FIERF FORGING FOUNDATION

To be filled out by FIA Staff Member
Amount Awarded: ________________
Funding Left: ____________________

Research Project Status Update: Final Report (Stage Gate Grant Year 2)

Date: (Originally Submitted) _10/15/2024_

University / College: Lehigh University

Project Title: Numerical Modeling of Tooling Improvements for Forging Processes

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Please complete the below questions to report your project status. The answers will be shared with the FIA Technical Committee.

1. Progress on accomplishments vs. deliverables:

- Printing and evaluation of acceptably dense material coupons and their corresponding cylindrical Gleeble samples
  - INC625 (pure)
  - INC625 + 5w%TiC
- Stress-strain curves obtained via Gleeble-3500 thermo-mechanical compression experiments for following materials (a total of 35 successful tests were performed):
  - H13 (annealed)
  - H13 (hardened [quenched and tempered])
  - INC625 (pure)
  - INC625 + 5w%TiC
- Use of stress-strain curves to generate material models and resulting simulations in DEFORM-2D

Summary of the above points:

This project, “Numerical Modeling of Tooling Improvements for Forging Processes” builds off of research conducted for the FIERF Stage Gate Previous Year Grant project, “Improvements of H13 forging tool life through TiC-reinforced Inconel 625 coatings produced by additive manufacturing”.

The first stage gate of that project involved the use of Lehigh University’s Renishaw AM400 SLM machine to iteratively print coupons of the materials being investigated: pure Inconel 625 (INC625) and INC625 reinforced with varying percentages (by weight) of Titanium Carbide (TiC). This combination of the INC625 nickel-based superalloy with the hard, refractory ceramic TiC forms a Metal Matrix Composite (MMC).

To obtain coupons of sufficient density, a sliding window approach was taken to adjust the controllable parameters that exhibit the most significant impact on SLM printing: laser power, hatch space, exposure time, and layer thickness. The sliding window approach involved selecting two variables being chosen to create a matrix while keeping the remaining variables at a fixed value. Once the first print is completed, the results are evaluated; it can be observed which parameters should be altered, and they are changed accordingly.

After reasonable density was achieved by visual inspection of the coupons, the test coupons (which are printed in cube form) were cut into rows and mounted in epoxy, then ground and polished in preparation for metallography evaluation.

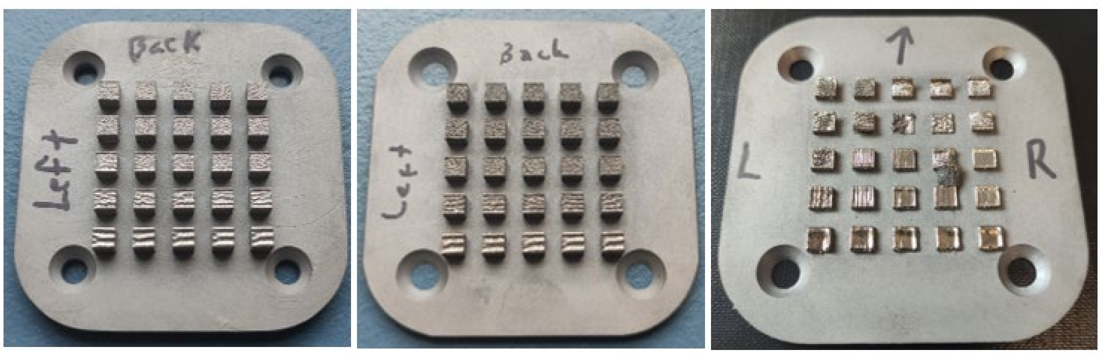


Figure 1: (Left) Pure Inconel 625 printed coupons, (Middle) INC 625 + 5w%TiC printed coupons, (Right) INC625 + 5w%TiC printed coupons (desired density not achieved)

The metallography process is comprised of grinding, polishing, and etching—with grinding and polishing being required to assess the coupons’ density percentage via Light Optical Microscopy (LOM), and etching is necessary to expose the microstructure and metal flow.

While several iterations of prints were performed for the INC625 + 10w%TiC, acceptable density was not able to be achieved; instead, the focus turned to optimizing the INC625 + 5w%TiC, which was able to achieve a density above 99.5%. The increase of TiC in the INC625 + 10w%TiC markedly altered the flow characteristic during printing; this, in conjunction with the differing morphologies of the powders (the INC625 powder being spherical while the TiC powder having a flakier shape) likely had a significant effect on the printability of the resulting mixed powder.

The predominant goal for this stage gate of the project was the prediction of the behavior of the material to produce process simulations by using the DEFORM finite element analysis (FEA) software package—specifically, DEFORM-2D. While DEFORM does contain materials libraries that can be used for process simulations, for materials for which libraries may not exist—such as specific MMCs—users can provide the resulting stress-strain curves from thermo-mechanical experiments to develop material models that can be used for process simulations.

Once the cylindrical samples were printed atop the sacrificial H13 cylinders, they were machined to the appropriate size and cut off from the H13 base cylinders. At this point, they are ready for use with the Gleeble 3500 to perform hot compression tests. These Gleeble experiments used multipart ISO-T anvils or single-piece tungsten carbide anvils. The cylindrical Gleeble sample then had 2 Type K thermocouple wires welded and placed between the anvils with a holding force of 0.2 to 0.4 kN.

The test begins by heating the sample with resistive heating; as current passes through the sample and the sample itself expands, the moving ram adjusts the position of the anvils to keep the same holding force throughout the heating process. After the user-specified temperature is reached, the unit maintains that temperature for a period (dwelling) to ensure a uniform temperature distribution throughout the sample. Next, the ram compresses the sample at the user-specified strain rate. Over the entirety of the process, the temperature, stress, strain, force, and ram position are all recorded into a file converted into a Microsoft Excel CSV to generate stress-strain plots. These plots—generated at different user-specified temperatures and strain rates—perform the material characterization in DEFORM.

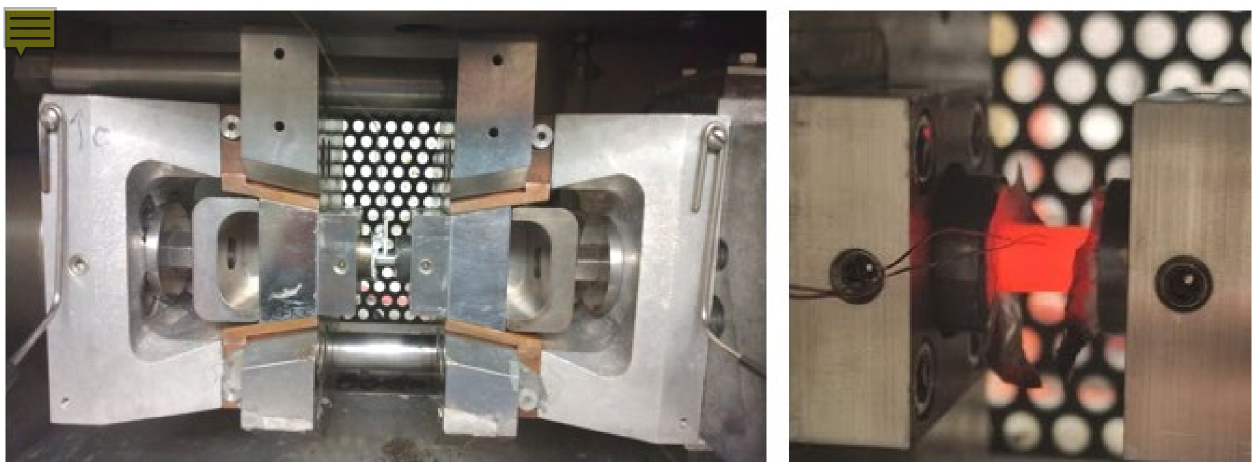


Figure 2: (Left) A sample mounted between the Gleeble 3500 anvils; (Right) A heated sample undergoing testing in the Gleeble 3500.

Gleeble tests were performed with annealed (as-received) H13, hardened H13 (quenched and tempered following the standard heat treatment), pure INC625, and INC625 + 5w%TiC. A total of 35 successful tests have been performed to obtain data for material modeling within DEFORM-2D; ***Table 1***, below, outlines the test breakdown:

Table 1: Summary of successful Gleeble tests for materials characterization.

Material	Experiment Temperatures	Experiment Strain Rates	Number of Successful Tests
H13 (annealed)	600°C 650°C 700°C	$1s^{-1}$ $5s^{-1}$ $10s^{-1}$ $20s^{-1}$	17
H13 (hardened)	650°C 750°C	$1s^{-1}$ $10s^{-1}$	4
INC625 (pure)	750°C 800°C 850°C	$1s^{-1}$ $5s^{-1}$ $10s^{-1}$ $20s^{-1}$	6
INC625 + 5w%TiC	750°C 800°C 825°C 850°C	$1s^{-1}$ $5s^{-1}$ $10s^{-1}$ $20s^{-1}$	8
		Total Successful Tests:	**35**

The 4 materials above were tested at the listed temperatures and strain rates—H13 data was gathered to establish a baseline performance for forging die material, while the pure INC625 and INC625 + 5w%TiC Gleeble tests were completed to observe the performance difference between pure INC625 and INC625 with 5w%TiC reinforcement.

Throughout these Gleeble experiments, certain temperatures were found to be unconducive for testing at certain temperature ranges—specifically, the initial testing temperatures were found to be too low. It was established that the Inconel 625—regardless of whether it was pure or contained the TiC reinforcement—was too hard to be tested below 750°C, with the Gleeble not providing accurate results at any temperature below 800°C. The reluctance for INC625 to interact with the lower temperature is to be expected, as the material has excellent temperature resistance (a condition considered in this project's initial materials selection phase). Due to this characteristic of INC625, the samples were tested on the Gleeble at higher temperatures—775°C, 800°C, and 850°C—using the strain rates of $1s^{-1}$ and $10s^{-1}$. These test conditions allow for better estimation of material behavior at lower temperatures when generating the DEFORM simulations.

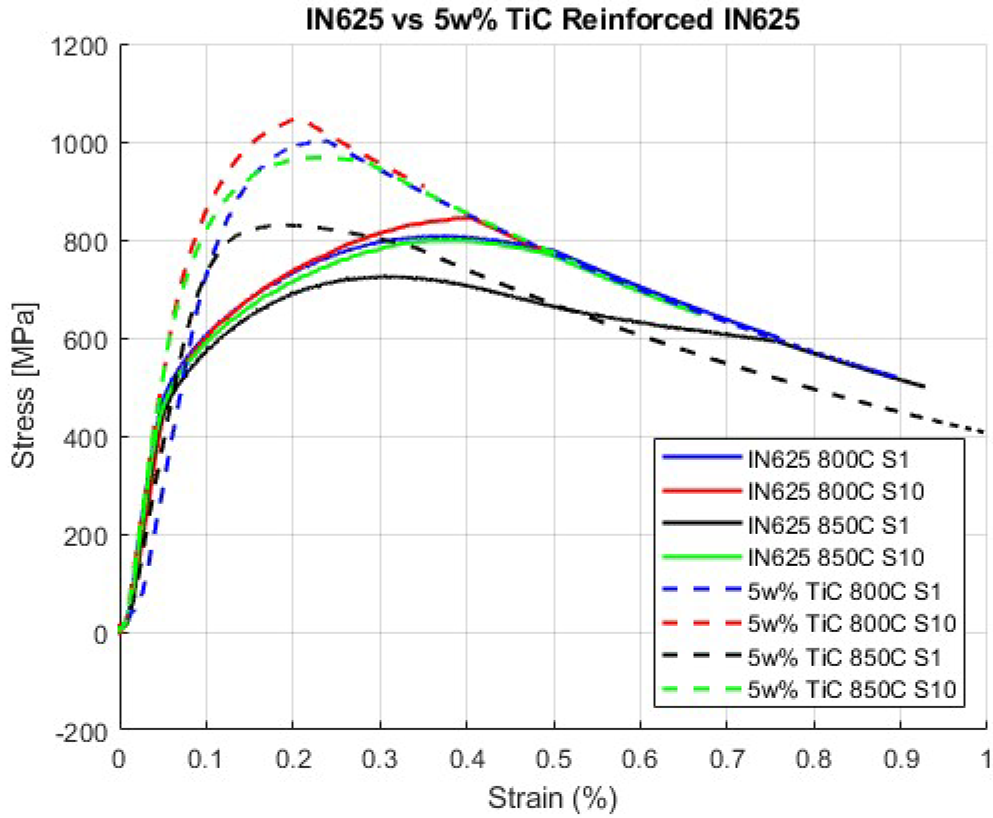


Figure 3: Stress-strain curves of INC625 and INC625 + 5w%TiC Gleeble experiment results.

Once a sufficient number of tests were performed for each material, the process of importing the stress-strain curves for use in DEFORM took place. A summary of DEFORM simulations—informed by the data collected over the course of the successful Gleeble experiments—follows.

Figure 4 shows simulation excerpts taken at 100 and 175 steps, from a total of 200 steps. The material sample's pre-deformation dimensions were 15mm height by 10mm diameter; total displacement specified for each compression test was 10mm. The range of temperatures tested were between 650°C and 800°C for the as-received H13, as well as for the hardened H13. Strain rates tested for all materials were $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$.

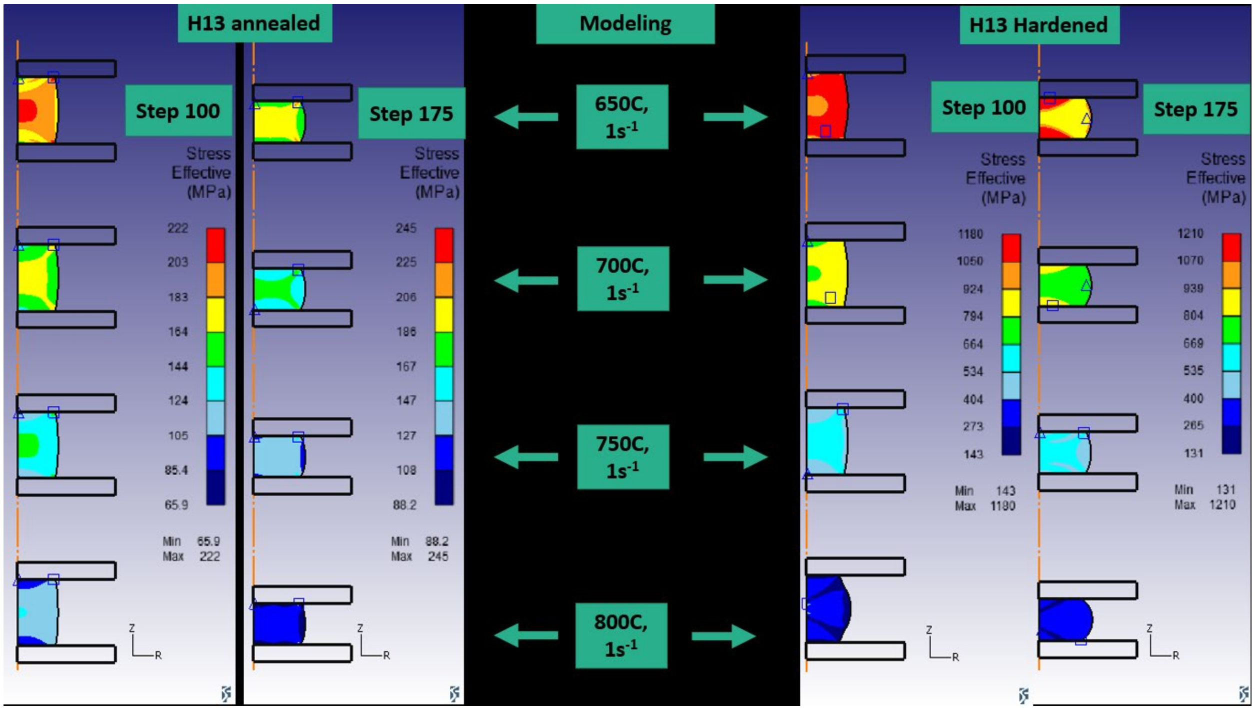


Figure 4: Example of comparison of H13 annealed (left) and hardened (right) at step 100 and step 175 (out of 200) of their respective simulations.

Evaluation of the local strain, stress, and strain for both the annealed and hardened H13 are presented; a listing of all parameters used for the DEFORM 2D simulations can be found in ***Appendix B***. Taking into account these parameters, the materials were tested at different ranges of temperatures: H13 samples—both annealed and hardened—underwent compression tests in the temperature range of 650°C and 800°C, while the pure INC625 samples and the MMC samples underwent compression tests in the range 750°C and 850°C. The points of samples that underwent extreme temperature and strain are shown in ***Figure 5***. In all cases, the range of strain rates of $1s^{-1}$ through $20s^{-1}$ was considered to evaluate the center and border regions, as indicated in ***Figure 5***.

