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42CrMo4 steel flow behavior characterization for high temperature closed dies hot forging in automotive components applications

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ABSTRACT

The application of new forming processes as the high temperature hot forging in closed dies in an industrial environment still requires further investigation due to the lack of flow stress data at these temperatures. To determine the flow behavior of the 42CrMo4 steel at high temperatures hot compression tests have been carried out in a Gleeble® 3800 thermomechanical tester for a temperature range that covers the material behavior from the hot forging until the Nil Ductility Temperature (1250 °C-1375 °C) and for three different orders of magnitudes for the strain rates (0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}). Then, the Hansel-Spittel model, widely used in automotive commercial software as FORGE®, has been employed to obtain the adequate constants of the constitutive equation for high temperatures.

Finally, the newly obtained flow behavior model has been validated by comparison between experimental and simulated compression tests and by the process simulation of a commercial automotive component comparing the results of the simulation with the already made experimental tests in a laboratory cellule of the new technology.

Hence, this paper shows the procedure for the determination and the obtention of a new constitutive model for the 42CrMo4 steel flow stress characterization at a temperature range between 1250 °C–1375 °C. This will contribute in the knowledge of material flow stress behavior models at high temperatures and will allow the prediction or simulation of high temperature hot forging in closed dies processes, enhancing the possibility of the application of these technologies from an industrial point of view.

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1. Introduction

The current energetic situation and the high competitiveness in industrial sectors as the automotive one have made the development of new manufacturing processes with less energy and raw material consumption a real necessity. As a consequence, new forming processes related with high temperature hot forging in closed dies have emerged in the last years as new solutions to expand the possibilities of hot forging and iron casting in the automotive industry.

These technologies are mid-way between hot forging and semi-solid metal processes, working at temperatures from 1250 °C to 1375 °C. These temperatures are higher than the usual hot forging working temperature but below the solidus temperature or the semi solid range, where no liquid phase is expected.

This represents an advantage compared to semi-solid forming processes such as thixoforging, due to the fact that lower temperatures are reached in the case of high melting point alloys as steels. This reduces the difficulties associated to semi-solid processing of steels related with the high melting point and narrow semi solid range of these alloys. These technical problems and the material requirements for steel thixoforming were studied by Püttgen et al. [1]. Moreover, investigations were performed by Rassili et al. [2,3] defining the potential steels which are amenable to thixoforming and technology considerations for their industrialization. Balan et al. [4] studied alternative routes that combine semi-solid zones at the heart of the material with surrounding solid zones within the part. However, despite all these researches, the industrial application of thixoforming processes for steels is still conditioned by the mentioned drawbacks, making the application of high temperature closed dies hot forging processes more interesting.

Compared to hot forging, high temperature hot forging in closed dies technology allows the production of parts with forged properties and more complex near-net shapes (thinner sidewalls), enhancing the possibility of designing lightweight components. From the process viewpoint, Lozares et al. [5] have demonstrated that the forging forces are significantly decreased and a significant reduction of the raw material, energy consumption and the forging steps are achieved by this new forming process.

Despite the mentioned advantages, from the material behavior point of view, the expansion of these technologies has shown the necessity of developing new material flow behavior models in the processes working temperature range, i.e., from 1250 °C to 1375 °C. These new models will make the simulation or the prediction of these new forming processes feasible, because commercial software as FORGE®, DEFORM®, QFORM® … widely used in automotive industry, restrict the current existing models up to 1250 °C.

Regarding the 42CrMo4 alloyed quenching and tempering steel, commonly used in automotive commercial components, several experiments have been implemented in the last years in order to determine its hot compressive deformation behavior.

Lin et al. [6] investigated the compressive deformation behavior of 42CrMo4 at temperaturesranging from 850 to 1150 °C and strain rates from 0.01 to 50 $s-^{1}$ and fitted it via the Arrhenius model. However, this temperature range is below 1250 °C which is the minimum temperature for the working temperature range of high temperature closed dies hot forging processes.

Moreover, Huang et al. [7] studied the hot tensile deformation behaviors of 42CrMo4 steel by uniaxial tensile tests within a similar temperature range of 850–1100 °C but in a lower strain rate range of 0.1–0.0001 s^{-1}. A constitutive equation was then established to determine the peak stress via Arrhenius model. Nevertheless, the studied temperature conditions are below the working temperature range of 1250 °C–1375 °C used in high temperature closed dies hot forging technology.

Ji et al. [8] worked at slightly higher temperatures ranges, from 800 °C to 1200 °C and at stain rates from 0.01 s^{-1}–10 s^{-1} and used these data to establish the Arrhenius model [9]. However, the considered temperature range is below the minimum temperature of 1250 °C needed in high temperature closed dies hot forging applications.

Higher temperatures were reached by Liu et al. [10] in their recent study. They adjusted and compared two constitutive models, the Arrhenius constitutive model of strain compensation and back propagation artificial neural network (BP ANN) model, considering hot compression tests results between 1200 and 1350 °C temperatures and 0.001–10 s^{-1} strain rates. They concluded that the strain compensated Arrhenius constitutive model in the determined temperature and strain rate ranges can be expressed by Equation (1).

$$\sigma = \frac{1}{\alpha(\varepsilon)} \ln\left\{ \left(\frac{z}{A(\varepsilon)}\right)^{\frac{1}{n(\varepsilon)}} + \left[\left(\frac{z}{A(\varepsilon)}\right)^{\frac{2}{n(\varepsilon)}} + 1\right]^{1/2} \right\} \tag{1}$$

where Z parameter can be obtained by Equation (2) and the relationship between strain and material constants (α, n, Q, and A) can be

Table 1
Z,α, n, Q, A parameters and flow stress values using the strain compensated Arrhenius model of Liu et al. [10] at 1250 °C and 10 s^{-1} conditions.

ε	α	n	Q (kJ/mol)	A	Z	σ (MPa)
0.05	0.0233	3.6877	383651.6110	1.8550E+12	9.0648E+12	52.2141
0.1	0.0216	3.5319	372893.1962	8.5645E+11	3.8761E+12	56.0428
0.15	0.0217	3.1885	359820.2540	3.2976E+11	1.3806E+12	56.6278
0.2	0.0216	3.0692	353168.0012	2.1944E+11	8.1643E+11	56.0707
0.25	0.0217	3.0321	349777.0842	1.7111E+11	6.2464E+11	55.8219
0.3	0.0222	2.9985	350117.2162	1.4961E+11	6.4164E+11	56.8608
0.35	0.0228	2.9886	355564.0974	2.5607E+11	9.8649E+11	54.1168
0.4	0.0231	3.0105	363185.6012	4.4615E+11	1.8008E+12	53.7531
0.45	0.0231	3.0159	366237.7804	5.1137E+11	2.2916E+12	55.1153
0.5	0.0226	2.9742	361015.8122	3.4604E+11	1.5173E+12	56.3590
0.55	0.0214	2.9505	353149.5708	1.8220E+11	8.1524E+11	59.9862
0.6	0.0195	2.9164	348878.0812	1.3509E+11	5.8183E+11	65.2657

fitted by a polynomial Equation (3).

$$Z = \dot{\varepsilon}^{-1/5} \exp\left(\frac{Q}{RT}\right) \quad (2)$$

$$\alpha(\varepsilon) = \alpha_0 + \alpha_1\varepsilon^1 + \alpha_2\varepsilon^2 + \alpha_3\varepsilon^3 + \ldots + \alpha_m\varepsilon^m \; n(\varepsilon) = n_0 + n_1\varepsilon^1 + n_2\varepsilon^2 + n_3\varepsilon^3 + \ldots + n_m\varepsilon^m \; Q(\varepsilon) = Q_0 + Q_1\varepsilon^1 + Q_2\varepsilon^2 + Q_3\varepsilon^3 + \ldots + Q_m\varepsilon^m \; A(\varepsilon) = A_0 + A_1\varepsilon^1 + A_2\varepsilon^2 + A_3\varepsilon^3 + \ldots + A_m\varepsilon^m \quad (3)$$

Considering the temperature and strain rate combinations that represent the extreme conditions of high temperature hot forging in closed dies technology, 1250 °C–10 s^{-1} and 1375 °C–0.1 s^{-1}, Tables 1 and 2 show the parameter and flow stress values obtained in each case:

Fig. 1(a) and (b) show the comparison of the obtained flow stress values with corrected flow stress results from experimental hot compression tests at 1250 °C–10 s^{-1} and 1375 °C–0.1 s^{-1} temperature and strain rate conditions respectively. Curves do not show a good fitting, which indicates that the suggested adjusted Arrhenius model does not reflect accuracy the material behavior for extreme temperature and strain rates of the high temperature hot forging in closed dies technology. Moreover, modified Arrhenius equation is only capable of predicting results until a strain of 0.6.

