The Research of Forgeability and Determination of Optimal Warm Forging Temperature using Computer Simulation

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Abstract. **Warm forming is most commonly used in production of die forgings manufactured by precise forging. The development of forging technology is connected to research of forgeability and plasticity of formed material at warm temperatures. The contribution brings a description of methodology used for determination of optimal forging temperature from recommended warm temperature interval concerning the chromium - manganic steel 16MnCr5. In order to verify the steel forgeability within the recommended warm forging temperatures interval 600, 650, 700 a 750 °C the upsetting test according to Židek was used. The computer simulation of technological test by means of program MSC.SuperForge confirmed correct selection of warm temperatures because testing samples showed good formability and after upsetting in a notch area no cracks or defects were revealed. The main factor of plasticity for optimal warm temperature selection from examined temperature interval is value of reduction of area that was determined by tensile test. Numeric simulation of forging process in closed die confirmed correct plastic flow of steel 16MnCr5 at recommended forging temperature 700 °C.**

Keywords: warm forging; warm temperature; forgeability; plasticity; upsetting test; tensile test; plastic flow; simulation

I. INTRODUCTION

Compared to standard hot forging, by warm forging higher exploitation of material, higher quality of surface and also dimensional precision of forgings is reached. At warm forming process it is important to determine an optimal upper forging temperature since the recommended temperature interval is quite narrow [1,2,3]. Consequently, there is a risk that when the recommended temperature interval is not kept the material can be easily brought to the area of brittleness. In order to obtain a fine-grained structure and good mechanical properties of forgings it is important to bring the temperature of forging finishing near to the recrystallization temperature. Important is especially the dependence between forming temperature and ductility of material. For the development of warm forging technologies it is reasonable to consider the influence of the temperature on mechanical properties and plasticity indexes concerning the specific type of steel [3,4].

II. SETTING THE INTERVAL OF WARM FORGING TEMPERATURES

The research of steel plasticity at the temperatures of warm forging was performed on 16MnCr5 steel alloy. It is chromium-manganic structural steel, suitable for case hardening, which has appropriate warm ductility, after spheroid zing also the cold ductility. It is used for production of case hardened machine parts with very hard surface and after quenching also with high rigidity of core. This kind of steel is suitable for precision die forging according to its chemical composition and mechanical properties.

For low carbon steels the temperatures of warm forging higher than recrystallization temperature T_{rec} but lower than structure change temperature A_{c1} are recommended. Therefore is it necessary to set the temperatures A_{c1} and T_{rec} for examined steel and consequently determine the temperatures for upsetting test within the pre-set interval.

TABLE 1 CHEMICAL COMPOSITION OF STEEL (wt%)

Element	C	Mn	Si	Cr	Ni	Mo	W	P,S
Composition	0.165	1.32	0.25	0.9	0.139	0.04	0.02	0.015

In order to define the temperatures T_{Ac1} and T_{rec} it is necessary to know exact steel alloy 16MnCr5 components percentage. The values were determined by optical emission spectroscopy according to table 1. The recrystallization temperature T_{rec}, melting temperature T_{tav} and structure change T_{Ac1} temperature were calculated as follows:

$$T_{rec} = 0.4T_{tav} \quad [°C] \tag{1}$$

where: T_{tav} – melting temperature

$$T_{tav} = 1537 - (88C + 8Si + 5Mn + 5Cu + 1.5Cr + 4Ni + 2Mo + 2V + 30P + 25S) \quad [°C] \tag{2}$$

$$T_{Ac1} = 723 - 10.7\,Mn - 16.9\,Ni + 29.1\,Si + 16.9\,Cr + 290\,As + 6.38\,W \quad [°C] \tag{3}$$

For steel 16MnCr5 is valid: $\mathbf{T_{rec} = 604\ °C}$ $\mathbf{A_{c1} = 729\ °C}$

Based upon calculated values of temperatures T_{Ac1} and T_{rec} the temperature interval for warm forging of 16MnCr5 steel was set at values from **600 to 750°C.**

III. RESEARCH OF 16MNCR5 STEEL FORGEABILITY

For the verification of steel forgeability by warm forging, the technological test of upsetting according to Židek is used. The test is based on deformation of cylindrical test sample with four notches under defined temperatures [5]. Samples with diameters of Ø30 x 40 mm are deformed by one third of their height. The presence of cracks in notches is evaluated.