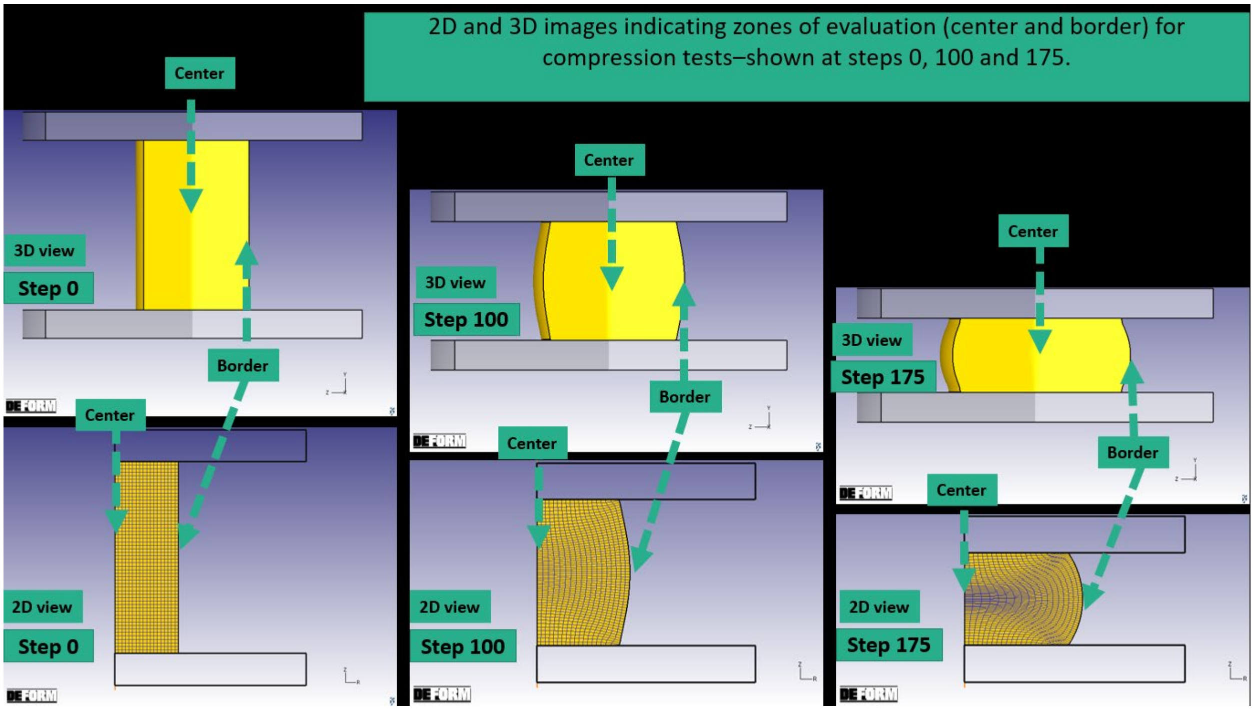


Figure 5: Regions of evaluation (center and border) with 2D and 3D views.

Selection of the appropriate higher temperatures and strain rates (different speeds) for Gleeble compression tests yielded curves for effective process modeling in DEFORM-2D. Shown below are the stress-strain curves obtained through heat and compression Gleeble experiments performed with the cylindrical, annealed H13 samples. These experiments with the annealed H13 samples were performed at the temperatures of 650°C (refer to ***Figure 6***) and 800°C (refer to ***Figure 7***) and at strain rates of $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$, with the corresponding results shown below:

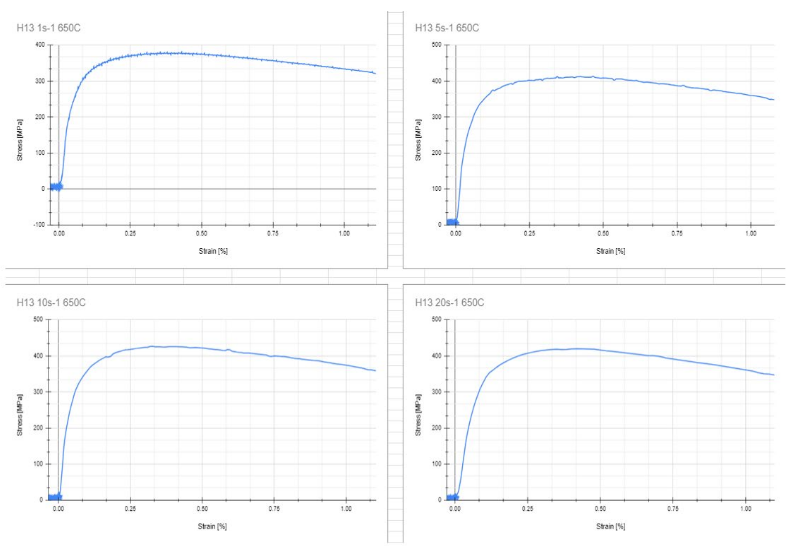


Figure 6: Plots of stress-strain curves obtained from Gleeble hot compression tests performed on H13 (annealed) samples at 650°C and strain rates of $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$.

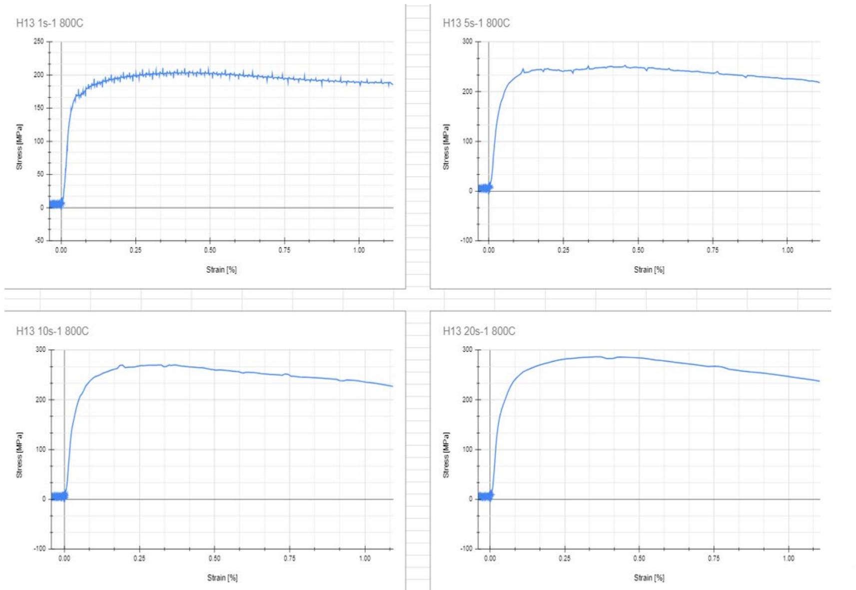


Figure 7: Plots of stress-strain curves obtained from Gleeble hot compression tests performed on H13 (annealed) samples at 800°C and strain rates of $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$.

Ultimately, it was observed that the DEFORM-2D simulations closely matched the results obtained through the physical experiments performed on the Gleeble. ***Figure 8*** and ***Figure 9*** are the DEFORM-2D simulations of the annealed H13's local behavior of the effective strain (in mm/mm) at steps 100 and 175 (out of 200 steps total). ***Figure 8*** shows this simulation performed at 650°C and strain rates of 1s-1 and 20s-1; ***Figure 9*** shows this simulation performed at 800°C at strain rates of $1s^{-1}$ and $20s^{-1}$.

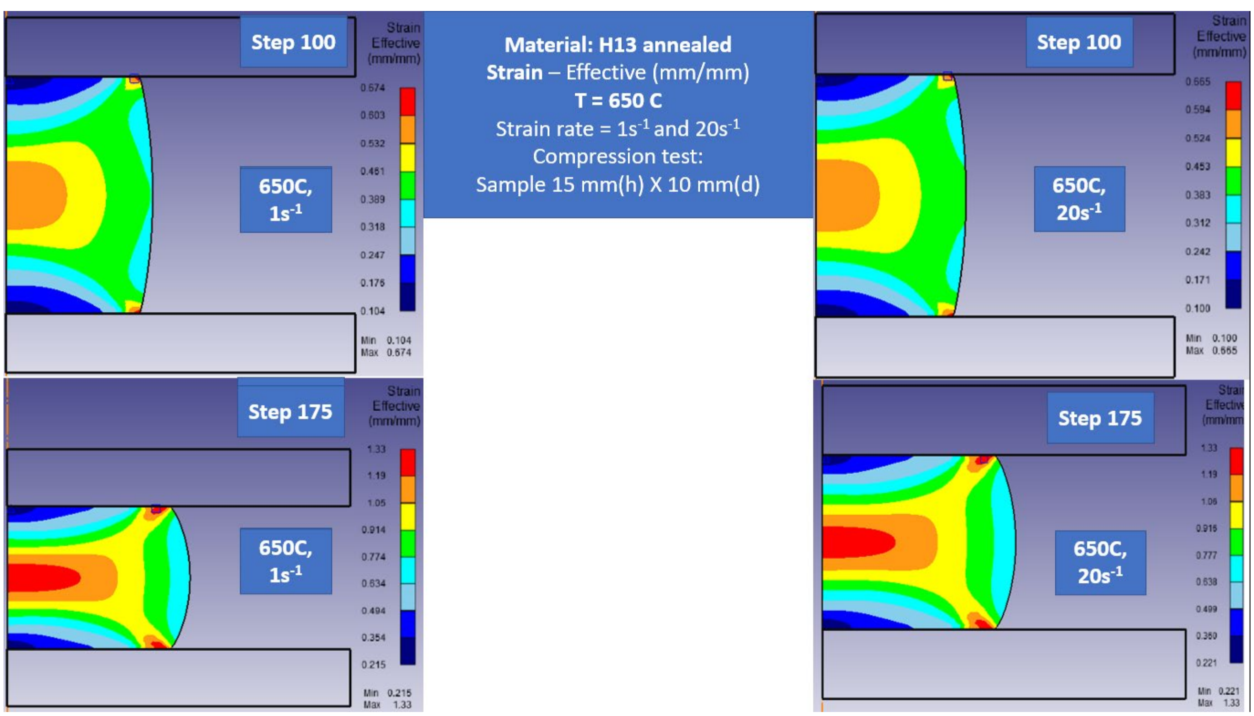


Figure 8: DEFORM-2D simulation results of annealed H13's effective strain behavior for steps 100 and 175 (out of 200) at temperature of 650°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

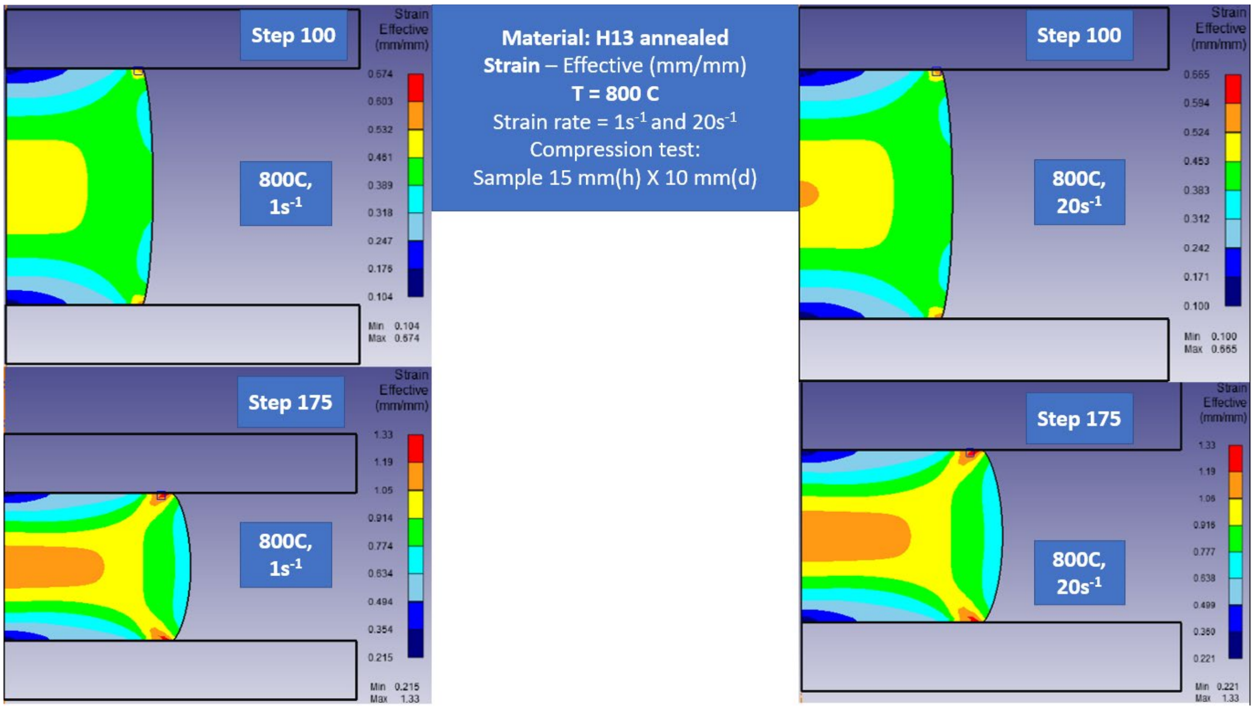


Figure 9: DEFORM-2D simulation results of annealed H13's effective strain behavior for steps 100 and 175 (out of 200) at temperature of 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

Table 2, presented below, summarizes the effective strain (in mm/mm) observed at steps 100 and 175 for the center and border regions of the annealed H13; these simulations' effective strains are shown at temperatures 650°C, 700°C, 750°C, and 800°C and strain rates $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$. It can be observed that as the speed—dictated by strain rate—is increased, the strain itself decreases slightly; almost no variation is seen as the temperature is increased, save for the experiments run at 800°C, where a decrease occurs:

Table 2: Overview of effective strain (designated as "Strain-Effective (mm/mm)" in DEFORM-2D) from annealed H13 simulations in the range of temperatures from 650°C to 800°C and strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 650 C	Step 100	0.6	0.45	0.59	0.45	0.59	0.45	0.59	0.45
	Step 175	1.33	0.77	1.33	0.77	1.33	0.77	1.33	0.77
T= 700 C	Step 100	0.6	0.45	0.59	0.45	0.59	0.45	0.59	0.45
	Step 175	1.33	0.77	1.33	0.77	1.33	0.77	1.33	0.77

T= 750 C	Step 100	0.6	0.46	0.66	0.45	0.59	0.45	0.59	0.45
	Step 175	1.19	0.77	1.33	0.77	1.33	0.77	1.33	0.77
T= 800 C	Step 100	0.53	0.46	0.66	0.45	0.52	0.45	0.59	0.45
	Step 175	1.19	0.77	1.19	0.77	1.19	0.77	1.19	0.77

Below, DEFORM-2D simulation excerpts ***Figure 10*** and ***Figure 11*** show the local behavior at steps 100 and 175 (out of 200) of the effective stress (in MPa) of the annealed H13 undergoing temperatures at 650°C and 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

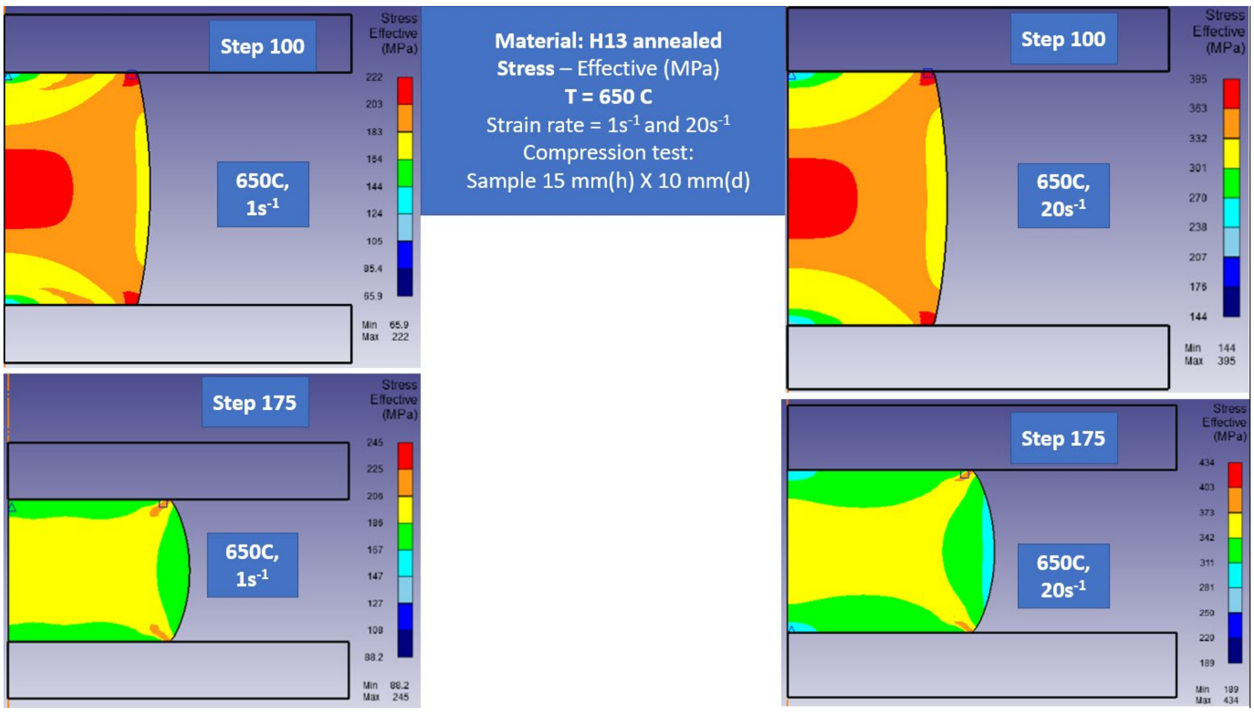


Figure 10: DEFORM-2D simulations showing the stress behavior—at steps 100 and 175—of annealed H13 at a temperature of 650°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