Therefore, in this work a new constitutive model for the 42CrMo4 steel that represents the flow stress behavior in a temperature range from 1250 °C to 1375 °C has been obtained. For that, the widely used Hansel-Spittel model in commercial software as FORGE® has been fitted from hot compression tests carried out at a temperature range between 1250 °C-1375 °C and 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1} strain rates magnitudes, covering the new process working conditions.

Then, hot compression tests simulations with the obtained new law have been used for validating the obtained model. Finally, a comparison between results of the high temperature hot forging in closed dies process simulation using the new material flow behavior law and the experimental results previously obtained in trials made by Lozares et al. [5] for an automotive commercial spindle has been carried out.

2. Experimental procedure

2.1. Hot compression test procedure

To determine the hot deformation behavior of the 42CrMo4 steel at high temperature hot forging processes working temperature range hot compression tests were executed in a Gleeble® 3800 thermomechanical tester shown in Fig. 2.

For these tests, a temperature range covering the material behavior from the hot forging until the Nil Ductile Temperature (NDT) was taken into account, i.e., from 1250 °C to 1375 °C.

The NDT is the temperature where, under tensile loading, the sample breakage happens in a brittle manner (without any observable ductility) of the steel and is associated with first small amount of liquid in grain boundaries that causes an intergranular breakage. That is why, it is considered the upper limit temperature of the high temperature hot forging processes, where no liquid phase is expected.

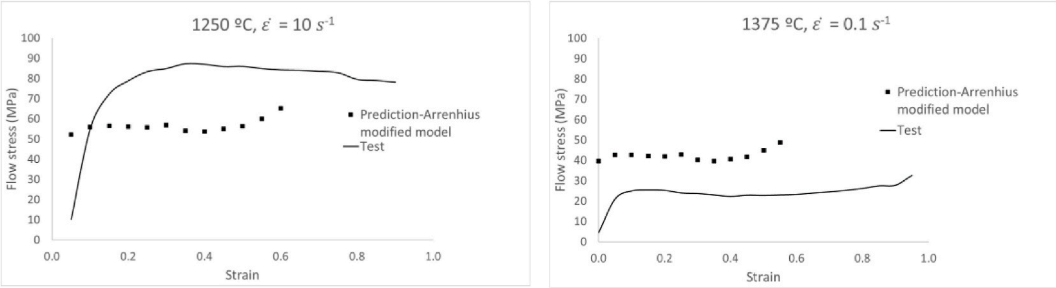
Cederblad and Grant [11] studied the hot workability of Ninomic 115 as a function of the strain rate and concluded that near the NDT the strain rate influence is insignificant.

For the determination of the NDT temperature, hot tensile tests each 5 °C starting at 1350 °C were carried out in a Gleeble® 3800 thermomechanical tester. The NDT was considered the temperature where the brittle breakage was achieved. The thermomechanical cycle applied is shown in Fig. 3.

Samples were heated at a heating rate of 50 °C/s until 1250 °C and then at 10 °C/s until temperatures of 1350 °C, 1355 °C, 1360 °C, 1365 °C, 1370 °C, 1375 °C, 1380 °C ... were held in each case. At these temperatures the specimens were maintained for 5 s to homogenize the temperature through them and they were brought to breakage at a 10 s^{-1} strain rate. For each temperature three specimens were tested. The upper temperature from which on the striction of the specimens is 0 % (Z = 0 %) was considered the NDT

Table 2
Z,α, n, Q, A parameters and flow stress values using the strain compensated Arrhenius model of Liu et al. [10] at 1375 °C and 0.1 s^{-1} conditions.

ε	α	n	Q (kJ/mol)	A	Z	σ (MPa)
0.05	0.0233	3.6877	383651.6110	1.8550E+12	2.2881E+12	39.6157
0.1	0.0216	3.5319	372893.1962	8.5645E+11	1.0435E+12	42.5688
0.15	0.0217	3.1885	359820.2540	3.2976E+11	4.0194E+11	42.5845
0.2	0.0216	3.0692	353168.0012	2.1944E+11	2.4735E+11	42.0067
0.25	0.0217	3.0321	349777.0842	1.7111E+11	1.9313E+11	41.8798
0.3	0.0222	2.9985	350117.2162	1.4961E+11	1.9798E+11	42.7488
0.35	0.0228	2.9886	355564.0974	2.5607E+11	2.9462E+11	40.1522
0.4	0.0231	3.0105	363185.6012	4.4615E+11	5.1383E+11	39.5509
0.45	0.0231	3.0159	366237.7804	5.1137E+11	6.4203E+11	40.5362
0.5	0.0226	2.9742	361015.8122	3.4604E+11	4.3858E+11	41.5987
0.55	0.0214	2.9505	353149.5708	1.8220E+11	2.4702E+11	44.7669
0.6	0.0195	2.9164	348878.0812	1.3509E+11	1.8087E+11	48.8223



(a) 1250 ºC, 10 s-1 *(b) 1375 ºC, 0.1 s-1*

Fig. 1. Comparison between experimental and predicted flow stress curves using the Arrhenius modified model of Liu et al. [10] at 1250 °C–10 s^{-1} and 1375 °C–0.1 s^{-1} temperature and strain rate conditions.

Fig. 2. Thermomechanical test set-up for hot compression tests.

temperature, being this temperature determination the aim of these tests in order to define the upper temperature limit of hot compression tests. This temperature will be also the upper temperature limit of high temperature hot forging in closed dies applications.

In Fig. 4 the force vs. displacement curve and a broken specimen at the NDT temperature where brittle fracture can be appreciated are shown. In Table 3 the value of this NDT for 42CrMo4 steel is defined, being this value repeated in the three specimens tested.

Considering the obtained temperature for the NDT determination as the upper temperature limit, and that the lower limit of the temperature range in high temperature hot forging must be approximately the upper limit of the usual hot forging process, the following temperature range was considered for hot compression tests:

Temperatures: 1250 °C, 1275 °C, 1300 °C, 1325 °C, 1350 °C and 1375 °C.

As for the strain rates, in order to cover the range of different rates of deformation that a part can suffer during its manufacturing by high temperature hot forging in closed dies, three different orders of magnitudes were considered:

Strain rates: 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}.

To perform the compression tests 10 mm diameter and 15 mm long cylindrical specimens of the selected steel grade were used. A tantalum foil was introduced between the tungsten carbide plates of 20 mm diameter of the Gleeble and the specimens to ensure a proper contact for the Joule heating and to avoid hot spots and sample sticking to the plates. Then the samples were heated at a 6 °C/s heating rate until the defined temperatures and were held at these temperatures for 60 s to homogenize the temperature through the specimen. Finally, the specimens were compressed at the previously defined strain rates until strain of 1 was achieved. Three specimens were considered for each temperature and strain rate conditions.