The test author Žídek recommends five classification degrees used for forgeability evaluation according to appearance of cracks in cylinder notches:

- 1 – without cracks (good forgeability)
- 2 – small separated cracks (lowered forgeability)
- 3 – small cracks in all notches (medium lowered forgeability)
- 4 – medium cracks in all notches (downgraded forgeability)
- 5 – big cracks (fractures) in all notches

Warm forgeability of steel is considered by mean value, which is given by classification level according to examined temperatures.

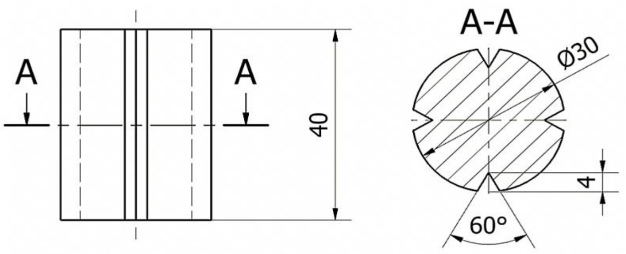

Figure 1. Shape and dimensions of test sample

Testing samples were made from a bar heat rolled, which was provided without any heat treatment. In order to harmonize mechanical properties and obtain fine-grained structure it was necessary to anneal the testing cylinders. The shape and dimensions of a test sample are shown in Fig. 1.

TABLE 2. EVALUATION OF CRACKS IN NOTCHES OF THE TEST SAMPLE

Temperature [°C]	600	650	700	750
Classification degree	1	1	1	2

The upsetting tests were performed at set temperatures 600, 650, 700 a 750 °C, whereas three testing samples were examined at each temperature. The cylinders with notches were upset on vertical forging press LZK 1600 by one third of its height and the appearance of cracks in notches was evaluated. Accordingly the appearance of cracks in notches pursuant to classification degrees at particular temperatures was evaluated - the results are stated in Table 2.

Before executing the laboratory experiment a computer simulation of technologic test was performed by means of program MSC.SuperForge. The simulation confirmed correct selection of warm temperatures, because testing samples showed good forgeability and after upsetting in notch area no defects or cracks were revealed. Example of a cylinder deformed during the experiment and simulation of upsetting process is shown on Fig. 2.

Figure 2. Shape of deformed test sample at temperature700 °C
a) laboratory experiment b) computer simulation

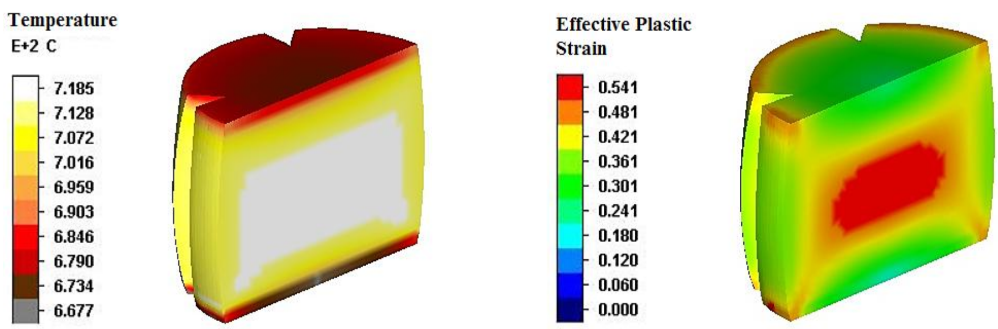

Figure 3. Simulation of temperature course, effective strain at the upsetting temperature 700 °C of the test sample

Forgeability of low-carbon steel 16MnCr5 in warm temperatures interval was evaluated on the basis of mean value concerning classification degrees for particular temperatures. Reached value 1 means good forgeability of 16MnCr5 steel at warm conditions with regard to temperatures 600, 650 and 700°C. Sporadic cracks in notches appeared at testing temperature 750°C. The mentioned temperature is not recommended as upper forging temperature.