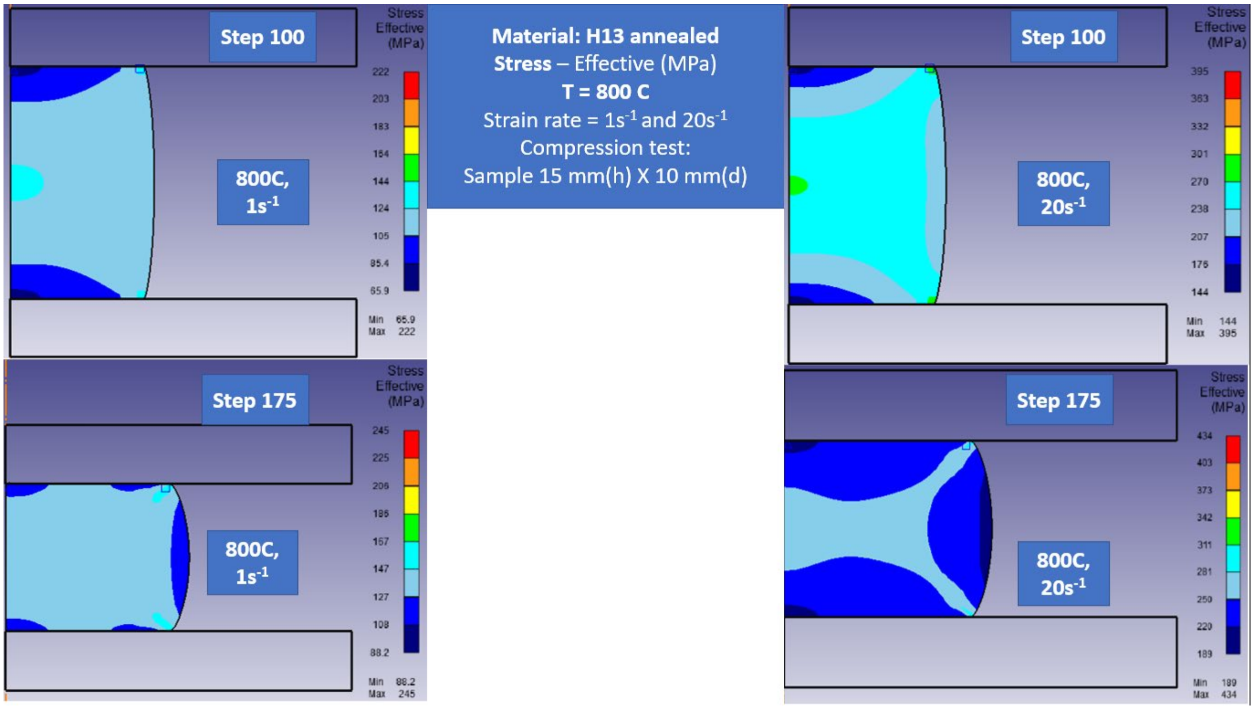


Figure 11: DEFORM-2D simulations showing the stress behavior—at steps 100 and 175—of annealed H13 at a temperature of 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

As outlined in ***Table 3***, within steps 100 and 175 the stress from the center to the border decreases the increasing temperature and increases with the higher speeds—that is, strain rates—of the process. It is also evident that between steps 100 and 175, stress decreases.

Table 3: Overview of effective strain (designated as "Strain-Effective (MPa)" in DEFORM-2D) from annealed H13 simulations in the range of temperatures from 650°C to 800°C and strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate → / Temperature ↓		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 650 C	Step 100	222	183	302	252	345	289	395	332
	Step 175	205	185	283	258	325	297	373	311
T= 700 C	Step 100	183	154	277	227	317	251	383	301
	Step 175	185	157	258	233	297	269	342	311
T= 750 C	Step 100	164	144	227	201	261	233	332	270
	Step 175	147	127	233	183	269	214	311	250
T= 800 C	Step 100	144	124	201	176	233	205	301	238
	Step 175	127	108	183	158	241	214	281	220

The DEFORM-2D simulation excerpts in ***Figure 12*** and ***Figure 13*** show the local effective strain rate (in [mm/mm]/s) behavior at steps 100 and 175 (out of 200) of the annealed H13, at temperatures 650°C (***Figure 12***) and 800°C (***Figure 13***) and at strain rates of $1s^{-1}$ and $20s^{-1}$.

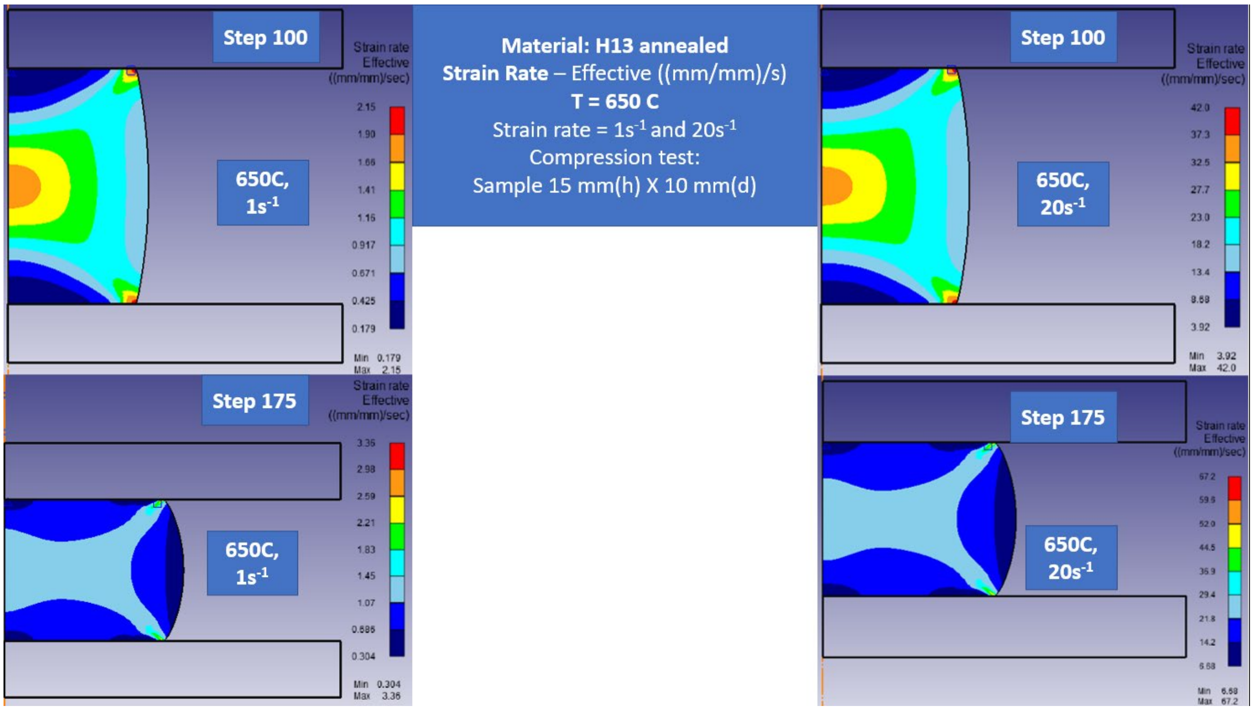


Figure 12: DEFORM-2D simulations showing the effective strain rate ([mm/mm]/s) behavior—at steps 100 and 175—of annealed H13 at a temperature of 650°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

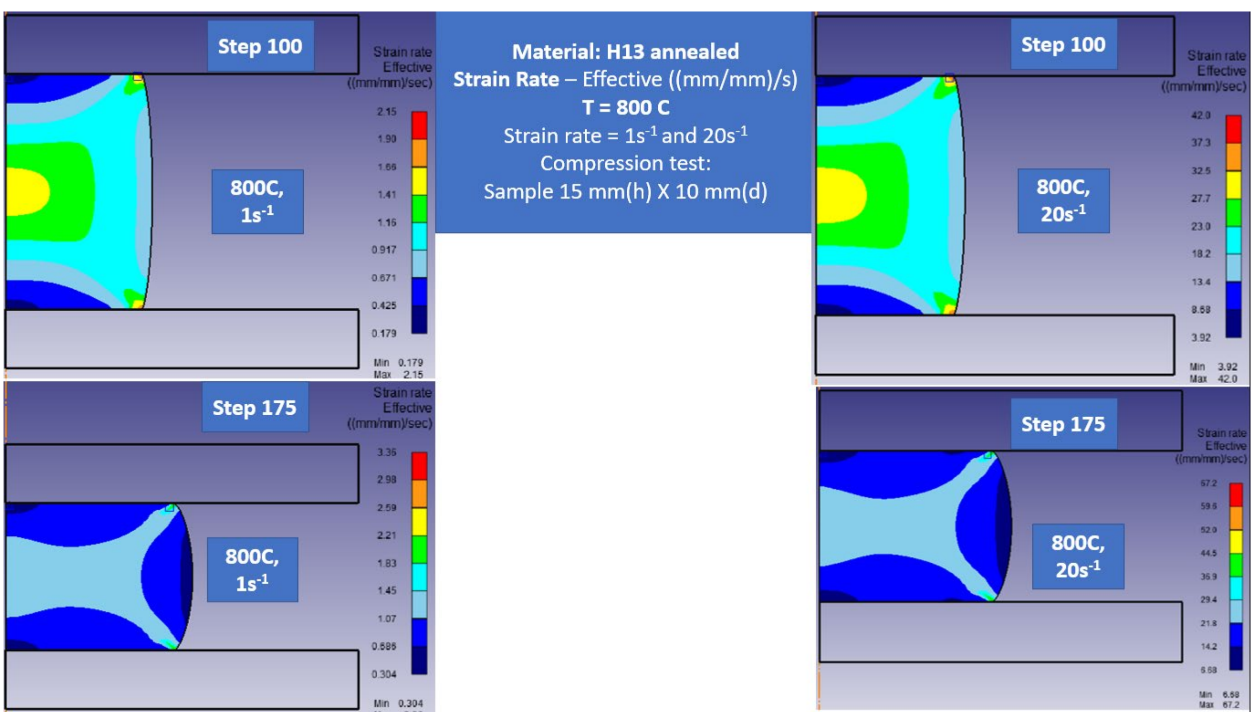


Figure 13: DEFORM-2D simulations showing the effective strain rate ([mm/mm]/s) behavior—at steps 100 and 175—of annealed H13 at a temperature of 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

Table 4 shows the strain rate behavior exhibited by the simulation between steps 100 and 175. It can be observed that strain rates slightly decrease with the increase in temperature; it is shown to be more significant at the center—as opposed to the border—in all cases. As the higher strain rates are employed, the effective strain rate increases.

Table 4: Summary of effective strain rate (in [mm/mm]/s) over the range of temperatures from 650°C to 800°C and strain rates from 1s-1 and 20s-1 for annealed H13 samples.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 650 C	Step 100	1.9	0.92	9.39	4.56	18.7	9.11	37.3	18.2
	Step 175	1.45	0.68	7.3	3.5	15.5	7.05	29.4	14.2
T= 700 C	Step 100	1.65	0.91	8.19	4.56	16.3	9.11	32.5	18.2
	Step 175	1.45	1.07	7.3	2.52	14.5	7.06	29.4	14.2
T= 750 C	Step 100	1.66	0.91	8.19	4.56	16.3	9.11	32.5	18.2
	Step 175	1.45	1.07	7.3	3.5	14.6	7.06	29.4	14.2
T= 800 C	Step 100	1.66	0.91	8.19	4.56	16.3	9.11	32.5	18.2
	Step 175	1.45	0.69	7.3	3.5	14.6	7.06	29.4	14.2

Selected excerpts from DEFORM-2D shown in ***Figure 14*** and ***Figure 15*** show the local effective strain (in [mm/mm]) at steps 100 and 175 (out of 200) of the hardened H13, at temperatures 650°C (***Figure 14***) and 800°C (***Figure 15***) and at strain rates of $1s^{-1}$ and $20s^{-1}$.

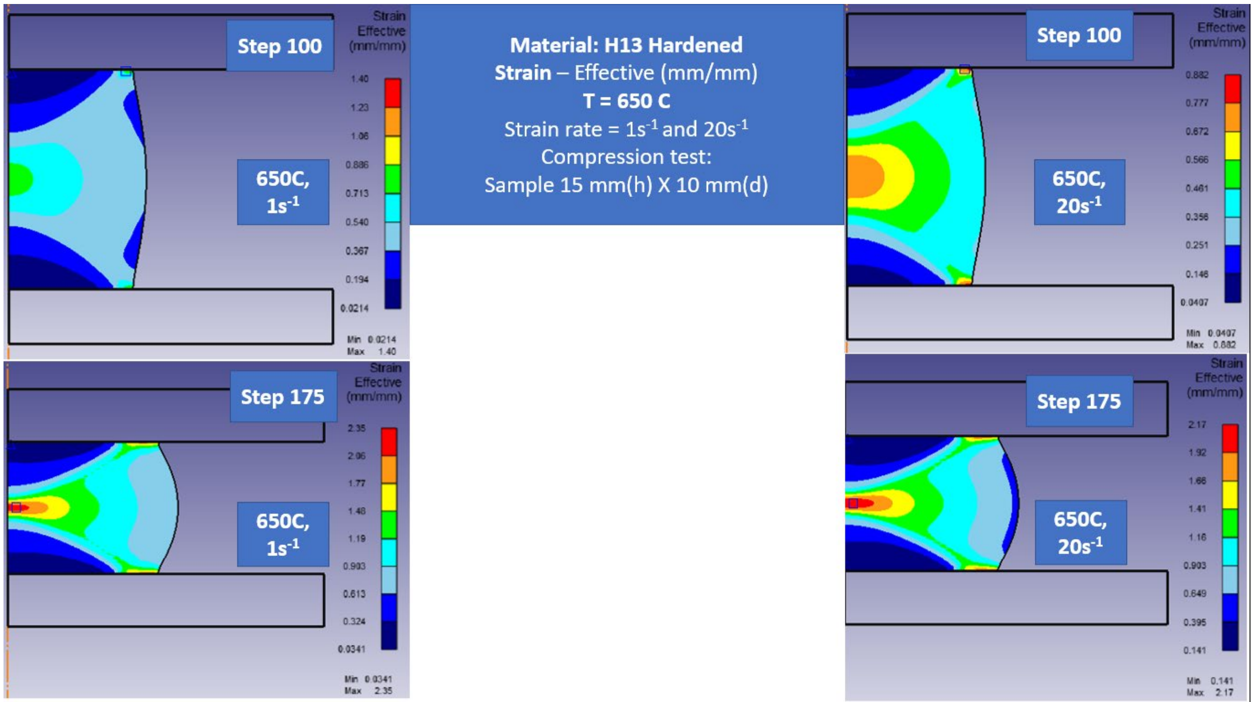


Figure 14: DEFORM-2D simulation effective strain (in [mm/mm]) results of hardened H13 at steps 100 and 175; at a temperature of 650°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

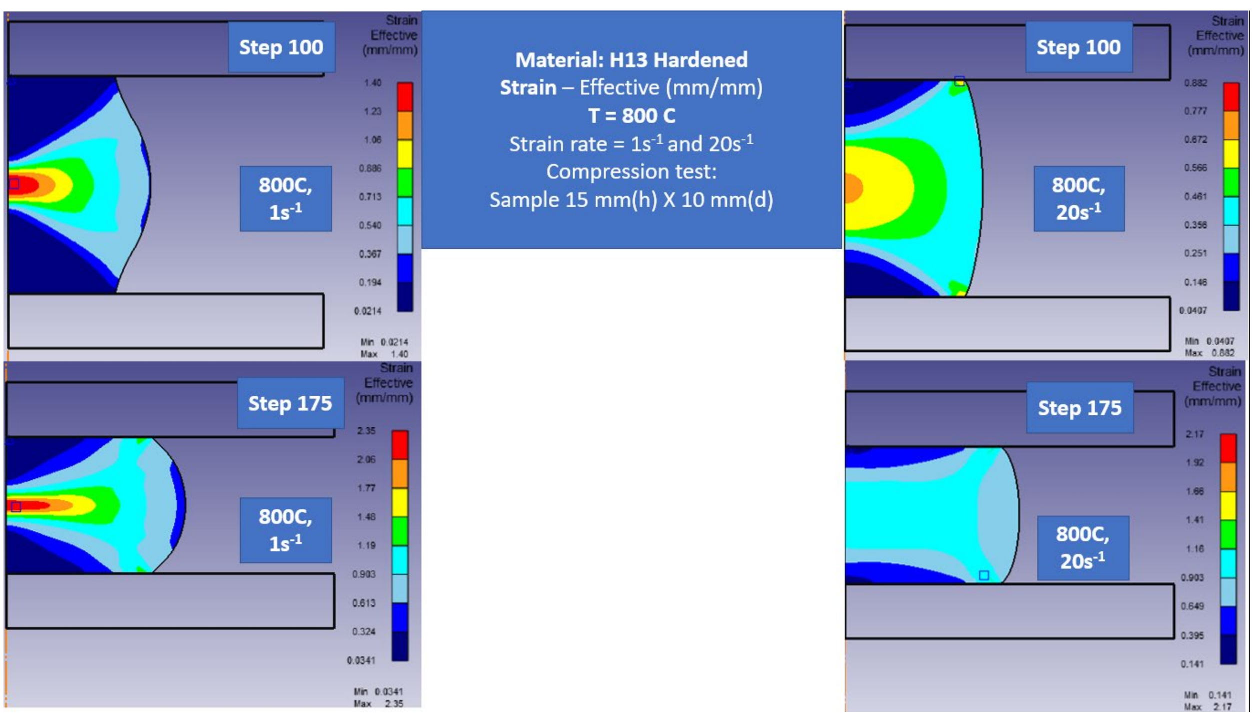


Figure 15: DEFORM-2D simulation effective strain (in [mm/mm]) results of hardened H13 at steps 100 and 175; at a temperature of 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

As shown in ***Table 5*** below, it can be observed that as the temperature is increased, the effective strain increases—however, this trend is not observed with the higher strain rate; it can be observed that it remains similar.