Fig. 5 shows the explained thermomechanical cycle and the geometry of one specimen before and after the test:

2.2. Data processing

Spittel and Spittel [12] determine Equation (4), Equation (5) and Equation (6) for the characterization of the hot deformation behavior, the yield stress and the plasticity from hot compression testing in steels:

$$\sigma_F = \frac{\sigma_0}{1 + \frac{\mu}{3}\frac{d}{h}} \tag{4}$$

$$\varepsilon = ln\frac{h}{h_0} \tag{5}$$

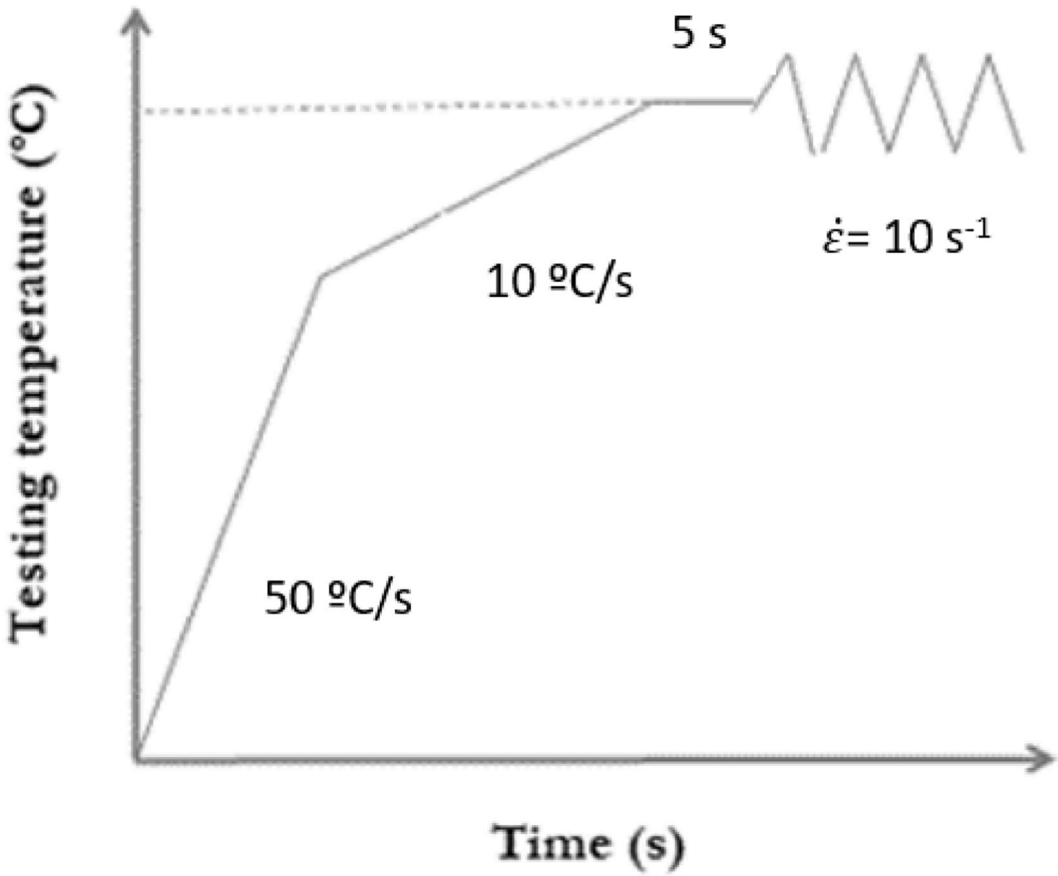


Fig. 3. Thermomechanical cycle used for the NDT temperature determination.

Fig. 4. Force vs. displacement curve and a broken specimen for the NDT temperature determination.

Table 3
NDT temperature for 42CrMo4 steel.

Steel grade	NDT temperature (°C)
42CrMo4	1380

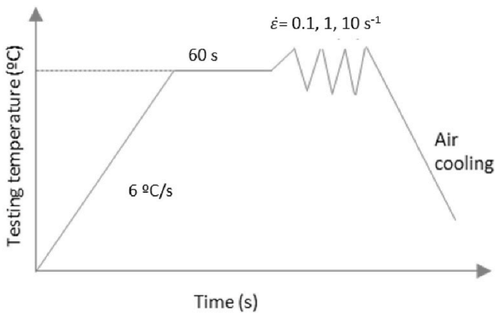


Fig. 5. Thermomechanical cycle and geometry of a compression test specimen before and after the compression test.

$$\dot{\varepsilon} = \frac{\Delta\varepsilon}{\Delta t} = \frac{v}{h} \tag{6}$$

where σ_F is the flow stress after the friction correction, σ_0 is the flow stress obtained in the compression test, μ is the friction coefficient, d and h are the diameter and height of the specimen respectively, ε is the strain, h_0 is the initial height of the specimen, $\dot{\varepsilon}$ is the strain rate and v is the compression rate.

As it can be seen, the uniaxial compression stress obtained from the tests need to be friction corrected in order to obtain accurate values of the flow stress. In fact, the main drawback of the hot compression test is that load results obtained are highly influenced by the friction between the plates and the specimen. This friction causes the barreling of the specimen and the experimental stress-strain curve deviates from the actual stress strain curve of the material, being this deviation more significant at high strains as Wang et al. [13] concluded in their work.

Moreover, Gholamzadeh and Karimi Taheri [14] proposed Equation (7) for the determination of the corrected flow stress:

$$\sigma_F = \frac{\sigma_0}{1 + \left(\frac{2}{3}\sqrt{3}\right) m \left(\frac{R_0}{h_0}\right) e^{3\varepsilon/2}} \tag{7}$$

where σ_F and σ_0 are the flow stresses after and before the friction correction, R_0 and h_0 are the initial radius and height of the specimen, ε is the strain and m is the friction factor equivalent to μ coefficient of Equation (4). This factor varies from 0 (perfect sliding) to 1 (sticking) and can be defined by Equation (8):

$$m = \frac{\frac{R}{h} b}{\frac{4}{\sqrt{3}} - \frac{2b}{3\sqrt{3}}} \tag{8}$$

The barreling factor b is determined by Equation (9):

$$b = 4 \frac{R_M - R_T}{R} \frac{h}{h_0 - h} \tag{9}$$

where the top radius is calculated by Equation (10):

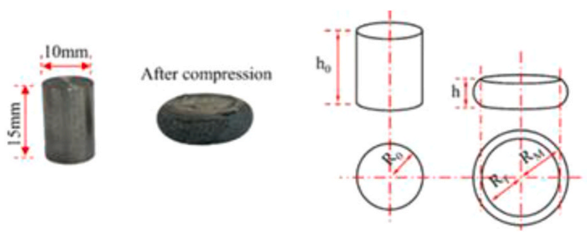


Fig. 6. Sample geometry before and after hot compression and the relevant parameters in friction correction.

$$R_T = \sqrt{3\frac{h_0}{h}R_0^2 - 2R_M^2} \tag{10}$$

R is the average radius of the deformed specimen defined as $R = R_0\sqrt{h_0/h}$ and R_T and R_M are the top and maximum radius of the deformed specimen respectively.

Fig. 6 shows a scheme of the sample geometry before and after hot compression and the relevant parameters in friction correction.

On the other hand, Li et al. [15] suggested Equation (11) for the flow stress correction and Equation (12) for the correction coefficient C:

$$\sigma_F = \frac{\sigma_0 \, C^2}{2[e^C - C - 1]} \tag{11}$$

$$C = \frac{2m\,R}{h} \tag{12}$$

where σ_F and σ_0 are the flow stresses after and before the friction correction, C is the correction coefficient, *mist* he friction coefficient defined in Equation (8), R is the average radius of the deformed specimen, and *h* is the specimen height.

Whatever the approximation used for the determination of the friction corrected flow stress similar values were obtained. Table 4 and Table 5 show the obtained friction corrected flow stress results with each approximation for the extreme conditions of temperature and strain rate in high temperature hot forging in closed dies application.

2.3. Hot compression test results

The friction corrected flow stress vs. strain curves obtained in the hot compression tests are shown in Fig. 7(a), (b) and (c).

Each curve for each temperature and strain rate condition has been obtained by results scattering and friction correction using Equation (4) of the three specimens tested in each condition.

The different curves show a mechanical characteristics decrement as the temperature increases for the same strain rate, and mechanical characteristics increment as the strain rates increases for same temperature. It is noticed that after reaching the steady state stage (ε > 0.6) it is shown an increment of stress which is caused by the increment of friction produced at higher strains of the specimen, that is why only values until ε = 0.6 have been considered in the development of the constitutive model. This increment of friction was produced by the contact between the plates and the specimen despite a tantalum foil was introduced between them. As the deformation of the specimen and the barreling phenomena of it increases, the friction between the specimen and the platens is higher because more surface of the specimen is in contact with the platens, and that is the reason why at higher strains the friction is higher and produces a not real increment of the force in the tests.

Table 4
Friction corrected flow stress values using different approximations at 1250 °C and 10 s^{-1} conditions.