IV. SELECTION OF OPTIMAL FORGING TEMPERATURE

In order to consider the temperature influence on plasticity and workability of examined steel 16MnCr5 within the scope of recommended warm forging temperature interval the tensile test was applied at increased temperature according to STN EN 10002-5 [1,5]. Testing cylinder bars were made out of a circle bar hot rolled and later annealed. For the purpose of test execution the testing machine LabTest with maximum loading force 250 kN was used. The machine includes a small electric furnace with heating up to 1000 °C.

The tensile test was performed at set temperatures 600, 650, 700 a 750 °C. After executing a static mechanical test, dimensions of testing bars were measured and using a calculation the basic characteristics of plasticity (reduction of area Z, and ductility A) and indicators of workability at increased temperatures were defined as follows:

- Index of plasticity according to Kolmogorov:

$$\lambda_R = 2.\sqrt{3}.\ln\frac{d_o}{d_u} \qquad [-] \qquad (4)$$

Where: d_o – initial diameter [mm], d_u – minimal diameter in rupture point of the sample [mm]

- Paur´s index of forming capacity:

$$D_{sm} = \frac{1}{1-Z} - 1 \qquad [-] \qquad (5)$$

Where applies: $Z = \frac{S_0 - S_u}{S_0} < 1$

Where: S_o – initial area [mm2], S_u – minimal area in rupture point of the sample [mm2]

- Yield strength – tensile strength ratio :