Table 5: Summary of simulation results for hardened H13, showing effective strain (mm/mm) for a range of temperatures from 650°C to 800°C and strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate → / Temperature ↓		$1s^{-1}$ Center	$1s^{-1}$ Border	$5s^{-1}$ Center	$5s^{-1}$ Border	$10s^{-1}$ Center	$10s^{-1}$ Border	$20s^{-1}$ Center	$20s^{-1}$ Border
T= 650 C	Step 100	0.88	0.54	0.85	0.38	0.77	0.45	0.77	0.45
	Step 175	2.35	0.9	2.2	0.85	2.19	0.7	2.17	0.7
T= 700 C	Step 100	0.7	0.54	0.74	0.4	0.77	0.45	0.77	0.45
	Step 175	1.77	0.7	1.9	0.85	1.9	0.9	1.75	0.9
T= 750 C	Step 100	0.7	0.5	0.62	0.38	0.66	0.45	0.66	0.45
	Step 175	1.48	0.9	1.39	0.85	1.42	0.9	1.42	0.9
T= 800 C	Step 100	1.4	0.53	0.98	0.4	0.88	0.45	0.77	0.46
	Step 175	2.35	0.65	1.65	0.85	1.4	0.9	1.16	0.9

Composite images from simulations in ***Figure 16*** and ***Figure 17*** present the local effective stress (in MPa) of the hardened H13 at steps 100 and 175 (out of 200) at temperatures of 650°C and 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

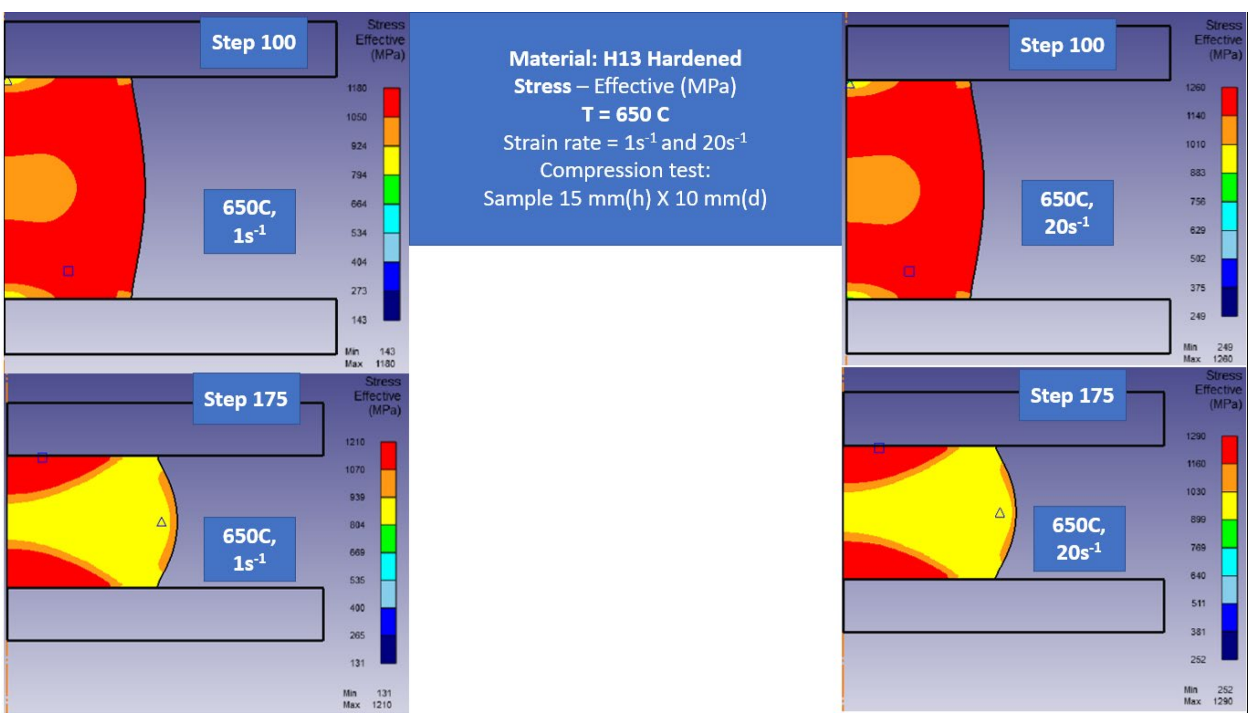


Figure 16: Simulation results at steps 100 and 175 (out of 200) of hardened H13 at a temperature of 650°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

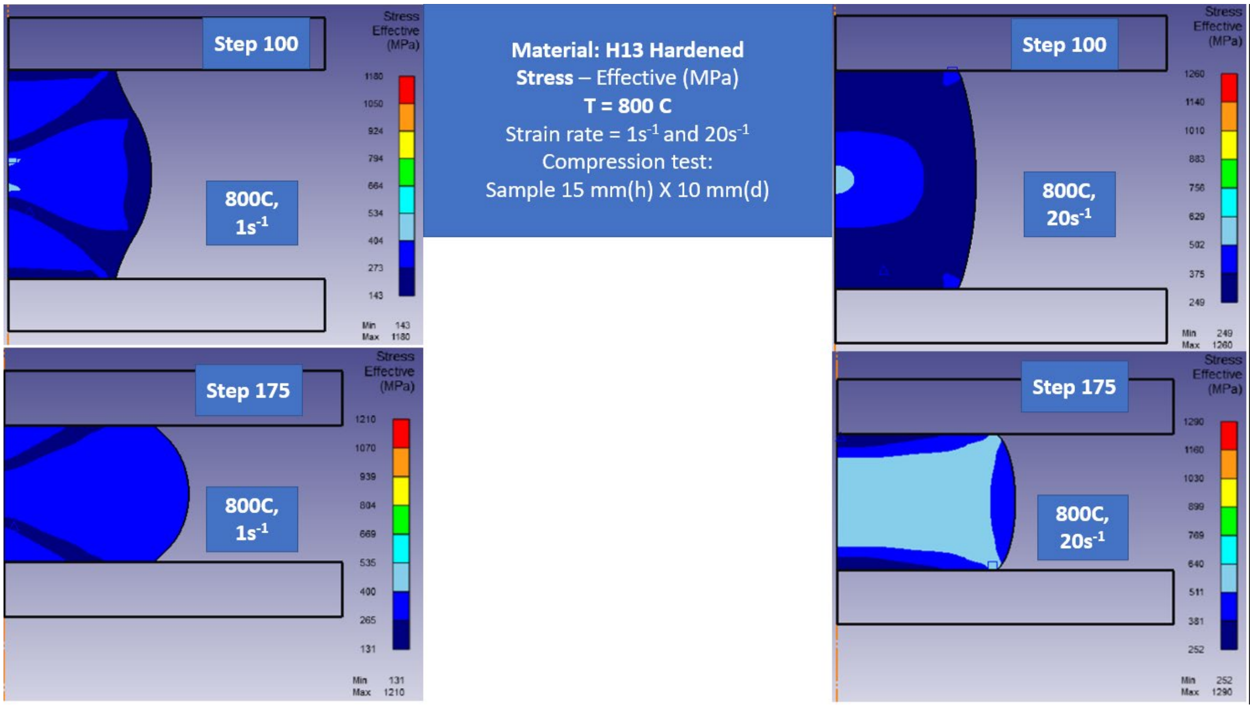


Figure 17: Simulation results at steps 100 and 175 (out of 200) of hardened H13 at a temperature of 800°C and strain rates of $1S^{-1}$ and $20S^{-1}$.

As presented below in ***Table 6***, it is evident that the effect of hardening the H13 through quenching and tempering heat treatments most significantly has an impact between the temperatures of 650°C and 700°C (where the higher stress values are exhibited). As the temperature increases—that is, within 750°C and 800°C—the decreased stress values are exhibited, as shown in the table. At steps 100 and 175, simulations performed at 750°C exhibit regular distribution of stress: with higher values observed from the center to the border. Viewing the data contained within this table, it becomes evident that as the temperature increases, there is a decrease of stress.

Table 6: Summary of hardened H13 simulation effective stress (in MPa) results over the temperature range of 650°C to 800°C for strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate / Temperature		$1s^{-1}$ Center	$1s^{-1}$ Border	$5s^{-1}$ Center	$5s^{-1}$ Border	$10s^{-1}$ Center	$10s^{-1}$ Border	$20s^{-1}$ Center	$20s^{-1}$ Border
T= 650 C	Step 100	1050	1180	1100	1230	1120	1240	1140	1260
	Step 175	939	1070	981	1120	1000	1130	1030	1160
T= 700 C	Step 100	764	924	842	970	862	989	883	1010
	Step 175	804	804	847	847	865	865	899	899

T= 750 C	Step 100	664	534	714	586	734	608	756	629
	Step 175	669	535	713	713	731	731	769	769
T= 800 C	Step 100	404	273	536	456	734	479	629	502
	Step 175	400	400	444	444	597	463	640	531

The composite simulation excerpts shown below in ***Figure 18*** and ***Figure 19*** display the simulation results for hardened H13 of effective strain (in ([mm/mm]/s)) at steps 100 and 175 (out of 100), the temperatures of 650°C and 800°C, and strain rates of 1s^{-1} and 20s^{-1}.

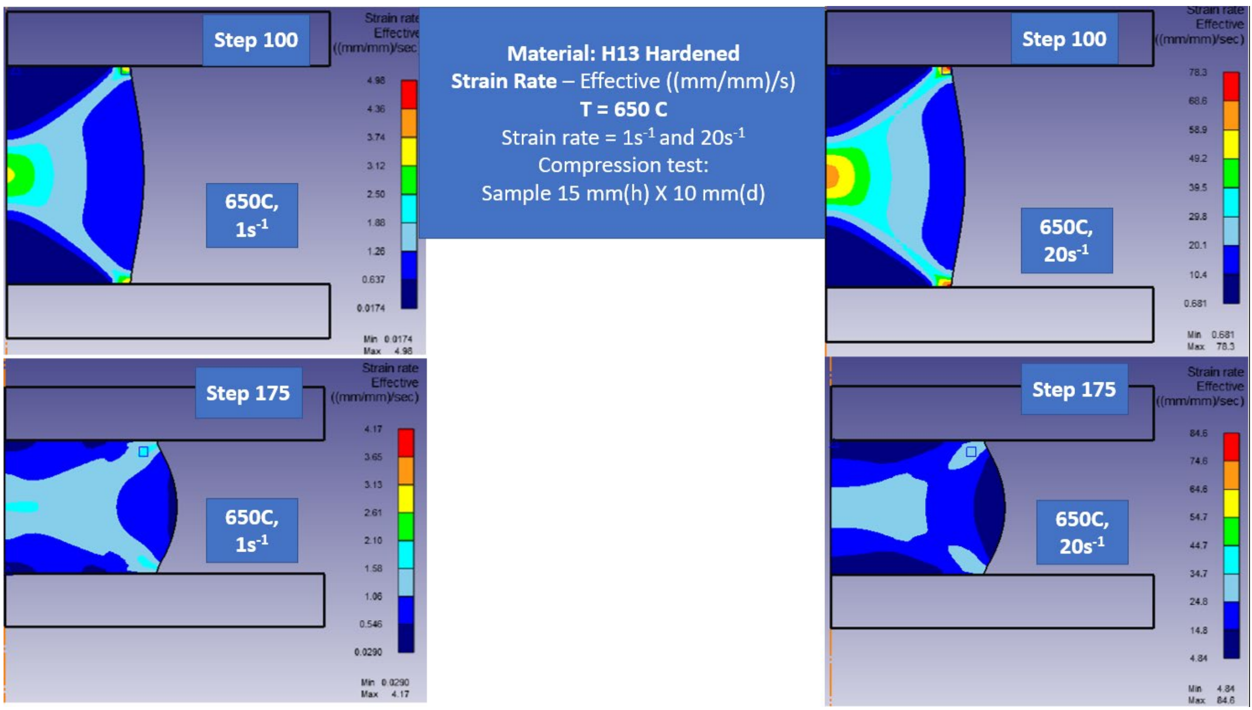


Figure 18: Effective strain rate behavior (in ([mm/mm]/s)) of hardened H13 at steps 100 and 175 (out of 200) at a temperature of 650°C and with strain rates of 1s^{-1} and 20s^{-1}.

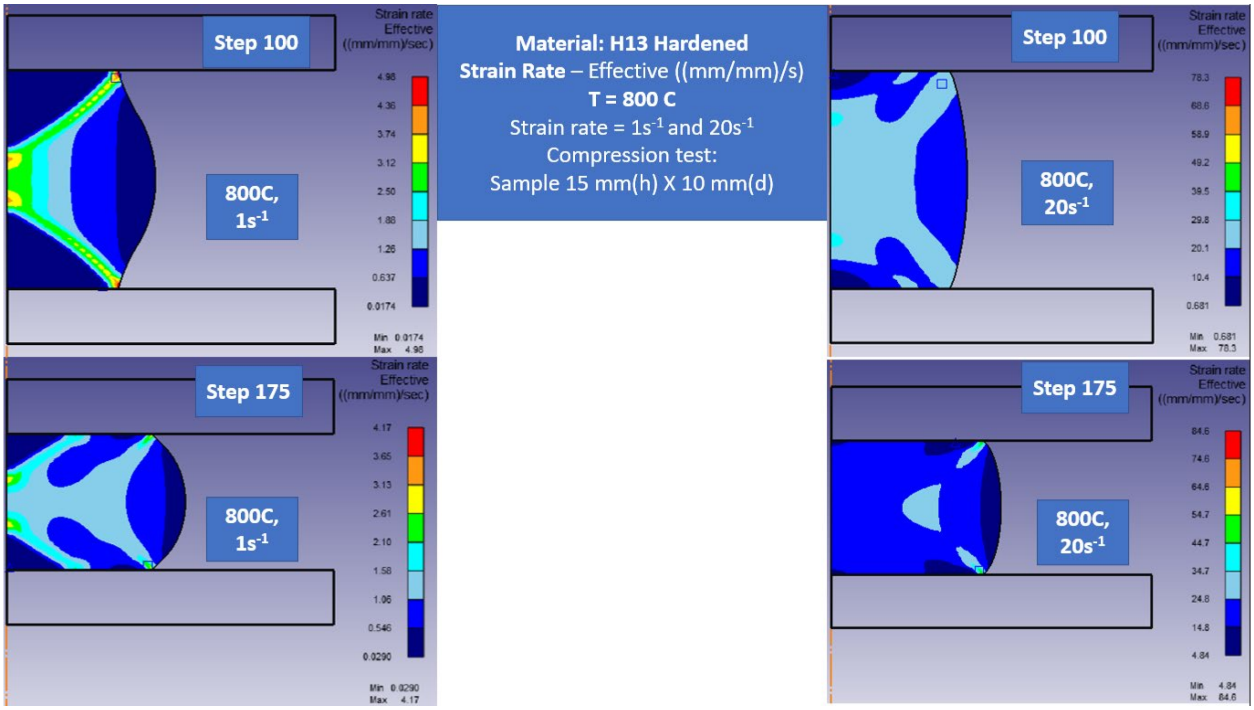


Figure 19: Effective strain rate behavior (in ([mm/mm]/s)) of hardened H13 at steps 100 and 175 (out of 200) at a temperature of 800°C and with strain rates of 1s^{-1} and 20s^{-1}.

