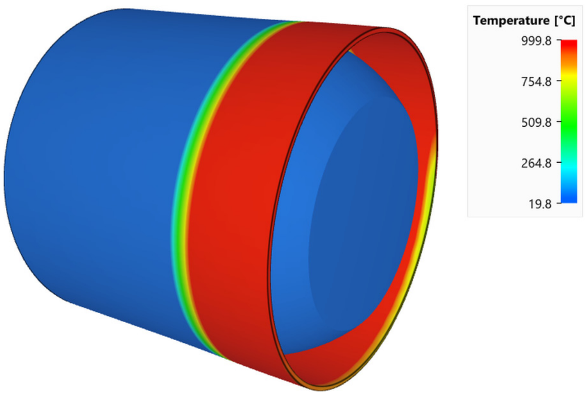

Fig. 8. Temperature distribution (70-th second of heating)

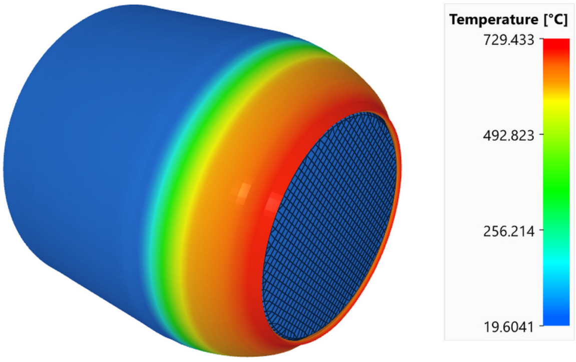

Fig. 9. Temperature distribution after the forming process (one pass of the forming roll)

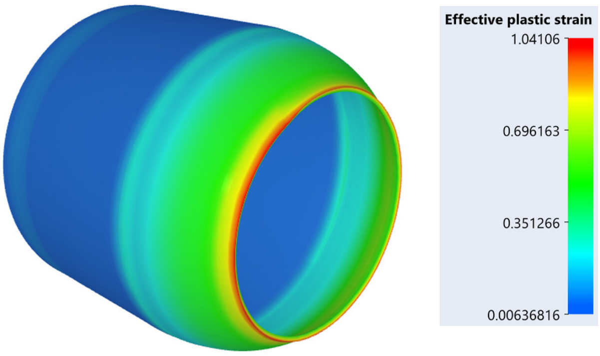

Fig. 10. Effective plastic strain distribution (one pass of the forming roll)

Figs. 9 and 10 show the temperature field and the strain field, respectively, for the forming variant with a single forming roll pass. In the simulation, stationary laser heating of the whole deformation zone (70 sec), spinner speed of 280 rpm, and the roll feed of 140 mm/min were applied. Analysing the obtained results, you may observe accumulation of the maximum strain values in the area of the highest reforming. No defects in the form of cracks (Fig. 6) or intensive wrinkling on the perimeter (Fig. 7) were observed. The maximum achieved temperature value after the process of virtual forming was 729°C (Fig. 9). During the experiments, the maximum temperature value after the forming process was achieved at 798°C. The relative error between the both values was 8.65 %.

Fig. 11 shows the wall thickness results for a product obtained in a single pass with laser reheating (experiment and

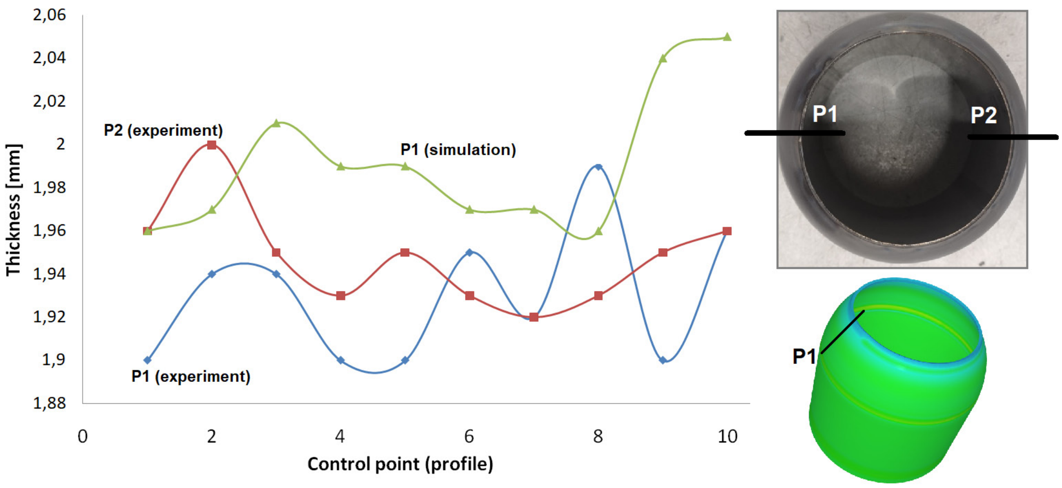

Fig. 11. Thickness measurement on the profile formed (experiment and simulation, one pass of the forming roll)

simulation). The measurements were made for 10 check points for the actual and virtual profile. The total relative error was 2.21%-3.16%. A small change in the wall thickness indicated that the fabrication test was correct, in line with all requirements and guidelines for the spinning process with reheating.

4. Conclusions

This paper presents a system for aiding design of the process of rotary forming with the laser beam reheating of the material formed. The proposed solution comprises two coupled modules (high performance computing (HPC) module and virtual reality (VR) module). The both modules were integrated at a level of graphic interfaces. Coupling of the digital copy of the machine with its actual counterpart is performed by reading/loading a complete program in a normalized recording/reading language for numerically controlled machines. The developed systemic solution allows the industrial process to be operationally and effectively controlled, and to virtually design and verify the engineering assumptions of the process designed. The suitability of the developed tool was verified during experiments to engineer the process of spinning a semi-product of stainless steel 316L. Not only did combining numerical tests with actual tests allow the obtained results to be verified, but also contributed to developing the optimal manufacturing process in much shorter time than before.

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