ε	$\sigma_F = \dfrac{\sigma_0}{1+\dfrac{\mu}{3}\dfrac{d}{h}}$	$\sigma_F = \dfrac{\sigma_0}{1+\left(\dfrac{2}{3}\sqrt{3}\right)m\left(\dfrac{R_0}{h_0}\right)e^{3\varepsilon/2}}$	$\sigma_F = \dfrac{\sigma_0\,C^2}{2[e^C - C - 1]}$
0	10.21	9.39	9.23
0.05	55.16	54.49	54.18
0.1	72.31	71.81	71.74
0.15	78.84	77.11	77.02
0.2	83.44	83.27	82.91
0.25	84.96	84.73	84.45
0.3	87.31	86.44	86.20
0.35	87.02	86.98	86.74
0.4	85.90	85.17	85.03
0.45	86.00	85.42	85.14
0.5	84.97	84.35	84.07
0.55	84.28	84.19	84.06
0.6	84.09	83.16	83.11
0.65	83.63	82.54	82.25
0.7	82.86	82.47	82.38
0.75	79.54	79.21	79.06
0.8	78.97	77.30	77.11
0.85	78.15	76.59	76.47
0.9	77.52	76.15	75.97
0.95	77.15	75.98	75.87
1	76.95	75.56	75.24

Table 5
Friction corrected flow stress values using different approximations at 1375 °C and 0.1 s^{-1} conditions.

ε	$\sigma_F = \frac{\sigma_0}{1 + \frac{\mu}{3}\frac{d}{h}}$	$\sigma_F = \frac{\sigma_0}{1 + \left(\frac{2}{3}\sqrt{3}\right) m \left(\frac{R_0}{h_0}\right) e^{3\varepsilon/2}}$	$\sigma_F = \frac{\sigma_0 C^2}{2[e^C - C - 1]}$
0	4.09	3.97	3.87
0.05	15.95	15.11	14.98
0.1	18.83	18.54	18.17
0.15	19.78	19.24	19.02
0.2	19.93	19.52	19.29
0.25	19.11	19.05	18.99
0.3	18.68	18.46	18.35
0.35	18.28	18.01	17.96
0.4	17.71	17.56	17.42
0.45	18.17	18.02	17.99
0.5	18.19	18.05	18.02
0.55	18.53	18.23	18.14
0.6	18.63	18.41	18.37
0.65	18.67	18.45	18.36
0.7	18.86	18.53	18.49
0.75	18.71	18.51	18.45
0.8	19.05	19.01	18.99
0.85	19.18	19.05	19.01
0.9	17.30	17.01	16.98
0.95	17.75	17.54	17.25
1	17.89	17.61	17.38

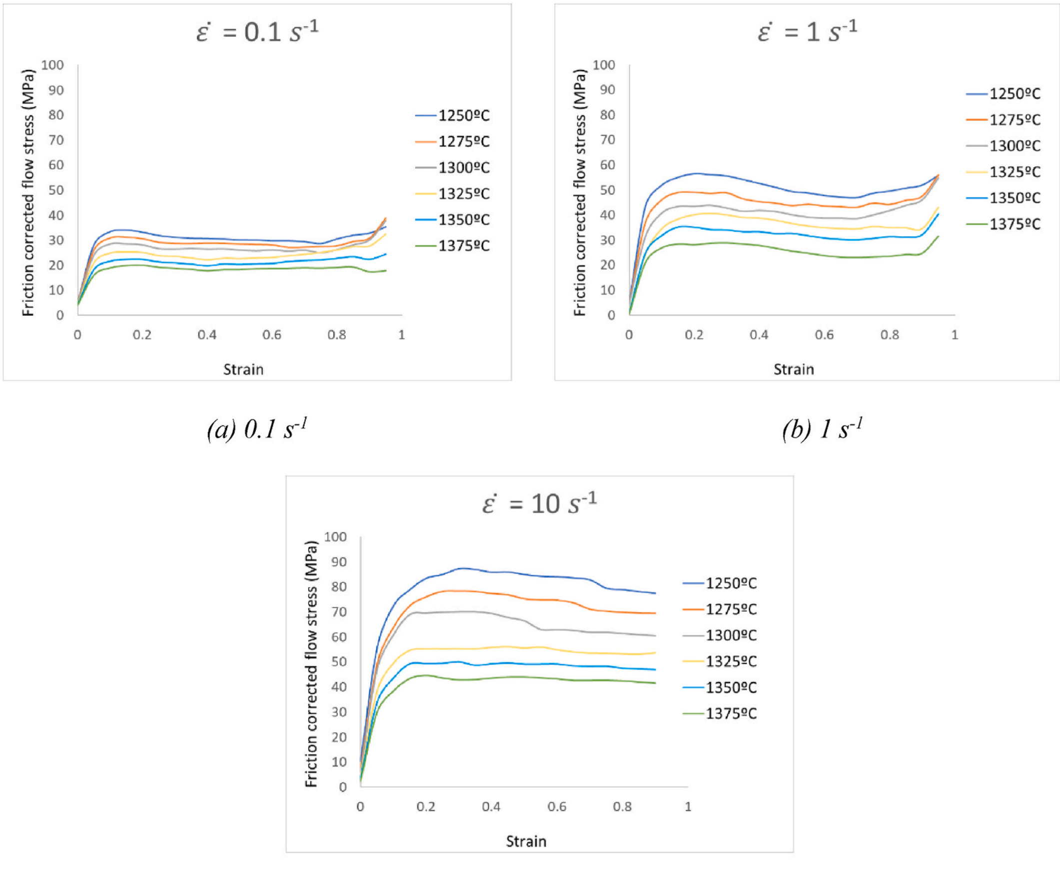


Fig. 7. Friction corrected flow stress vs. strain curves of 42CrMo4 steel under 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} deformation conditions.

3. Development of constitutive model

As mentioned above, the Hansel-Spittel model is the most widely used model for hot flow behavior description in commercial software as FORGE®. This model considers the material viscoplastic behavior and is written as follows:

$$\sigma = A e^{m_1 T} \varepsilon^{m_2} \dot{\varepsilon}^{m_3} e^{m_4/\varepsilon} (1+\varepsilon)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{T m_8} T^{m_9} \tag{13}$$

where σ is the flow stress, ε is strain, $\dot{\varepsilon}$ is strain rate and T is deformation temperature. The variables m_1 and m_9 describe the material sensitivity to temperature; m_5 defines the coupling between temperature and strain; m_8 represents the coupling between temperature and strain rate, m_2, m_4 and m_7 define the material sensitivity to strain and m_3 is the material sensitivity to strain rate. And finally, A is the material constant.

In addition to its widely extension in commercial simulation software as FORGE® which simplifies its application from an industrial point of view, the Hansel-Spittel model has been considered an appropriated constitute equation due to the capacity that the model shows to reproduce the different zones of the flow stress curves: the hardening region, the softening region and the steady-state region. Moreover, it is capable of predicting an accuracy value of the peak stress.

Converting the values obtained in the tests according to Equations (4)–(6) and replacing them in Equation (13), a linear regression has been applied for the obtention of the Hansel-Spittel law parameters in the temperature range from 1250 °C to 1375 °C as shown in Table 6:

The analysis of variance (ANOVA) of the model with nine parameters allows to obtain the statistical constant values of the regression shown in Table 7, and indicates a good prediction for flow stress variations:

However, the ANOVA between obtained model parameters, shows a high correlation existence between m_1 and m_9; m_3 and m_8 and m_5 and m_7 parameters, which reflects that no all parameters are necessary to represent flow stress variations. Table 8 shows the correlation between material parameters using the model of nine parameters.

Moreover, the risk analysis (possibility that the concerned parameter should not be significant) of the obtained parameters explains that a high risk is being assumed in this case with values obtained for m_9 and A constant parameters.

The risk associated with the analysis of variance allows to determine whether a parameter is statistically significant for the model of the response analyzed (flow stress).

During the analysis of variance, to determine the importance of each parameter of the model, a Fisher test is carried, calculating a F-value index by making the ratio:

$$F - value = \frac{\frac{parameter\ square\ sum}{parameter\ degree\ of\ freedom}}{\frac{residues\ or\ error\ square\ sum}{residues\ or\ error\ degree\ of\ freedom}}$$

The F-value is the test statistic used to determine whether the parameter is associated with the model of the response (flow stress). A sufficiently large F-value indicates that the parameter is significant.