The table shown below, ***Table 7***, summarizes the values for strain rate obtained via modeling the hardened H13 over the range of temperatures from 650°C to 800°C (in increments of 50°). Similar to what was observed with the annealed material, it is shown that the effective strain rates slightly decrease as the temperature increases—however, note that there is a significant difference between the observed effective strain rate at the border versus the observed effective strain rate at the border. It is also evident that higher experimental strain rates resulted in higher effective strain rates.

Table 7: Summary of hardened H13 effective strain rate (in ([mm/mm]/s)) simulation results for a range of temperatures from 650°C to 800°C and strain rates from 1s^{-1} to 20s^{-1}.

Strain Rate → / ↓ Temperature		1s^{-1} Center	1s^{-1} Border	5s^{-1} Center	5s^{-1} Border	10s^{-1} Center	10s^{-1} Border	20s^{-1} Center	20s^{-1} Border
T= 650 C	Step 100	1.9	0.92	9.39	4.56	18.7	9.11	37.3	18.2
	Step 175	1.45	0.68	7.3	3.5	15.5	7.05	29.4	14.2
T= 700 C	Step 100	1.65	0.91	8.19	4.56	16.3	9.11	32.5	18.2
	Step 175	1.45	1.07	7.3	2.52	14.5	7.06	29.4	14.2
T= 750 C	Step 100	1.88	1.26	9.92	5.01	19.8	10.1	39.8	20.1
	Step 175	1.58	1.06	8.27	5.72	12.4	7.38	24.8	14.8
	Step 100	3.12	0.63	9.92	5.01	15	10.1	29.8	20.1

T= 800 C	Step 175	1.58	1.06	5.72	3.17	12.4	7.36	24.8	14.8

The evaluation of MMC coatings to improve die life (for dies made of H13) involved testing various combinations of Inconel 625 (INC625) and Titanium Carbide (TiC). Pure INC625 was evaluated as a coating material, and INC625 in combination with various percentages of TiC mixed in by weight. Initially, INC625 with weight percentages of TiC of 5w%, 10w%, and 15w% were to be tested. However, only the INC625 with 5w% TiC produced prints of acceptable density and lack of cracks / significant pores. Despite extensive attempts at printing INC625 reinforced with 10w% TiC—including altering print parameters and mixing strategies—the resulting prints showed extensive brittleness, as well as cracking and considerable porosity.

Pure INC625 and INC625 reinforced with 5w% TiC were printed into cylindrical samples of dimensions 15mm height and 10mm diameter for use with Gleeble experiments. These samples were tested in the same manner as the annealed H13 and hardened H13: simulation results were noted at steps 100 and 175 (out of 200) for each simulation, and strain rates of $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$ were utilized, with a displacement of 10mm for each compression test. However, these simulations were run at slightly higher temperatures: the range of 750°C to 850°C was used.

Figure 20 and ***Figure 21*** show the composite simulation results of the local effective strain (in [mm/mm]) at steps 100 and a175 (out of 200) for the compression simulation of INC625 + 5w%TiC. The temperature parameters for these simulations are those used in the compression tests: temperatures of 750°C and 850°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

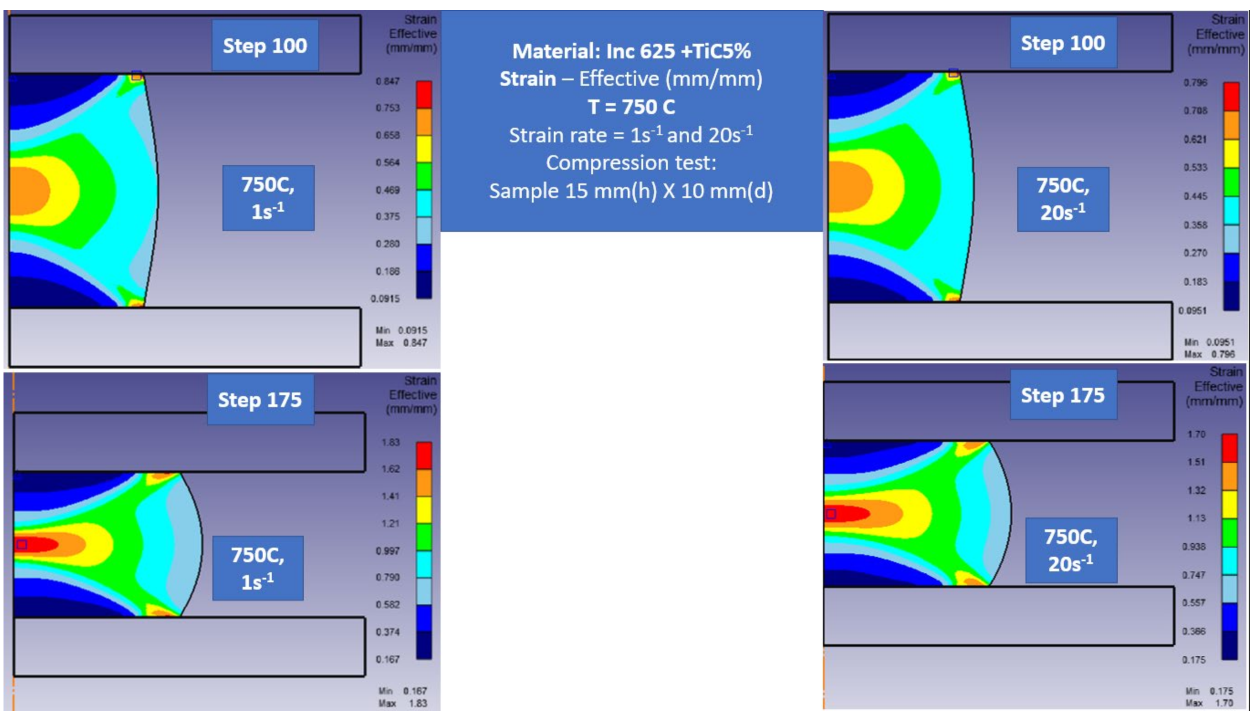


Figure 20: Composite image showing the behavior of effective strain (in [mm/mm]) for INC625 + 5w%TiC at steps 100 and 175 (out of 200) for DEFORM-2D simulations. The temperature at which these simulations were run was 750°C; the strain rates used were $1s^{-1}$ and $20s^{-1}$.

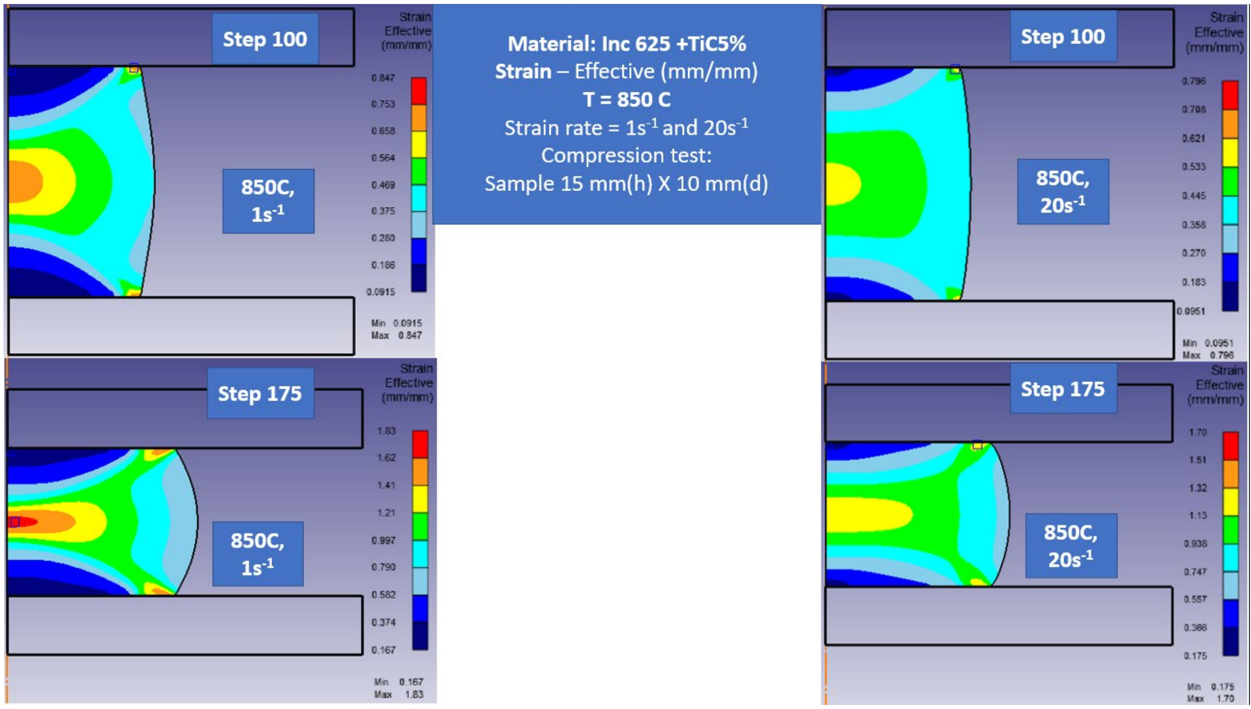


Figure 21: Composite image showing the behavior of effective strain (in [mm/mm]) for INC625 + 5w%TiC at steps 100 and 175 (out of 200) for DEFORM-2D simulations. The temperature at which these simulations were run was 850°C; the strain rates used were $1s^{-1}$ and $20s^{-1}$.

Presented below in ***Table 8*** are the effective strain (in [mm/mm]) values for the INC625 + 5w%TiC simulations run at temperatures 750°C, 800°C, and 850°C and strain rates $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$. It can be observed from this table that there are no significant variations for this range of temperatures and strain rates (speeds) simulated. Examining the center region, it can be determined that an increase in temperature drives the increase in strain.

Table 8: Simulation effective strain (in [mm/mm]) results for evaluation of INC625 + 5w%TiC over temperatures 750°C, 800°C, and 850°C and strain rates $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 750 C	Step 100	0.75	0.46	0.75	0.46	0.72	0.45	0.7	0.44
	Step 175	1.83	0.79	1.79	0.77	1.76	0.76	1.7	0.74
T= 800 C	Step 100	0.75	0.46	0.73	0.46	0.73	0.45	0.79	0.44
	Step 175	1.83	0.79	1.79	0.77	1.76	0.76	1.7	0.74
T= 850 C	Step 100	0.75	0.46	0.73	0.46	0.63	0.45	0.6	0.44
	Step 175	1.83	0.79	1.59	0.77	1.56	0.76	1.32	0.74

Figure 22 and *Figure 23* show the local effective stress (in MPa) at steps 100 and 175 (out of 200) for the simulation of INC625 + 5w%TiC. These simulations were run at temperatures of 750°C and 850°C, and strain rates of $1s^{-1}$ and $20s^{-1}$.

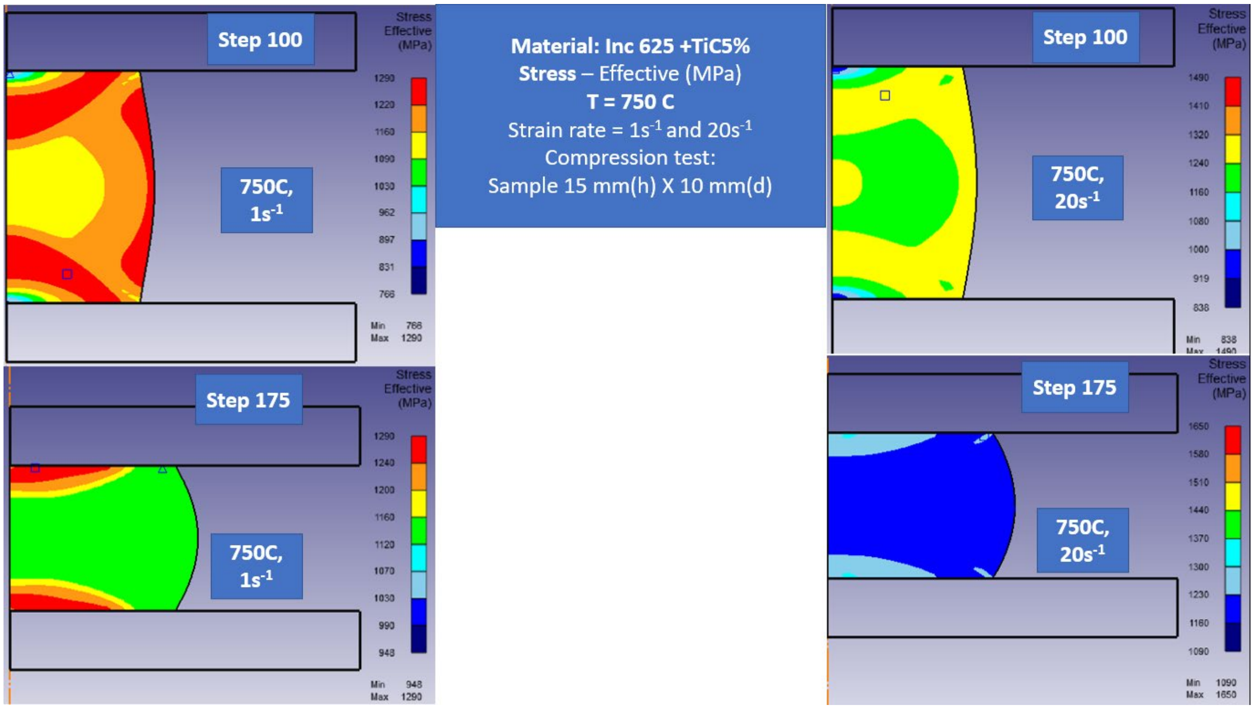


Figure 22: Composite image of INC615 + 5w%TiC DEFORM-2D simulations showing the behavior of the effective stress (in MPa) for steps 100 and 175 (out of 200) at a temperature of 750°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

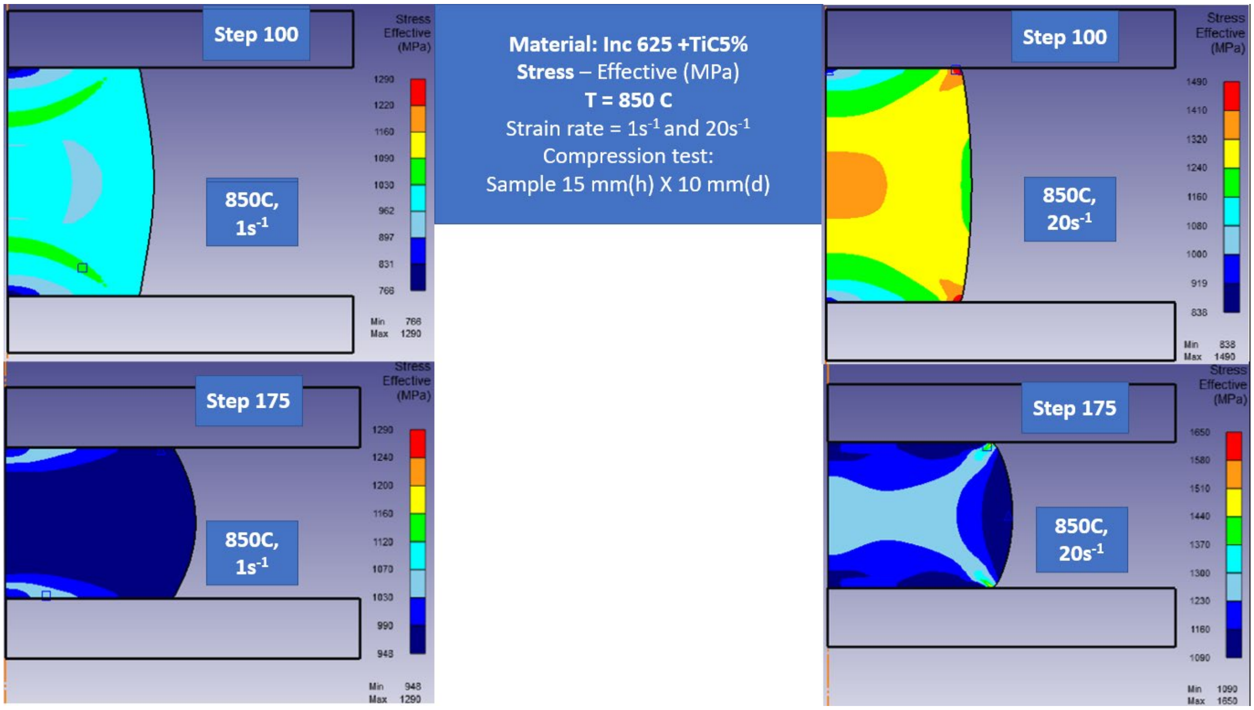


Figure 23: Composite image of INC615 + 5w%TiC DEFORM-2D simulations showing the behavior of the effective stress (in MPa) for steps 100 and 175 (out of 200) at a temperature of 850°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

As shown in ***Table 9***, there are a few variations of effective stress (in MPa) over the specified range of temperature; this may be due to the combination of high limits of stress with this combination of materials. These results suggest that an increase in temperature would result in a decrease of effective stress observed.