$$\frac{R_e}{R_m} < 0{,}7 \qquad [-] \qquad (6)$$

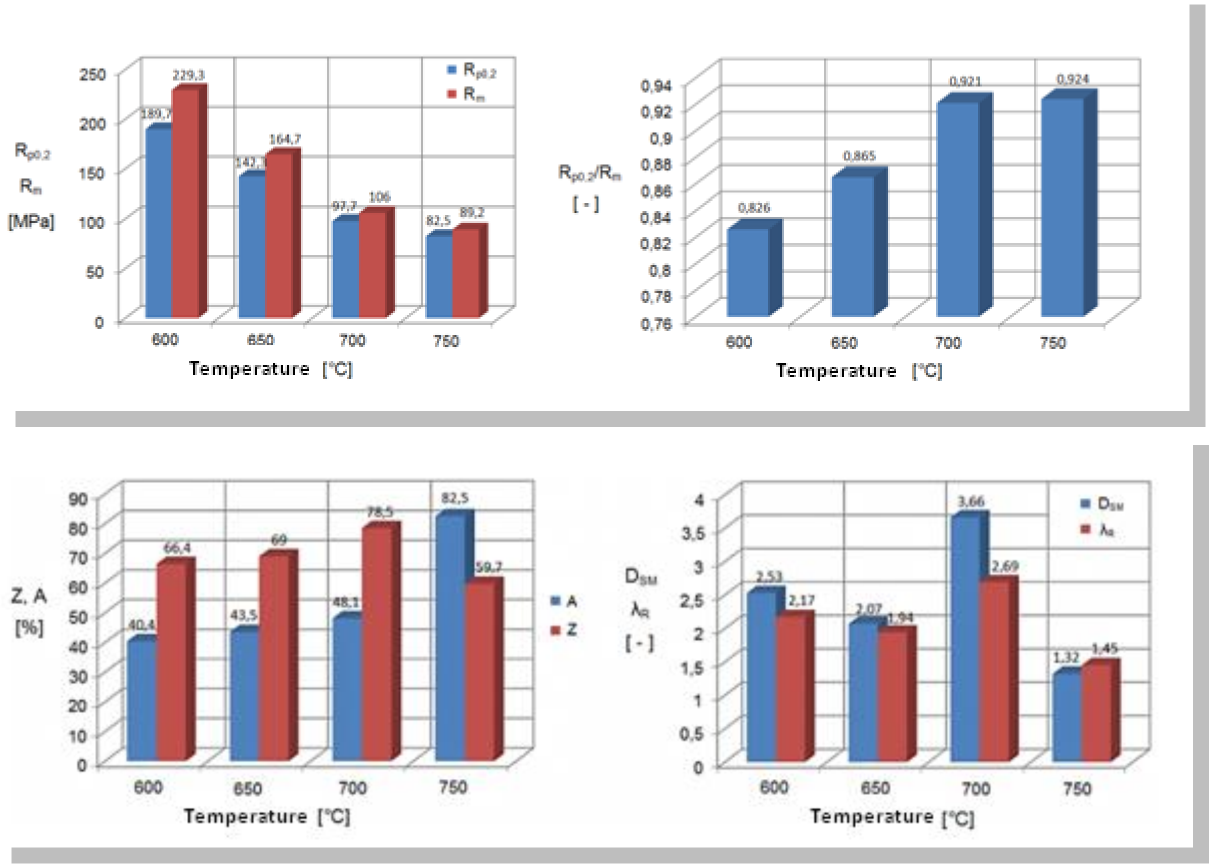

Figure 4. Courses of graphic relations examined parameters depending on defined temperatures

The graphic relations displayed in fig. 4 were designed pursuant to average values of calculated parameters resulted from the tensile test. The course of strength characteristics R_m and $R_{p0,2}$ of examined steel proves declining tendency depending on increasing temperature. On the basis of thermal course of plasticity characteristics (reduction of area Z, ductility A) we are able to observe reduction of area decline at the temperature 750 °C. At the mentioned temperature the plasticity decreased and it is not possible to recommend the same as upper forging temperature.

For the purpose of optimal warm temperature selection from examined temperature interval the crucial indicator of steel 16MnCr5 plasticity is value of reduction of area Z. This plasticity characteristic provides reliable results comparable to production practice. As reduction of area Z achieves its maximum value at the temperature 700 °C, the same will be recommended as optimal temperature of steel 16MnCr5 for warm forming. Furthermore, indicators of workability D_{sm} and λ_R reached maximum values at the examined temperature 700 °C, as well.

V. COMPUTER SIMULATION OF WARM FORGING PROCESS

Computer simulation is useful solution for prediction of the forging process course and material behaviour in die cavity. In this way, it is possible to optimize the tool shape and design technological process and thus considerably reduce financial costs of preproduction stages and production itself. Utilization of computer simulation at the forging processes also enables to increase quality and precision of drop forgings and tool life [1,6,7,8]. Computer simulation of warm forging process was realized by MSC.SuperForge simulation program which uses finite element method (FEM) and finite volume method (FVM). The program is suitable for simulation of bulk forming processes with regard to hot, warm and also cold forming. Plasticity and forgeability of steel 16MnCr5 at recommended warm temperature 700 °C was verified using simulation of die forging process in closed die. The correct plastic flow in closed die cavity and flawless forging of very complicated shape of forged piece Flange at the temperature 700°C were confirmed.