The F-value is compared with a $F_{theoretical}$-value which is defined for a risk (noted α), a probability which measures the significance level. Usually, a risk of 0.1 or 0.05 works well. A significance level or risk of 0.05 indicates a 5 % risk of concluding that the parameter of the model explains the variation in the response when in reality does not.

The $F_{theoretical}$-value can be obtained from Snédécor tables for a significance level (5 % for example), depending on the degree of freedom of the parameter and of the residues or error. If the F-value is higher than the $F_{theoretical}$-value, the parameter is significant and explains the variation of the response (flow stress) for the model used. The other possibility is to use the inverse cumulative distribution function (ICDF) to determine the significance level or risk for which F-value = $F_{theoretical}$-value. This solution has been used in this contribution.

Table 9 shows the different significance level associated to each of the nine parameters of the model. One can conclude that parameters A and m_9 are not significant.

So, starting from this initial analysis based in the Hansel-Spittel complete constitutive model of nine parameters, successive regressions have been launched eliminating from the model the parameters that show high-risk or high correlation with another parameter one by one. The aim has been to obtain a new constitutive model where in addition to obtaining good values of the regression analysis that indicate a good prediction for flow stress variations, all parameters show no correlation and low risk values. Hence, the obtained new constative model will represent appropriately the flow stress variation at the temperature range of 1250 °C-1375 °C, in which the new manufacturing process is interested in. The followed steps are summarized in the flow chart of Fig. 8.

So, as it can be seen in Fig. 8, first, starting from the complete model of nine parameters, a regression eliminating the A constant has been launched giving a better regression coefficient and reducing the risk of m_9 parameter, but with a high-risk value of m_2 parameter. Then, this parameter has been removed and despite the regression coefficient has been maintained at high values, the risk of the m_5 constant has increased. Finally, the m_5 parameter has been annulled and the final constitutive model with six parameters that

Table 6
Values of material parameters from 1250 °C to 1375 °C for 42CrMo4 steel based on Hansel–Spittel model.

Ln (A)	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
−32.9124	−0.0108	−0.1541	0.4836	−0.0355	0.0008	−0.9048	−0.0002	7.0578

Table 7
Statistical constant values of the regression using the model of nine parameters.

Regression coefficient (r)	Fisher parameter (F)	Confidence (%)
0.9652396	352.9016	100

Table 8
Correlation between material parameters using the model of nine parameters.

	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
m_1	1							
m_2	0	1						
m_3	0	0	1					
m_4	0	−0.9372	0	1				
m_5	0.0671	0.9595	0	−0.8096	1			
m_7	0	0.9459	0	−0.7822	0.9955	1		
m_8	0	0	0.9995	0	0	0	1	
m_9	0.9999	0	0	0	0.0671	0	0	1

Table 9
Risk of the obtained material parameter values using the model of nine parameters.

Variable	Risk %
A	76.57
m_1	42.53
m_2	49.18
m_3	0.05
m_4	1.32
m_5	59.1
m_7	41.22
m_8	4.11
m_9	69.28

represents the material flow stress behavior at high temperatures has been achieved.

The obtained new parameters values and the statistical results of the new constitute model of six parameters are shown in Table 10 and Table 11, evidencing not only a good prediction of flow stress variations at high temperatures as it could be seen also in Table 7, but also and a low risk of the considered model parameters:

Fig. 9 shows the comparison of predicted and experimental flow stress by the Hansel-Spittel model with 6 parameters.

The obtained new constitutive model is represented by Equation (14) and the surfaces that represent the new constitutive model for 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1} strain rates at different temperatures, flow stress and strain conditions are shown in Fig. 10(a), (b) and (c) respectively:

$$\sigma = e^{m_1 T}\, \dot{\varepsilon}^{m_3}\, e^{m_4/\varepsilon}\, e^{m_7 \varepsilon}\, \dot{\varepsilon}^{T\, m_8}\, T^{m_9} = e^{-0.006T}\, \dot{\varepsilon}^{0,4836}\, e^{-0.0265/\varepsilon}\, e^{-0.5191\varepsilon}\, \dot{\varepsilon}^{-0.0002T}\, T^{1.7389} \tag{14}$$

4. Validation of the obtained constitutive model

4.1. Simulation of hot compression tests

Fig. 11(a), (b) and (c) show the comparison between the corrected flow stress values obtained from the experimental hot compression tests and from the simulation of these tests with the proposed constitutive model.

For the simulation at each experimental temperature of 1250 °C, 1275 °C, 1300 °C, 1325 °C, 1350 °C and 1375 °C cylindrical specimens of 10 mm diameter and 15 mm long used in experimental tests have been compressed at different strain rates conditions of 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1} applied in trials. For the compressions two plates of 20 mm diameter have been used and a friction of 0.3 has been considered between plates and the specimens in order to characterize the tantalum foil introduced between them in the tests. As trials have been carried out in a thermal camera where temperature is maintained, adiabatic boundary conditions have been considered in the simulations keeping the temperature of the specimens and plates constant during the simulation. For material flow stress behavior the obtained new constitutive model has been considered.

The main limitation of the simulation is the determination of the real value of the friction coefficient generated between specimens and the plates or the tantalum foil, which cannot be experimentally determined at so high temperatures. So, it has been considered as 0.3 based in experience.

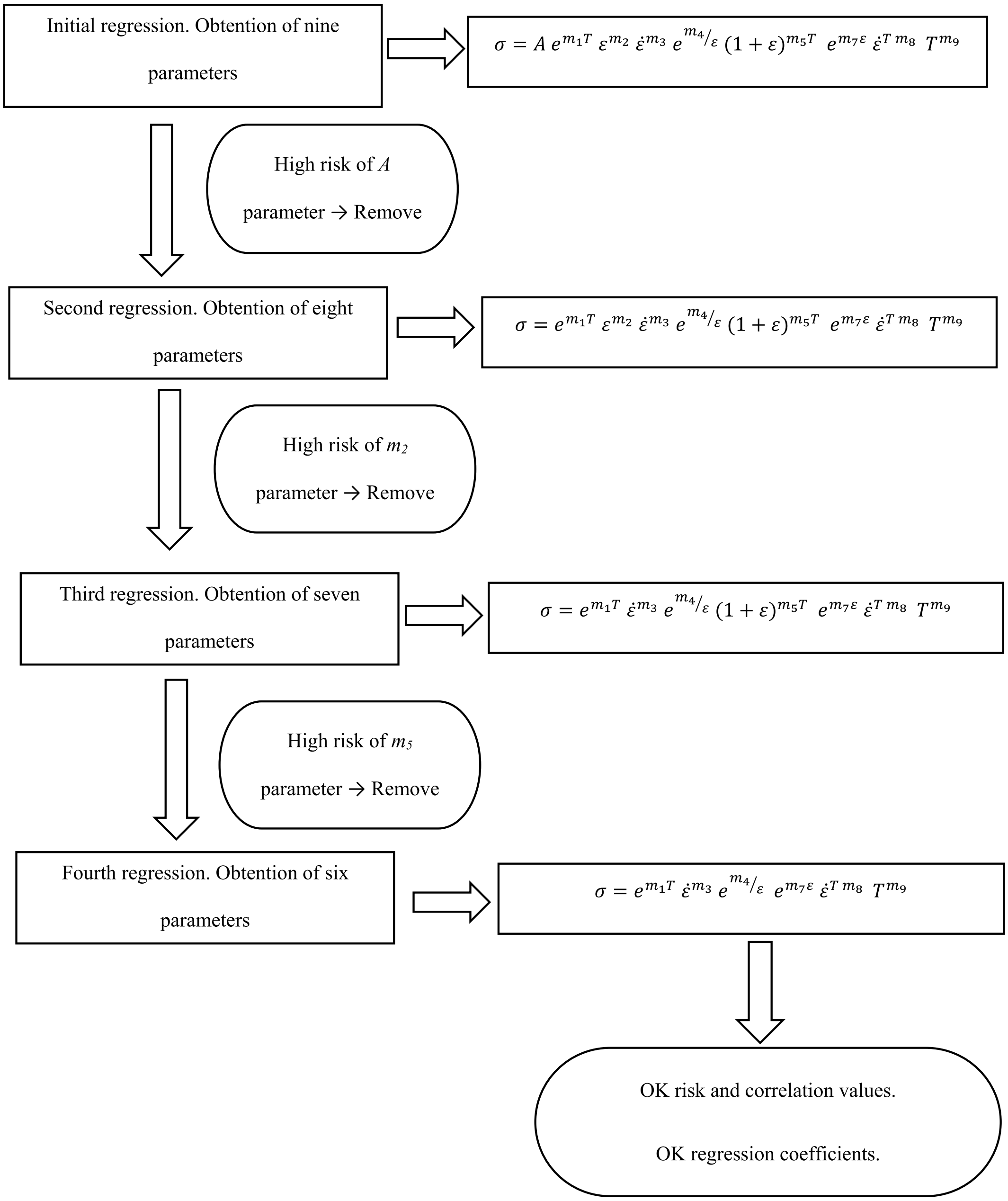


Fig. 8. Flow chart of the followed procedure to obtain the parameters of the new constitutive equation.