Table 9: Evaluation of effective stress (in MPa) of INC615 + 5w%TiC simulations run in the temperature range of 750°C to 850°C and at strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate / Temperature		$1s^{-1}$ Center	$1s^{-1}$ Border	$5s^{-1}$ Center	$5s^{-1}$ Border	$10s^{-1}$ Center	$10s^{-1}$ Border	$20s^{-1}$ Center	$20s^{-1}$ Border
T= 750 C	Step 100	1160	1290	1230	1290	1230	1290	1320	1320
	Step 175	1160	1160	1170	1170	1200	1200	1230	1230
T= 800 C	Step 100	1160	1220	1170	1230	1180	1230	1240	1240
	Step 175	1120	1120	1130	1130	1150	1100	1230	1230
T= 850 C	Step 100	1030	1030	1120	1060	1230	1120	1410	1240
	Step 175	1030	1030	1050	1010	1150	1060	1300	1160

Shown in ***Figure 24*** and ***Figure 25*** are the local effective strain rate behavior (in [mm/mm]/s) values for simulations of INC615 + 5w%TiC at steps 100 and 175 (of 200) with applied temperatures of 750°C and 850°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

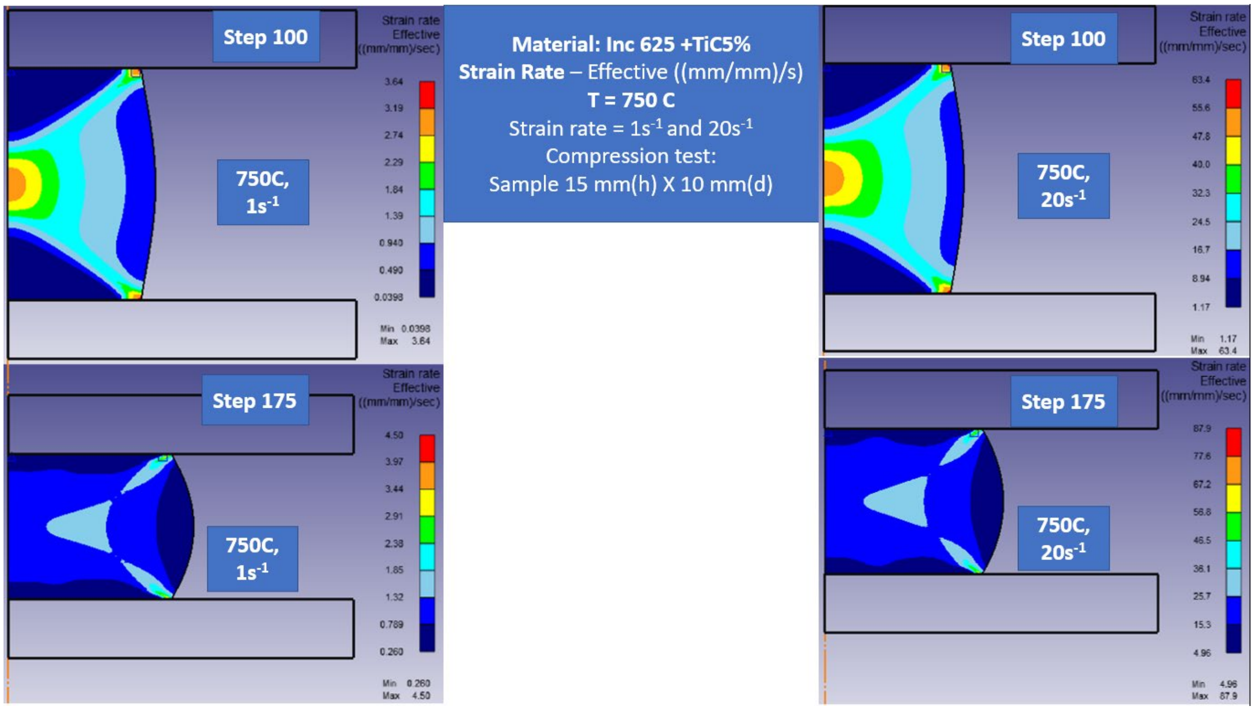


Figure 24: Composite image showing steps 100 and 175 (out of 200) of the effective strain rate behavior for INC625 + 5w%TiC simulations, run at 750°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

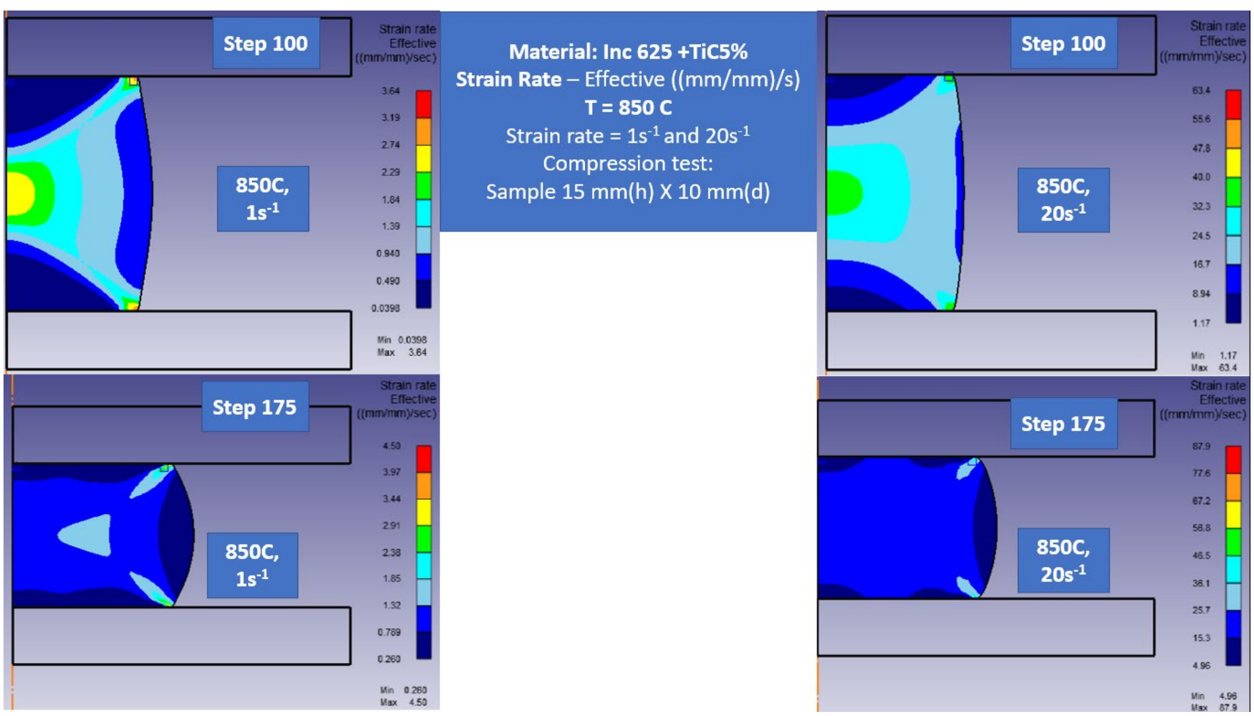


Figure 25: Composite image showing steps 100 and 175 (out of 200) of the effective strain rate behavior for INC625 + 5w%TiC simulations, run at 800°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

Shown below in ***Table 10*** is a summary of the effective strain (in [mm/mm]/s) for DEFORM-2D simulations of the INC615 + 5w%TiC at temperatures 750°C, 800°C, and 850°C, and strain rates $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$. It is evident that the effective strain rises as the strain rate increases. It is also apparent that there is no substantial change in the effective strain in the range of temperatures between 750°C and 850°C (for each respective step).

Table 10: Summary of INC625 + 5w%TiC simulation effective strain (in [mm/mm]/s) results at steps 100 and 175 (out of 200) for temperatures 750°C, 800°C, and 850°C and strain rates of $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, and $20s^{-1}$.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 750 C	Step 100	3.19	0.94	15.4	4.56	29.7	8.83	55.6	16.7
	Step 175	1.32	0.78	6.56	3.92	13.1	7.82	25.7	15.3
T= 800 C	Step 100	3.19	0.9	15.4	4.56	29.7	8.83	55.6	16.7
	Step 175	1.32	0.78	6.56	3.92	13.1	7.82	25.7	15.3
T= 850 C	Step 100	2.74	0.94	13.3	4.56	21.3	8.83	42	19.7
	Step 175	1.32	0.78	6.55	3.92	13.1	7.82	25.7	15.3

Figure 26 and ***Figure 27*** show the local effective strain behavior (in mm/mm) at steps 100 and 175 (of 200 total) for the hot compression simulations of pure INC625. The shown simulations were performed at 750C and 850C and strain rates of $1s^{-1}$ and $20s^{-1}$.

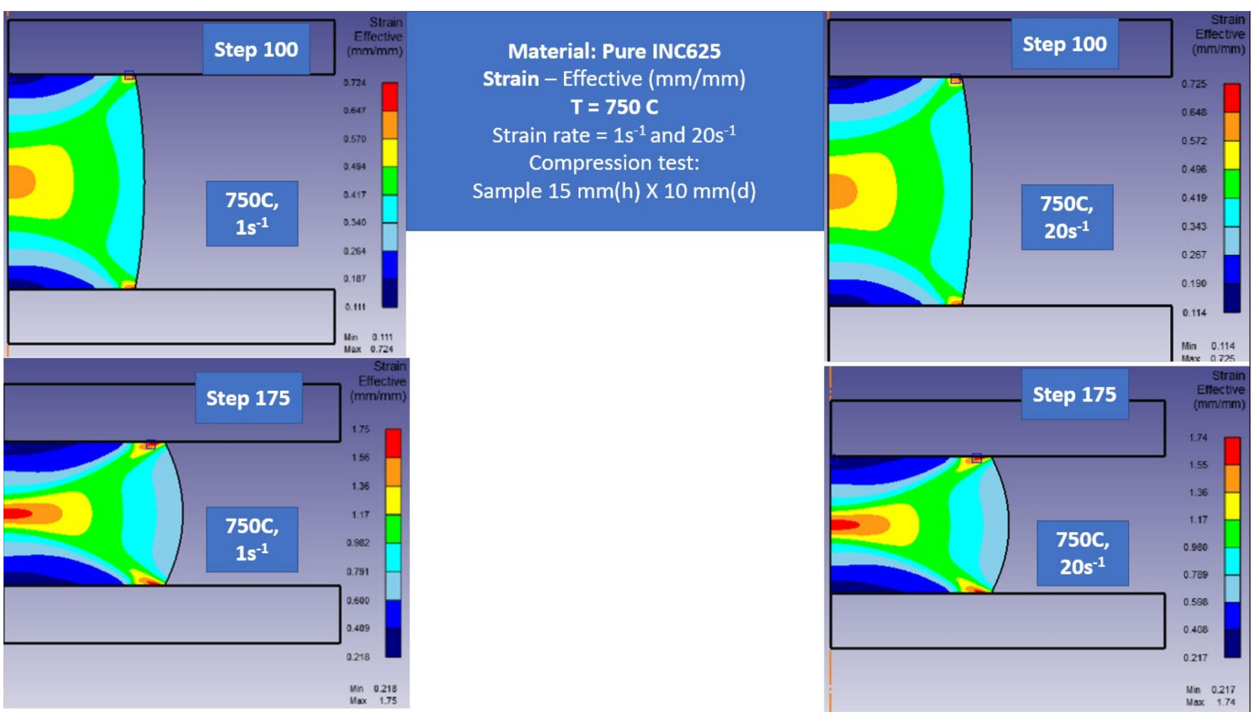


Figure 26: Composite image of effective strain (in mm/mm) simulation results for pure INC625 hot compression at 750°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

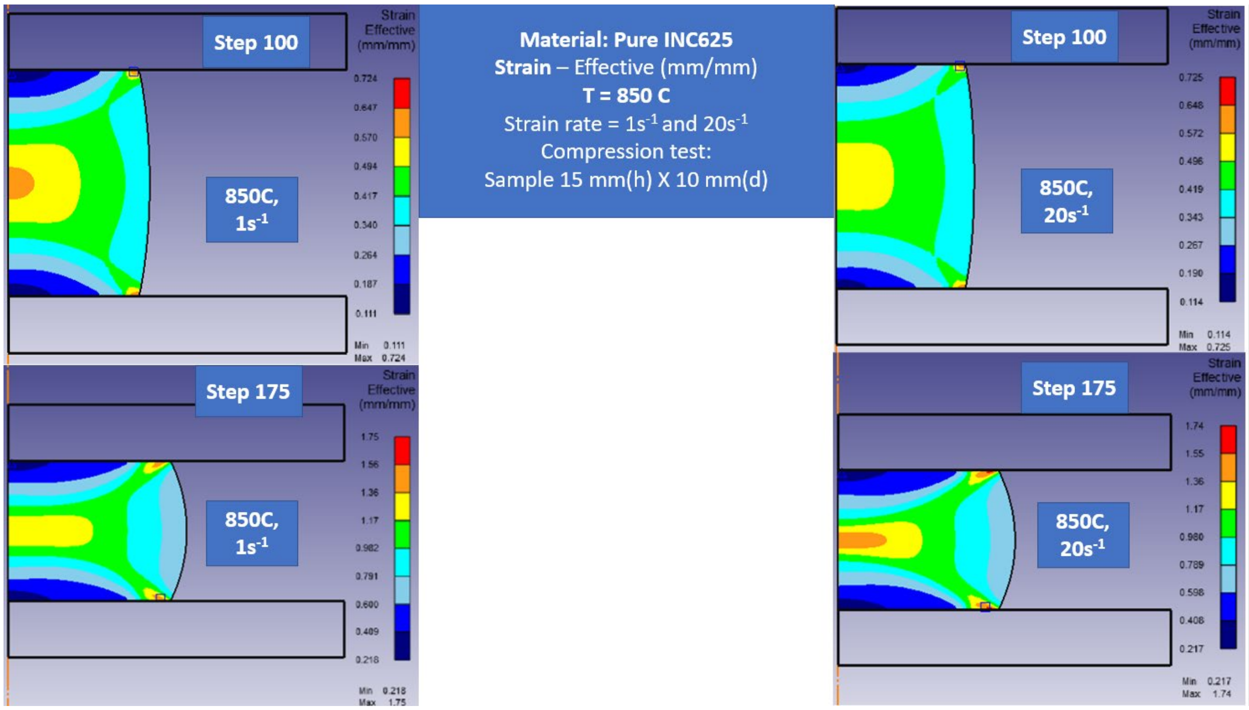


Figure 27: Composite image of effective strain (in mm/mm) simulation results for pure INC625 hot compression at 850°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

As presented in ***Table 11*** (below), for all cases, the effective strain values increase with the number of simulation steps, with higher effective strain values at the center than at the border. Virtually no variations are observed with the increase of the strain rate.

Table 11: Summary of effective strain (in mm/mm) values for pure INC625 hot compression simulations performed in the temperature range of 750C to 850C and at strain rates of $1s^{-1}$ to $20s^{-1}$.

Strain Rate → / Temperature ↓		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 750 C	Step 100	0.64	0.41	0.64	0.41	0.64	0.41	0.64	0.41
	Step 175	1.75	0.79	1.74	0.79	1.74	0.79	1.74	0.79
T= 800 C	Step 100	0.64	0.41	0.64	0.41	0.64	0.41	0.64	0.41
	Step 175	1.75	0.79	1.74	0.79	1.74	0.79	1.74	0.79
T= 850 C	Step 100	0.64	0.41	0.57	0.41	0.57	0.41	0.57	0.41
	Step 175	1.36	0.79	1.55	0.79	1.55	0.79	1.55	0.79

Figure 28 and ***Figure 29***, shown below, display the local effective stress behavior (in MPa) at steps 100 and 175 for pure INC625 at temperatures 750°C and strain rates $1s^{-1}$ and $20s^{-1}$.