For starting a simulation of forging of forged piece Flange it is necessary to properly define the input data – these data were set as follows:

- process: closed die forging
- forging machine: mechanical press type LZK
- material of billet: DIN 17210 (1.7131)
- material of tool: ASTM A 681 (H13)
- temperature of billet: 700 °C
- temperature of tool: 250 °C
- coefficient of friction: 0.25

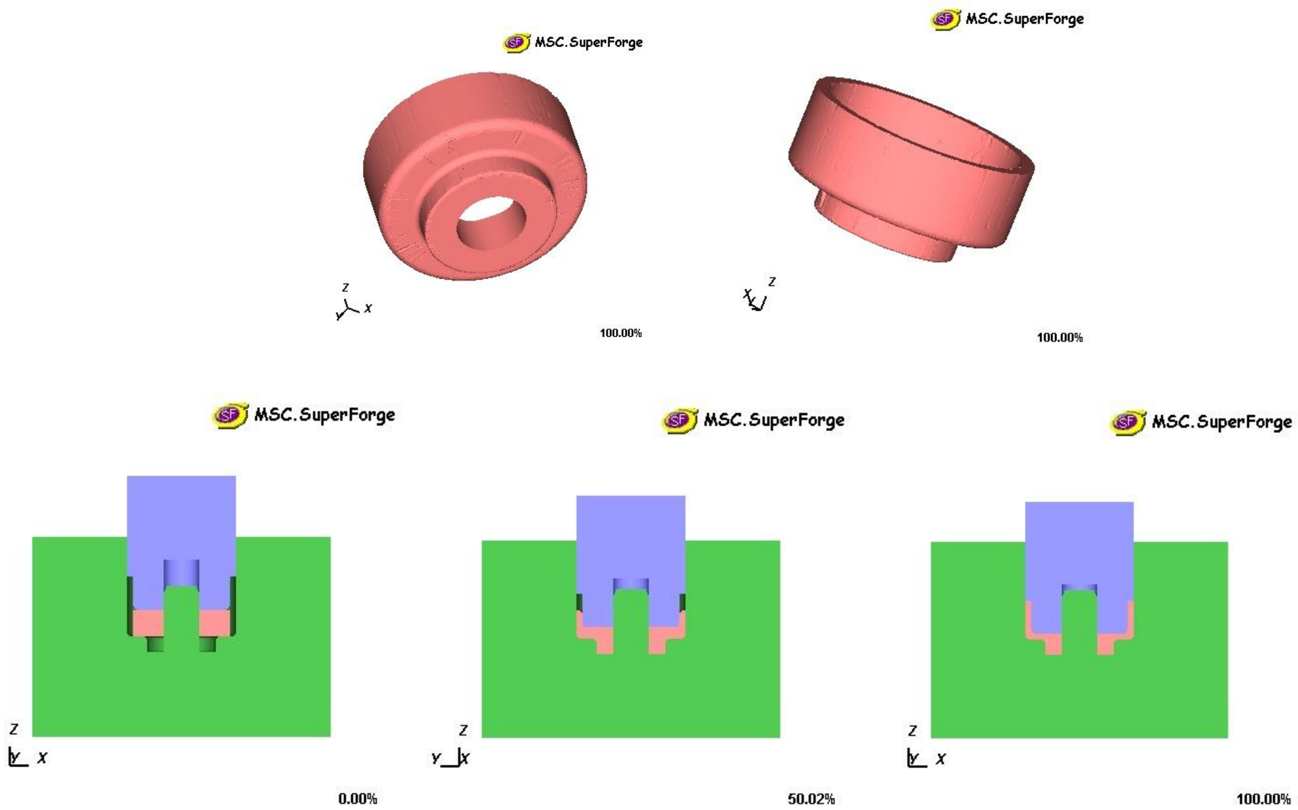

Figure 5. Shape of forged piece Flange and simulation of correct material flow in closed die cavity