Table 10
Results and risk of the obtained material parameter values using the model of six parameters.

Variable	Value	Risk %
m_1	−0.006	0
m_3	0.4836	0.05
m_4	−0.0265	0
m_7	−0.5191	0
m_8	−0.0002	3.99
m_9	1.7389	0

Table 11
Statistical constant values of the regression using the model of six parameters.

Regression coefficient (r)	Fisher parameter (F)	Confidence (%)
0.99942402	30356.2768	100

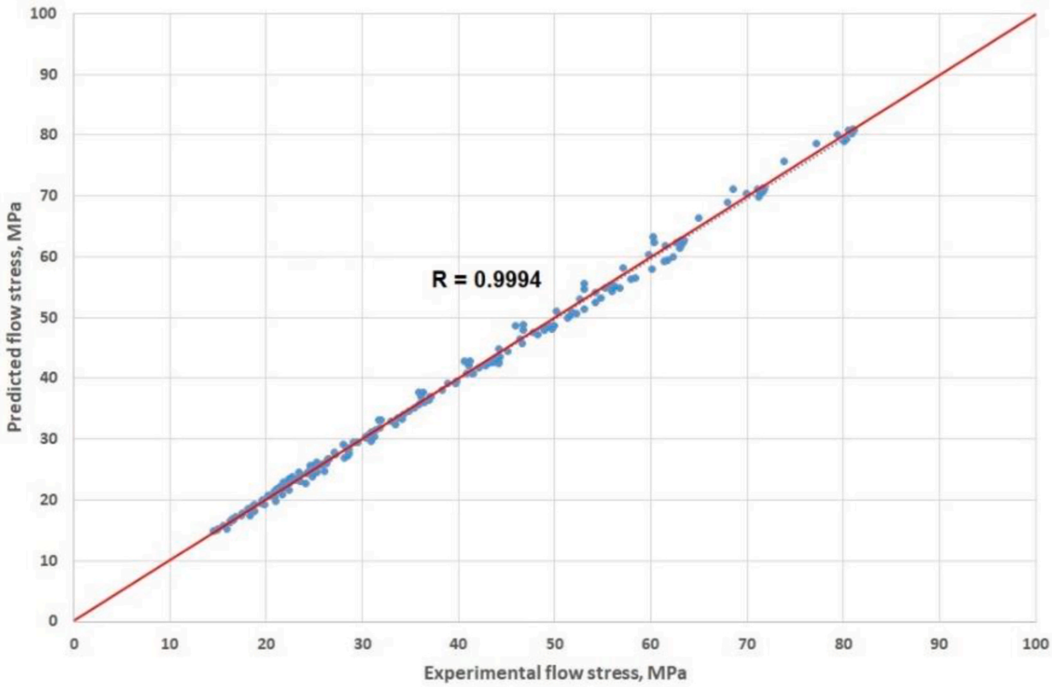


Fig. 9. Comparison of predicted and experimental flow stress by the Hansel-Spittel model with 6 parameters.

It can be seen that the flow stress predicted through the constitutive model agrees with the experimental result quite well. The obtained curves in the simulation using the new constitutive model are capable of representing the straightening zone, the peak stress, the softening zone and the steady-state zone until a strain of 1. Main differences can be noticed for values of strain higher than 0.6, because while the predicted curves still show a slight softening or a steady-state zone, the experimental tests show an increment of the stress related with the friction phenomenon between the specimens and the platens. In the case of curves tested at a strain rate of 10 s^{-1}, this difference is not so notable because the experimental curves do not show such increment of stress. This is related with the less influence of friction at higher strain rates, where the specimen does not have time to suffer so high deformation and then the friction is less.

4.2. Simulation of automotive spindle

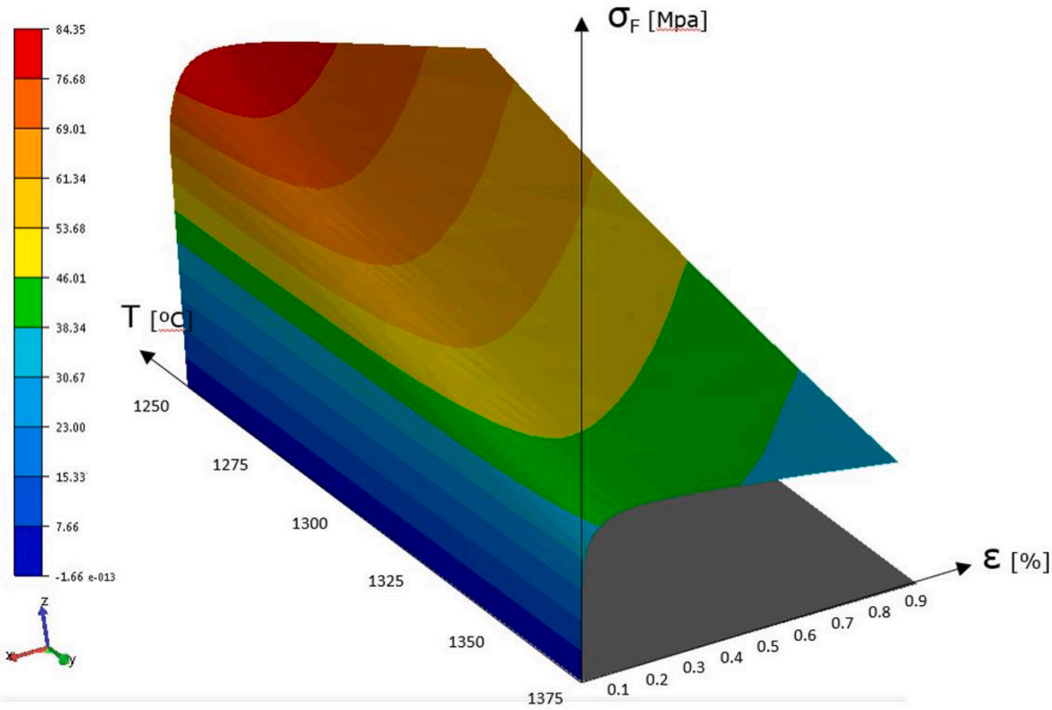
Moreover, in order to prove the validation of the new material constitutive model in high temperature hot forging in closed dies automotive applications, the process simulation of a previously manufactured automotive commercial spindle shown in Fig. 12 was executed [5].

Considering the manufacturing conditions expressed by Lozares et al. in their research [5], the parameters used for the numerical simulation are summarized in Table 12:

As Lozares et al. [5] determined that Ceraspray® acts not only as lubricant but also as thermal shock barrier of the dies, no temperature drop of the dies was considered during the simulation. Moreover, they only notice a temperature loss of approximately 40 °C on the surface of the billet used for the manufacturing of the part during its manipulation, while the required temperature inside the billet was maintained [5]. That is why, adiabatic conditions, i.e., no temperature losing was considered during the simulation as boundary conditions. For the material flow behavior conditions, the obtained new constitutive model was applied.

Fig. 13(a), (b) and (c) show the carried out simulation of the automotive commercial spindle at initial, intermediate and final stages respectively:

The curve represented in Fig. 14 shows the filling force value during the part filling, with a maximum force value around 260 Tn for the complete filling of the component. This result agrees with force results obtained in experimental tests [5]. So, results of simulations using the new constitutive model for material flow stress behavior show a good correlation with the experimental results regarding



(a) 0.1 s⁻¹

Fig. 10. Surfaces that represent the flow stress vs. temperature vs. strain for 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} strain rates considering the obtained new constitute model.

peak force at the complete filling of the part. This indicates that the obtained new constitutive model for the material flow stress characterization represents well the material behavior for high temperature hot forging in closed dies process applications.