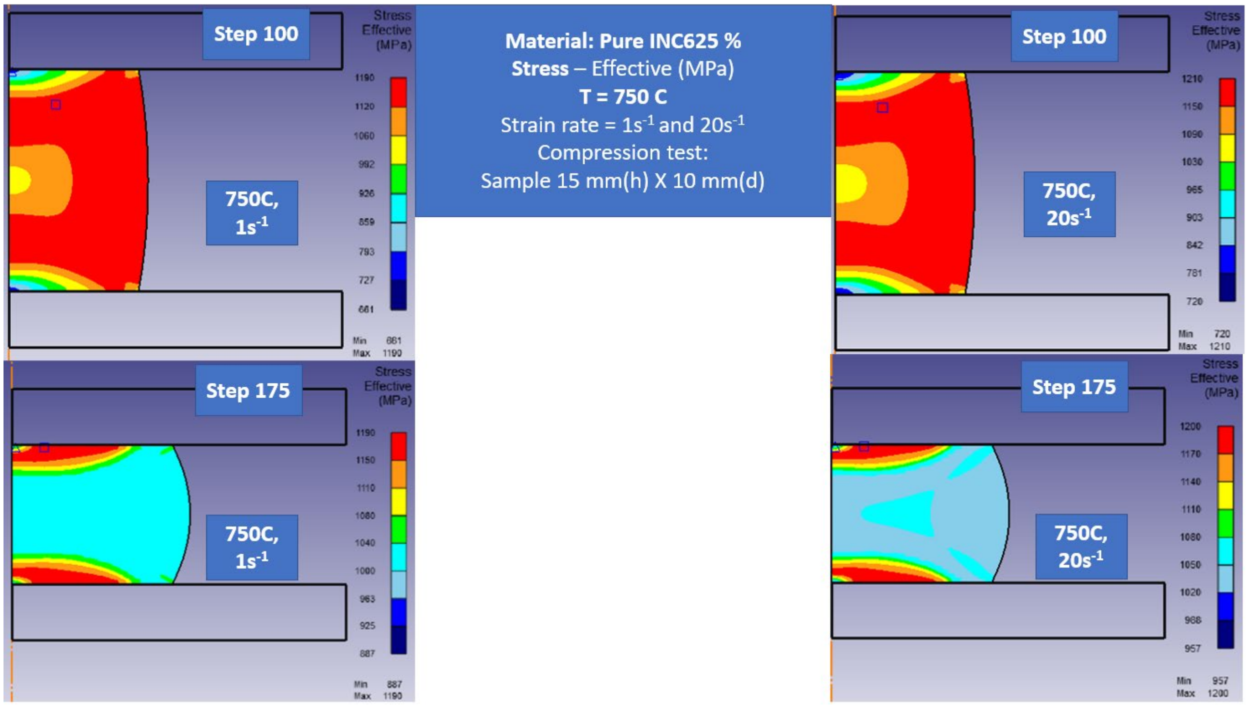


Figure 28: Composite image showing the effective stress (in MPa) for pure INC625 hot compression simulations at steps 100 and 175, a temperature of 750°C, and strain rates of $1s^{-1}$ and $20s^{-1}$.

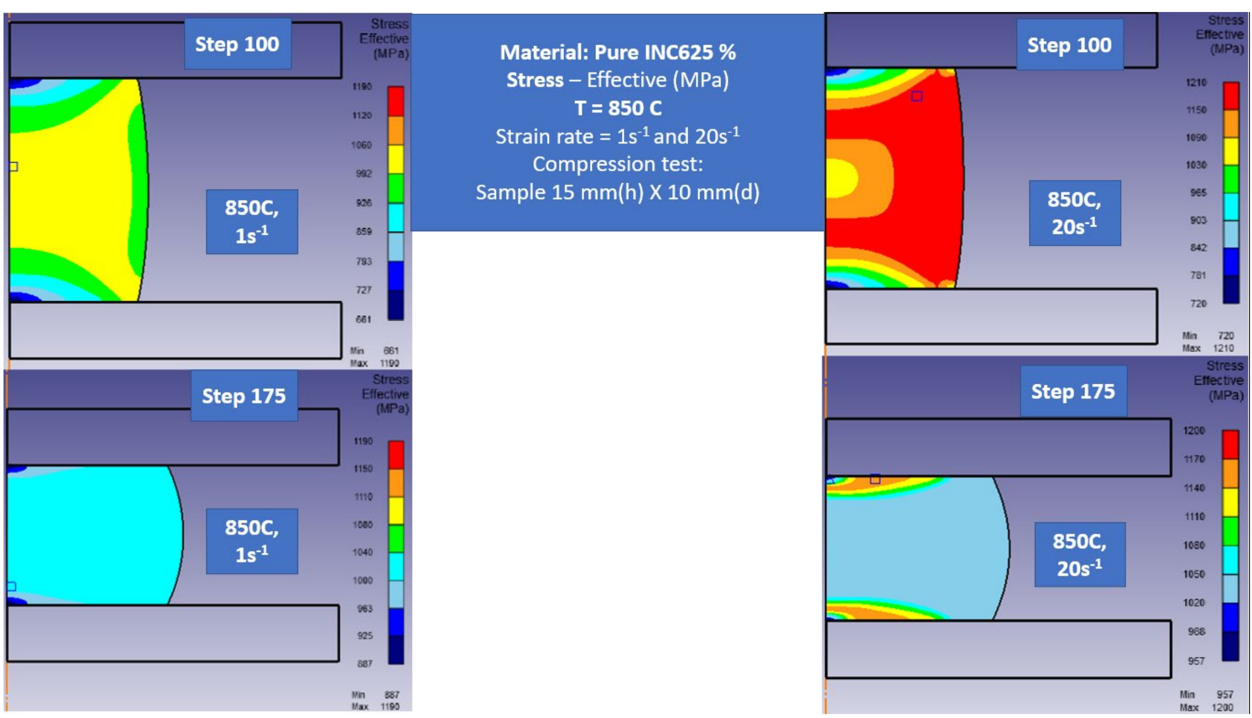


Figure 29: Composite image showing the effective stress (in MPa) for pure INC625 hot compression simulations at steps 100 and 175, a temperature of 850°C, and strain rates of $1s^{-1}$ and $20s^{-1}$.

As shown below in ***Table 12***, higher effective stress is observed when compared with the H13 materials, with few variations in the range of temperatures explored—suggesting an increase in temperature would lead to a decrease in stress.

Table 12: Summary of effective stress values (in MPa) for pure INC625 hot compression simulations over 750°C to 850°C, at strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 750 C	Step 100	1060	1190	1070	1200	1080	1200	1090	1210
	Step 175	1040	1040	1060	1060	1070	1070	1050	1050
T= 800 C	Step 100	1060	1190	1070	1200	1080	1200	1090	1210
	Step 175	1040	1040	1080	1030	1040	1040	1050	1050
T= 850 C	Step 100	1060	992	1070	1130	1080	1140	1090	1210
	Step 175	1040	1040	1030	1030	1040	1040	1050	1050

Viewable in ***Figure 30*** and ***Figure 31*** below are the results of simulations showing the local behavior of the effective strain rate (in [mm/mm]/s) for steps 100 and 175 of pure INC625 simulations performed at 750C and 850C and strain rates of $1s^{-1}$ and $20s^{-1}$.

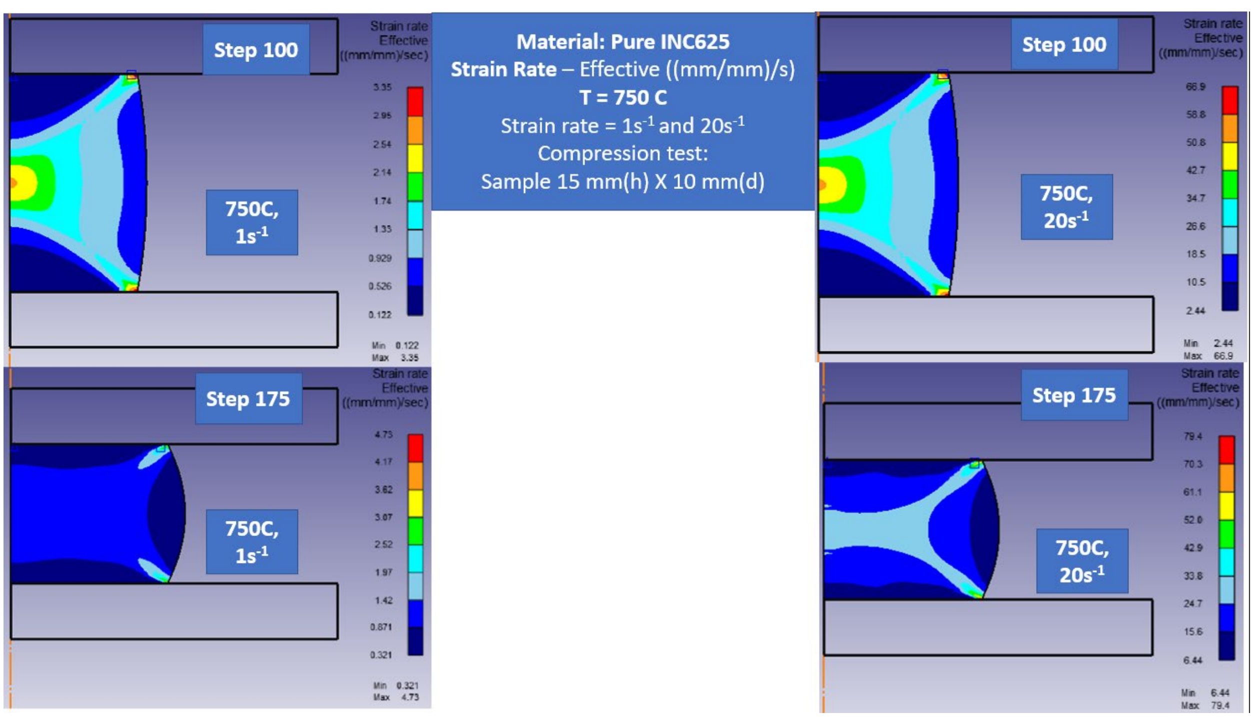


Figure 30: Composite image showing effective strain rate (in [mm/mm]/s) simulation results—at steps 100 and 175 (out of 200)—of pure INC625 at a temperature of 750°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

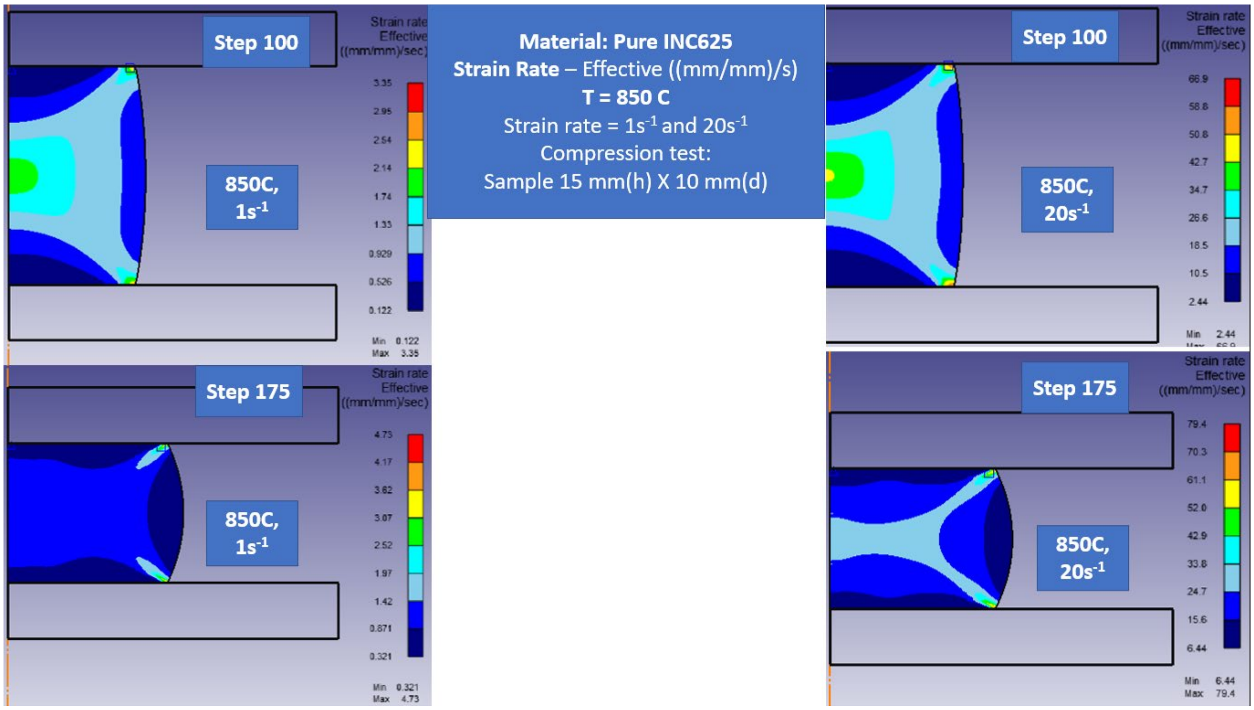


Figure 32: Composite image showing effective strain rate (in [mm/mm]/s) simulation results—at steps 100 and 175 (out of 200)—of pure INC625 at a temperature of 850°C and strain rates of $1s^{-1}$ and $20s^{-1}$.

Presented in ***Table 13*** are the effective strain rate (in [mm/mm]/s) values resulting from the pure INC625 simulations at varying strain rates and temperatures in the range of 750°C to 850°C. There exists a considerable increase in the effective strain rate with the increase in strain rate/process speed, particularly at $20s^{-1}$. However, the strain rate remains relatively unchanged in the temperature range of 750°C to 850°C.

Table 13: Summary of effective strain rate (in [mm/mm]/s) simulation results for INC625 in the temperature range of 750°C to 850°C, at strain rates from $1s^{-1}$ to $20s^{-1}$.

Strain Rate / Temperature		**$1s^{-1}$ Center**	**$1s^{-1}$ Border**	**$5s^{-1}$ Center**	**$5s^{-1}$ Border**	**$10s^{-1}$ Center**	**$10s^{-1}$ Border**	**$20s^{-1}$ Center**	**$20s^{-1}$ Border**
T= 750 C	Step 100	2.95	0.92	14.7	4.64	29.4	9.28	58.8	18.5
	Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6
T= 800 C	Step 100	2.54	0.92	12.7	4.64	21.4	9.28	50.8	18.5
	Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6
T= 850 C	Step 100	2.14	0.92	10.7	4.64	21.4	9.28	50.8	18.5
	Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6

Preliminary Evaluation:

This research involved the simulation of hot compression for four different materials: annealed H13, hardened H13, INC625 + 5w%TiC, and pure INC625. It is essential to be aware of the plastic deformation behavior of components involved in the metal-forming process from these results and use this data to address forging die concerns; for the specific use case this research addresses, the involved consideration/application is for cylindrical parts. It is important to consider homogeneous conformation conditions and then evaluate a range of deformations which make use of this specific geometry (for dies or molds). The yield stress of uniaxial compression tests as a function of strain, strain rate, and temperature, can produce the necessary data for flow stress comparisons. The hardness which results from specific heat treatments can bring about the necessary, suitable properties required for parts needing to undergo certain amounts of compression, exhibit hardness in higher temperatures, and possess fatigue- and wear-resistance.

A comparison of the simulation results for annealed H13 and hardened H13 can be made with data from published literature; it shows that when the steel receives the hardening heat treatments (quenching and tempering), there is a greater resistance to stress at higher temperatures (confirmed in the Gleeble compression tests and simulation process). H13 steel is a type of medium-carbon, hot work steel which is used to make tools for cutting, forming, and shaping materials—therefore, this steel must exhibit higher hardness for resistance to compression as well as exhibit higher hardness in higher temperature.

There exists strong potential for additive manufacturing to form the coatings which contain the necessary wear properties for dies. The results observed in this report—as well as data encountered during the literature review—support the idea that the LBPF-printed pure INC625 as well as INC625 + 5w%TiC are contenders for effective H13 die coatings. This research focused on evaluation of strain, strain rate, and stress with regards to hardened H13, which showed better resistance when compared with higher stress and high temperatures

The model presented below in ***Figure 32***, ***Figure 33***, and ***Figure 34*** shows the early stages of a simulation examining the boundary between the INC625 + 5w%TiC for coating and hardened H13. The following steps would involve evaluating the behavior of this material with the goal of assessing its response to wear on the superficial parts of hardened H13 dies.