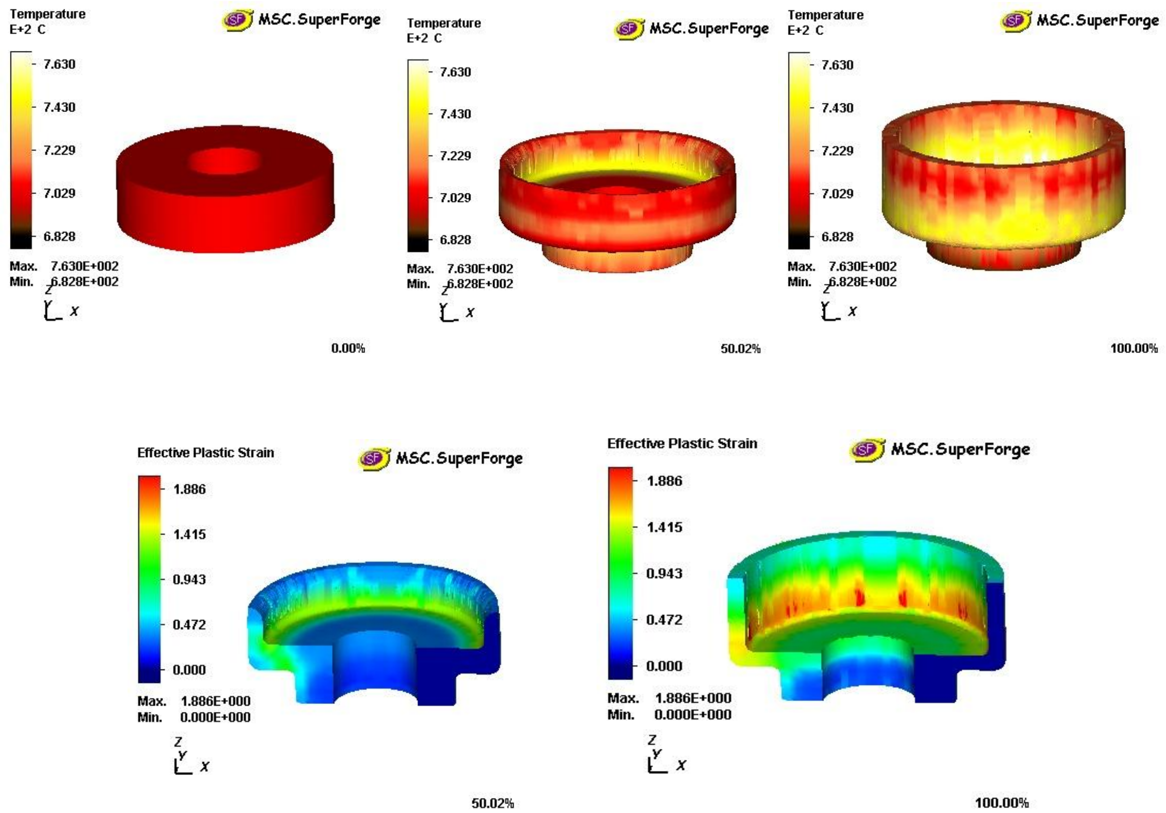

Figure 6. Temperature fields and courses of plastic strain in a forged piece at the 50 % and the 100% of simulation process

VI. CONCLUSION

The technology of warm forging brings considerable economic profit through material and energy savings. Economy of mentioned technology is mostly influenced by correctly selected interval of warm temperatures [1,3,9]. The method used for determining of temperature interval for warm forging, which is described in this contribution, is applicable to various types of structural steels. Furthermore, basic tensile test at increased temperatures as well as upsetting test by Židek used for forgeability determination are appropriate also for research of non-ferrous metals, especially for Al and Mg alloys. For further development of warm forging technology it is necessary to focus on research of temperatures influence on material plasticity.

Successful application of warm forging in production area depends on selection of optimal upper forging temperature from determined interval. Computer simulation plays an important role as it manages to verify correctness of forging temperature selection by process of plastic flow in die cavity. Numeric simulation of Flange forging described in this contribution confirmed by correct plastic flow that the selection of forging temperature 700 °C was appropriate. Achieved results are beneficial for practical application at production of steel die forgings using warm forging.

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