Moreover, Fig. 15 shows the comparison between the filling force curve vs. the height of the punch (ram position) for the simulation parameters described in Table 12 obtained with the new constitutive equation and with the Hansel-Spittel constitutive equation used in FORGE® library, restricted until 1250 °C. It is apparent how the equation of FORGE® library predicts a double force value than the force obtained in the experimental tests, whereas the new constitutive model agrees well with the obtained results. This clearly reflects that existing models in commercial simulation software do not represent the material condition at high temperature hot forging in closed dies process application and that the obtention of new constitutive models is necessary.

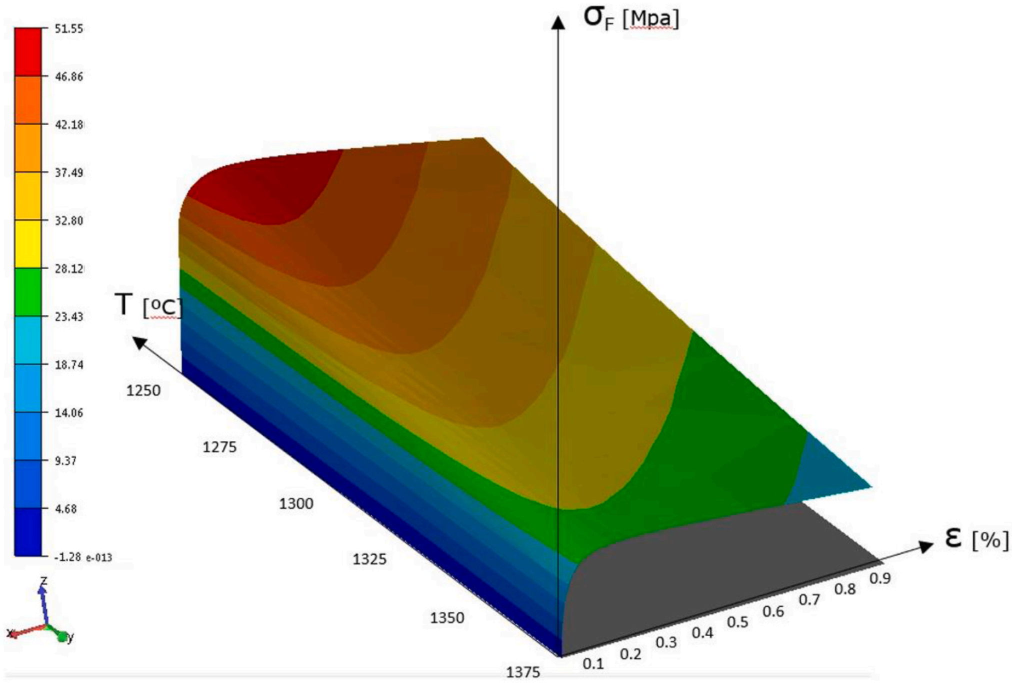
5. Conclusions

a. The comparison between experimental trials and simulation results using the Hansel-Spittel model currently used in the FORGE® software library for hot forging applications, clearly reflects the necessity of a new material flow behavior constitutive model development for the high temperature range used in the new forming process.

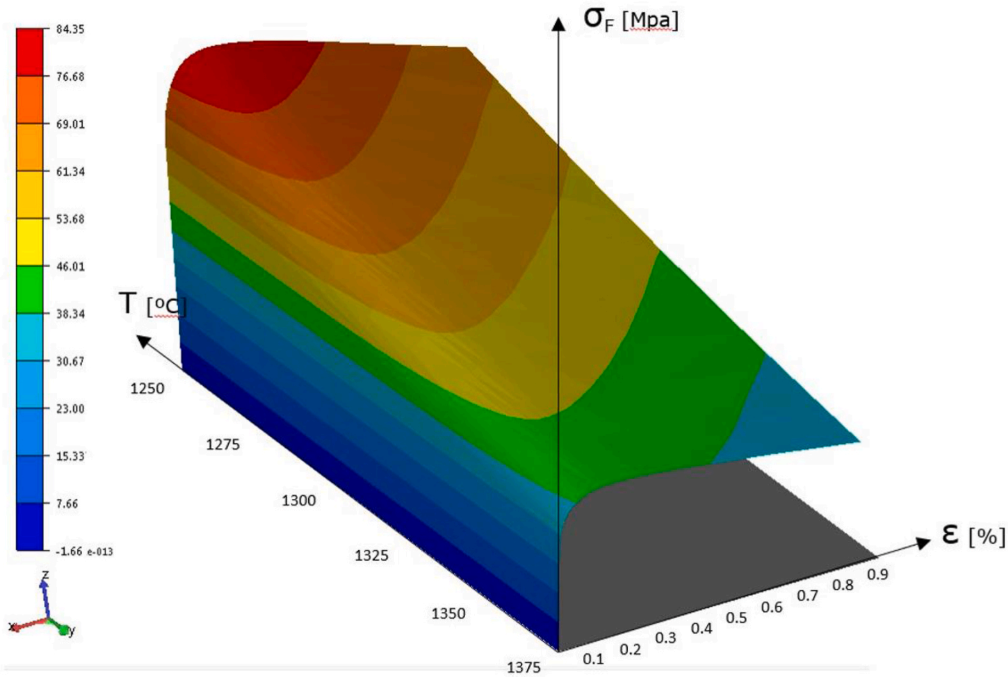
While existing models restrict the material characterization for applications up to 1250 °C leading to no accurate values of needed peak force for component manufacturing by high temperature hot forging in closed dies process, the obtained new constitutive model is capable of representing the material flow stress behavior along a temperature range of 1250 °C–1375 °C used in high temperature hot forging in closed dies process. This allows to predict or simulate the new manufacturing process, making feasible the extension of its application from an industrial point of view.

b. Existing material constitutive models search in bibliography for 42CrMo4 steel in the temperature range of 1250 °C–1375 °C used in high temperature hot forging in closed dies applications do not represent the hardening, softening and steady-state zones of flow stress curves, not fitting well with hot compression experimental results obtained in this research and limit their use until 0.6 of strain. These points restrict their application for high temperature hot forging in closed dies technology.

However, the obtained new constitutive model is able to represent the different regions of the flow stress curve in the interesting temperature range of 1250 °C-1375 °C. Moreover, it predicts accurate peak stress values of the curves and extends its application until

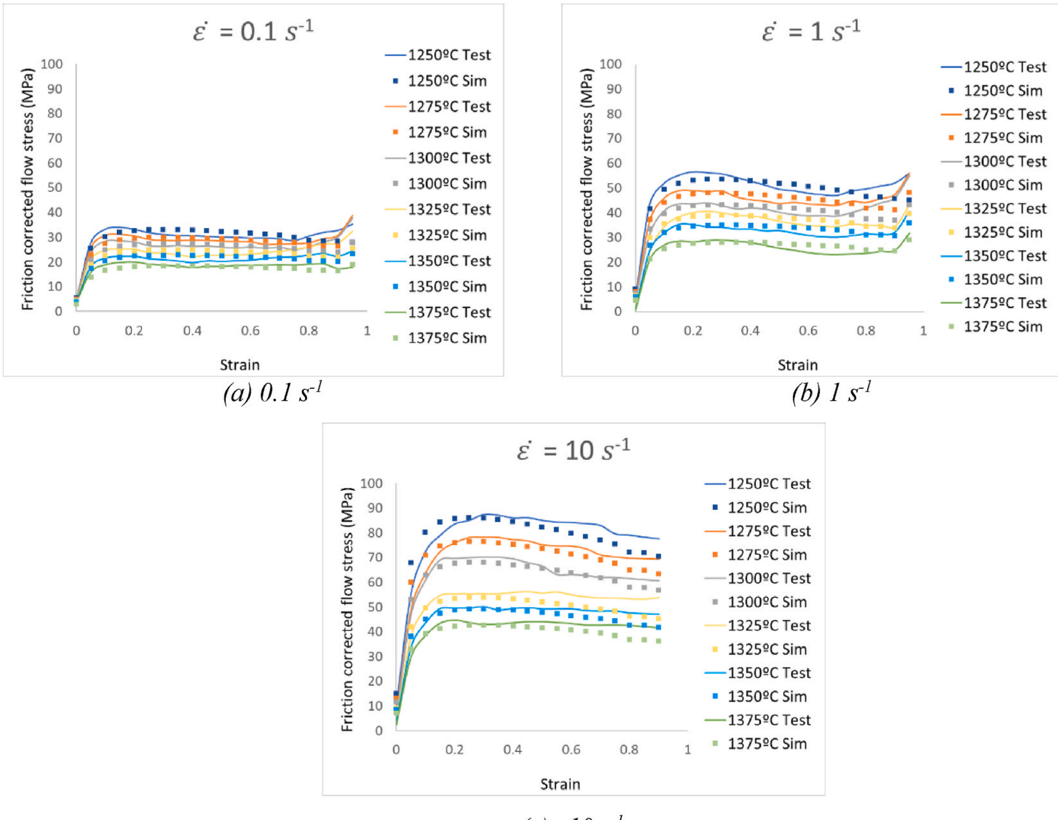


(b) 1 s^{-1}



(c) 10 s^{-1}

Fig. 10. (*continued*).



(a) 0.1 s^{-1} *(b) 1 s^{-1}*

(c) 10 s^{-1}

Fig. 11. Comparison between friction corrected experimental and predicted flow stress curves using the new constitutive equation at different temperatures for 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1} strain rates.

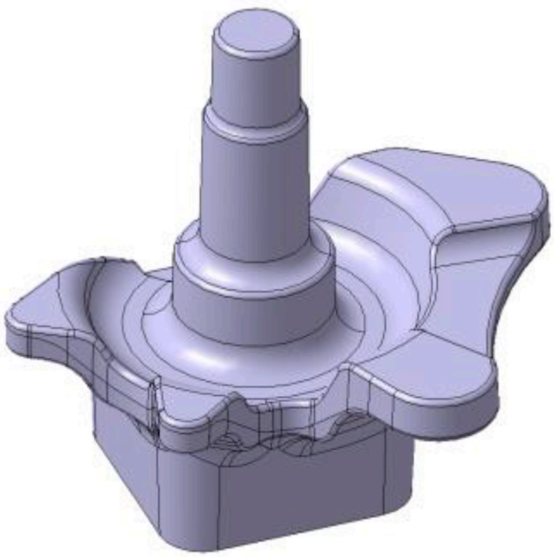


Fig. 12. 3D of the automotive commercial spindle.

Table 12
Parameters for numerical simulation.

Friction type	*Initial forging temperature (°C)*	Die temperature (°C)	*Extrusion speed (mm/s^{-1})*[a]
Ceraspray ®	1360	270	400

[a] A servomechanical cycle has been considered during the simulation, being this the maximum speed registered.

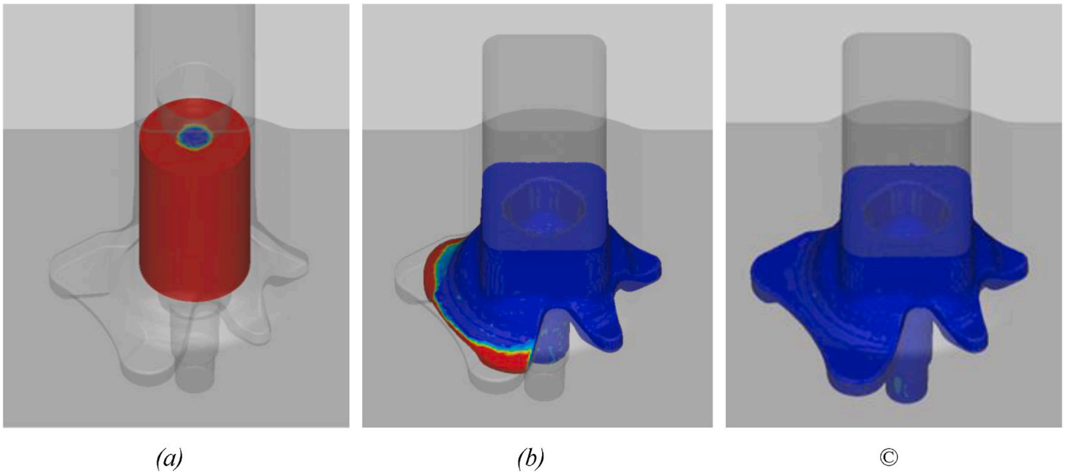


Fig. 13. Simulation of automotive commercial spindle at different stages (a) initial stage (b) intermediate stage and (c) final stage.

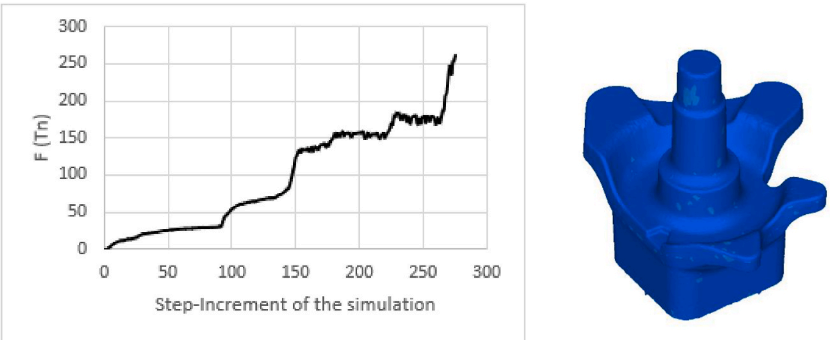


Fig. 14. Filling force curve for the automotive commercial spindle.

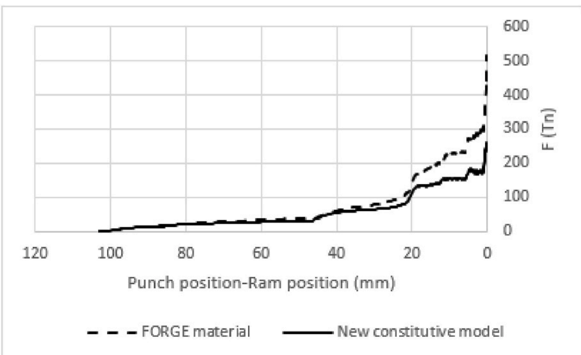


Fig. 15. Comparison of the filling force vs. the ram position curves obtained with the new constitutive model and with the model until 1250 °C (FORGE® library) for the automotive commercial spindle.

higher strains, obtaining flow stress vs. strain curves until a strain of 1.

c. The simulation of compression tests with the proposed new constitutive equation of six parameters for 42CrMo4 steel at high temperatures based in Hansel-Spittel model, agrees well with experimental results obtained in hot-compression tests, which verifies the validation of the suggested model.
d. The 42CrMo4 steel deformation behavior at high temperature hot forging process can be represented by the proposed new constitutive model for the manufacturing of commercial automotive spindles, predicting an accurate value of the peak force needed for the parts manufacturing. This model is based in Hansel-Spittel model, which considers the viscoplastic behavior of materials and is widely used in automotive commercial software as FORGE®.
e. The extension of the application of high temperature hot forging in closed dies technology in an industrial environment will need the obtention of the six parameters of the new constitutive model for different materials or alloys considering the explained methodology.
f. The model can be improved provided that the number of tests is increased to take into account the variability of the material in terms of chemical composition and more … In this case, the model would consist of our Hansel-Spittel model to which would be added a residual coming from the difference between our model and the experimental results. This residue would odelledled by Artificial Intelligence and Machine Learning as recommended by Chinesta and Cueto [16]. This type of model is based on a physical model (Hansel-Spittel) associated with a Data-driven yield enrichment. This kind of solution is currently under investigation.

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Data availability statement

Data included in article. Supplementary data associated with the study is confidential, so it has not been deposited into a publicly available repository.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Olatz Bilbao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing, Resources, Software, Supervision. **Iñigo Loizaga:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Supervision. **Jaime Alonso:** Conceptualization, Visualization. **Franck Girot:** Conceptualization, Data curation, Formal analysis, Resources, Software, Supervision, Validation, Visualization. **Amaia Torregaray:** Conceptualization, Formal analysis, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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