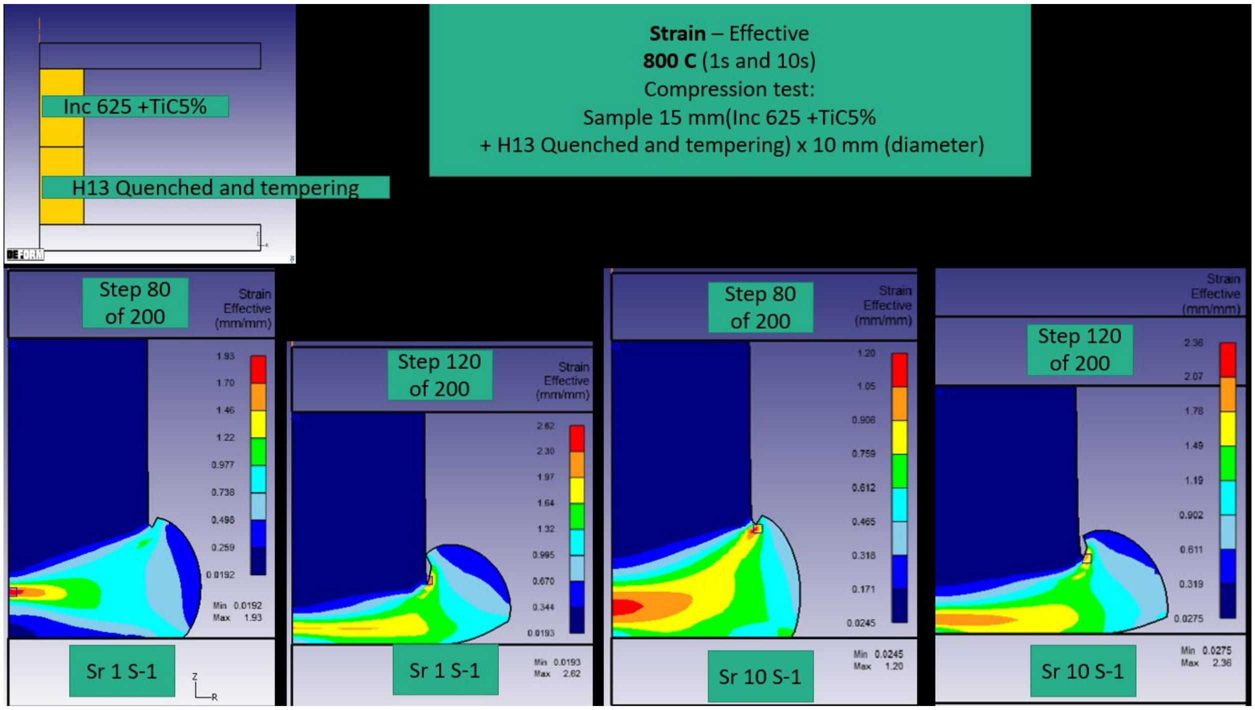


Figure 32: Simulation prepared with hardened H13 and INC625 interface + 5w%TiC at steps 80 and 120 (of 200 total) to observe the effective strain (in mm/mm).

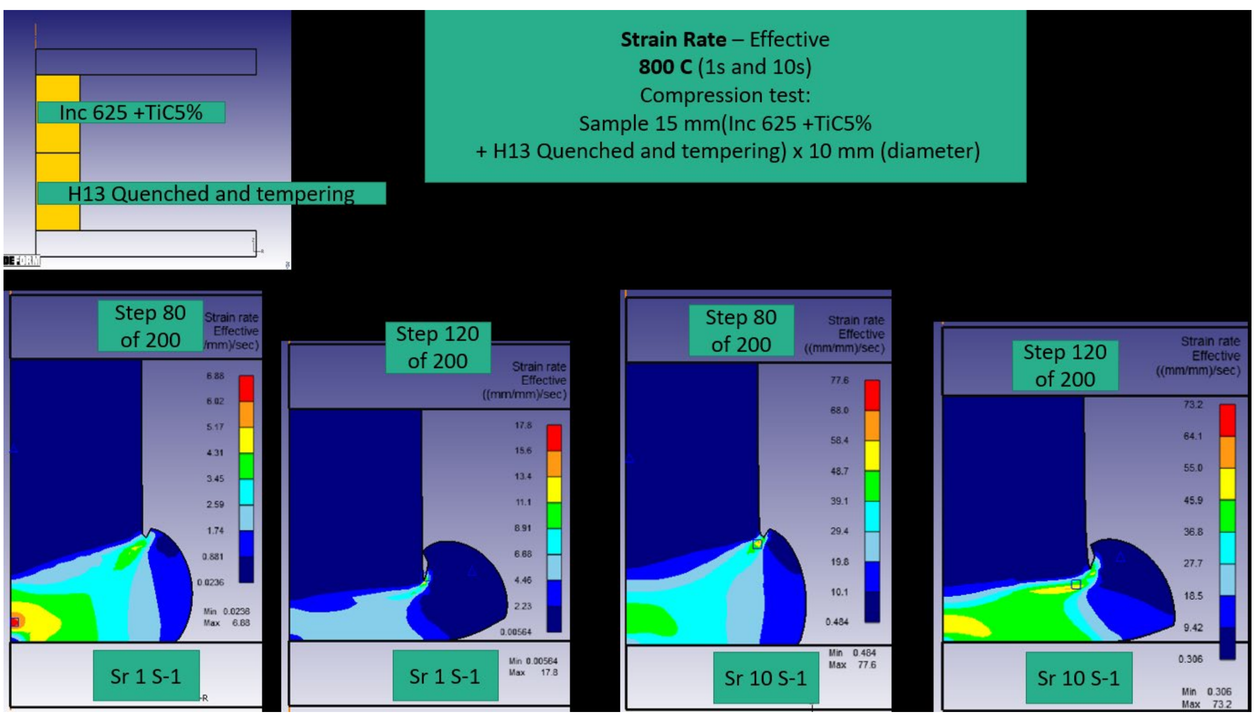


Figure 33: Simulation prepared with the interface of hardened H13 and INC625 + 5w%TiC at steps 80 and 120 (of 200 total) to observe the effective strain rate (in [mm/mm]/s).

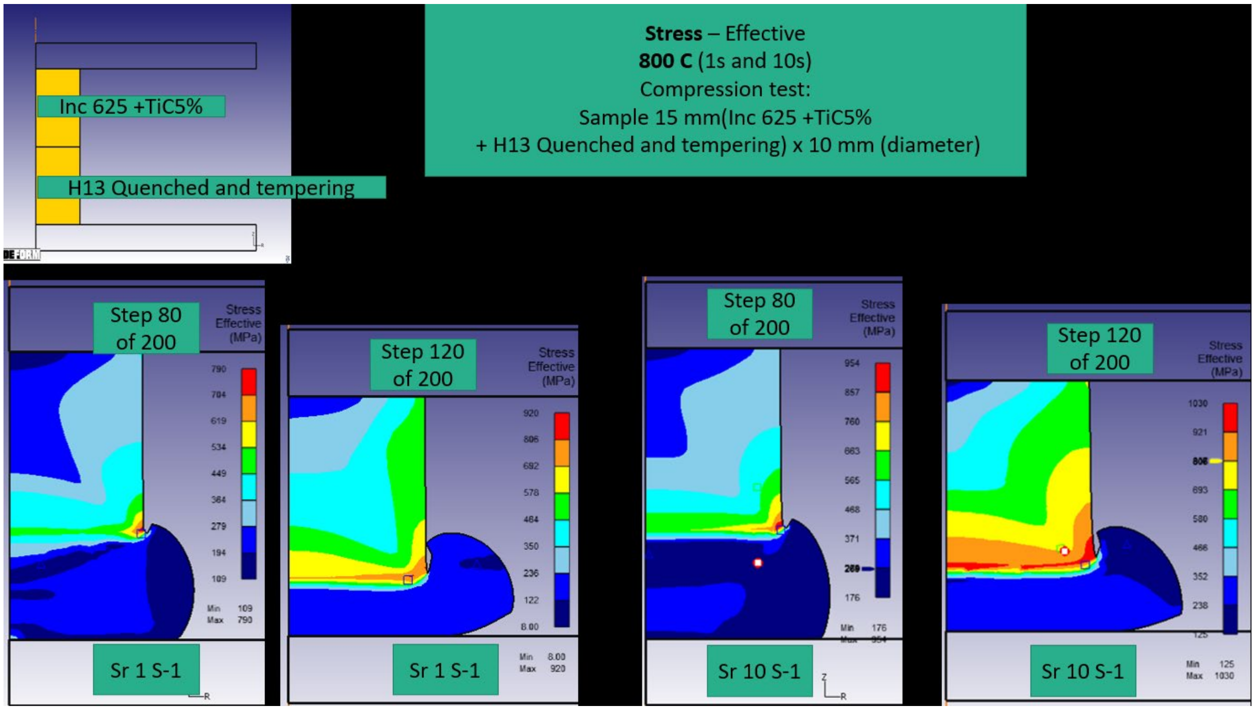


Figure 34: Simulation prepared with the interface of hardened H13 and INC625 + 5w%TiC at steps 80 and 120 (of 200 total) to observe the effective stress (in MPa).

The composite image, ***Figure 35***, shows a proposed application for the results obtained from the research conducted in this report. The model for a forging process is shown below, using hardened H13 as the die and punch material and examining the effect on wear behavior, where the tools to be coated with INC625 + 5w%TiC.

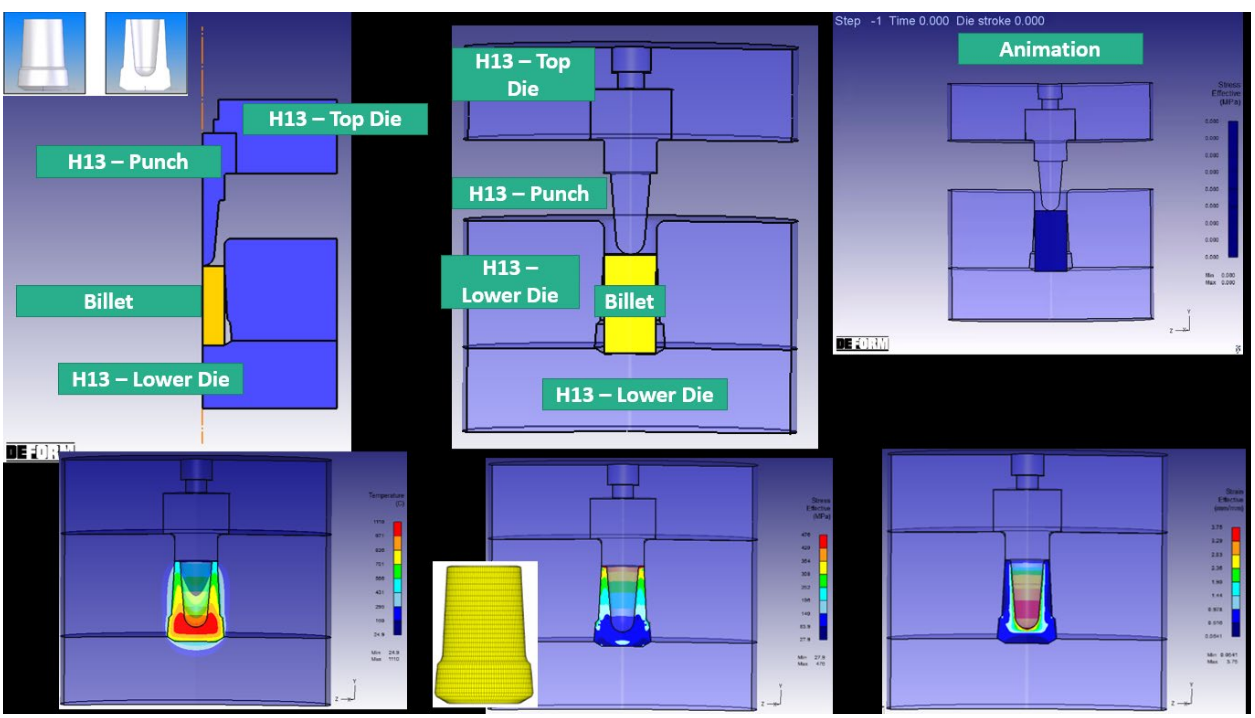


Figure 35: Model for hot forging process prepared for wear-coating evaluation in DEFORM-2D and DEFORM-3D.

2. Identify any project changes, and justification:

- Elimination of INC625 + 10w%TiC and INC625 + 15w%TiC from consideration
- Assessment of pure INC625

Summary of above points:

Several parameter changes and setup considerations were explored to produce INC625 + 10w%TiC coupons with less porosity / better densification and lack of cracks. However, the INC625 + 10w%TiC coupons consistently exhibited a high degree of porosity and cracking; the overall brittleness of the printed coupons led to some of the coupons shearing off of the substrate when the powder spreading wiper made contact with them. As a result, focus shifted to optimizing densification of the INC625 + 5w%TiC coupons.

INC625 + 15w%TiC has not been explored due to the issues already surrounding the INC625 + 10w%TiC coupon density. Additionally, as this research builds off of Loewy Institute PhD candidate Trevor Verdonik's work (which identified INC625 as a strong contender for forging tooling coating from an assortment of other candidates), it was deemed necessary to perform separate Gleeble experiments with pure INC625 in order for the results to be compared with the MMCs.

3. Project still on track?

- Performing additional MMC Gleeble experiments
- Continued revision of simulations in DEFORM-2D

Summary of above points:

As additional samples of INC625 + 5w%TiC are printed with the Renishaw AM400, additional Gleeble experiments will be run to further gather stress-strain curves to inform additional DEFORM-2D modeling.

4. Plans for next stage (or to complete):

- Additional experimental investigation into printing INC625 + 5w%TiC coating atop industry partner-provided H13 knockout (K.O.) pins
- Metallographic assessment of K.O. pin coatings
- Collaboration with industry partner, AAM, to assess coating effectiveness in industrial environment

Summary of above points:

An initial print of the INC625 + 5w% coating atop 1 of the 3 industry partner-provided K.O. pins resulted in poor densification, potentially due to the powder packing method used. To address this, it was decided that several smaller hardened H13 samples should be printed upon to further assess how the packing technique may affect the final print. Additionally, it has been discussed that some initial printing of pure INC625 on the first few layers of the hardened H13 (prior to print the INC625 + 5w%TiC) may assist the remaining portion of the coating—comprised of INC625 + 5w%--to adhere to the K.O. pin.

Once the coating achieves the desirable densification, metallography will be performed on the coating, and another pin will be coated and sent to AAM for active use in one of their production lines. After the K.O. pin has completed a set lifecycle, it will be removed from production and the surface will be assessed.

5. Any concerns about completing the planned work?

- Currently, there are no concerns regarding the completion of the planned work.

Summary of the above point(s):

At this point there are no concerns regarding completion of the planned work. A methodology has been developed: from print evaluation / metallography, to Gleeble testing, to DEFORM modeling, which will be used to complete the scope of this stage gate of work.

6. Attach an updated milestone plan.

- This project is completed at this point.

APPENDICES OVERVIEW

APPENDIX A: References

APPENDIX B: Additional DEFORM Simulation Images

APPENDIX A: References (Organized by Project Topics)

Topic: DEFORM

Khanawapee, Uten and Butdee, Suthep. “A study of barreling and DEFORM 3D simulation in cold upsetting of bi-material.” *MaterialsToday: PROCEEDINGS*, Vol. 26, Pt. 2, 2020, pp. 1262-1270.

Seriacopi V., et al. “Finite element analysis of the effects of thermos-mechanical loadings on a tool steel microstructure.” *Engineering Failure Analysis*, Vol. 98, 2019, pp. 383-398.

Rajendran, Nijenthan et al. “Hot Forging Die Design Optimization Using FEM Analysis for Near-Net Forming of 18CrNiMo7-6 Steel Pinion Shaft.” *Metals*, Vol. 13, No. 4, 2023.

Topic: H13 Surface Evaluation

Castro, G. et al. “Influence of the nitriding time in the wear behaviour of an AISI H13 steel during a crankshaft forging process.” *Wear*, Vol. 263, Iss. 7-12, pp. 1275-1385.

Chen, Yong-gui et al. “Improvement of the wear and corrosion resistance of nitrocarburized H13 steel using hydrothermal-synthesized zeolite coating.” *Surface and Coatings Technology*, Vol. 447, 2022.

Pérez, Marcos, and Belzunce, Francisco Javier. “A comparative study of salt-bath nitrocarburizing and gas nitriding followed by post-oxidation used as surface treatments of H13 hot forging dies.”

da Silva, Sinval Pedroso, et al. “Surface modification of AISI H13 steel by die-sinking electrical discharge machining and TiAIN coating: A promising hybrid technique to improve wear resistance.” *Wear*, Vol. 462-463, 2020.

Wang, Yanjiang, et al. “Determining the wear behavior of H13 steel die during the extrusion process of pure nickel.” *Engineering Failure Analysis*, Vol. 134, 2022.

Topic: TiC Reinforcement

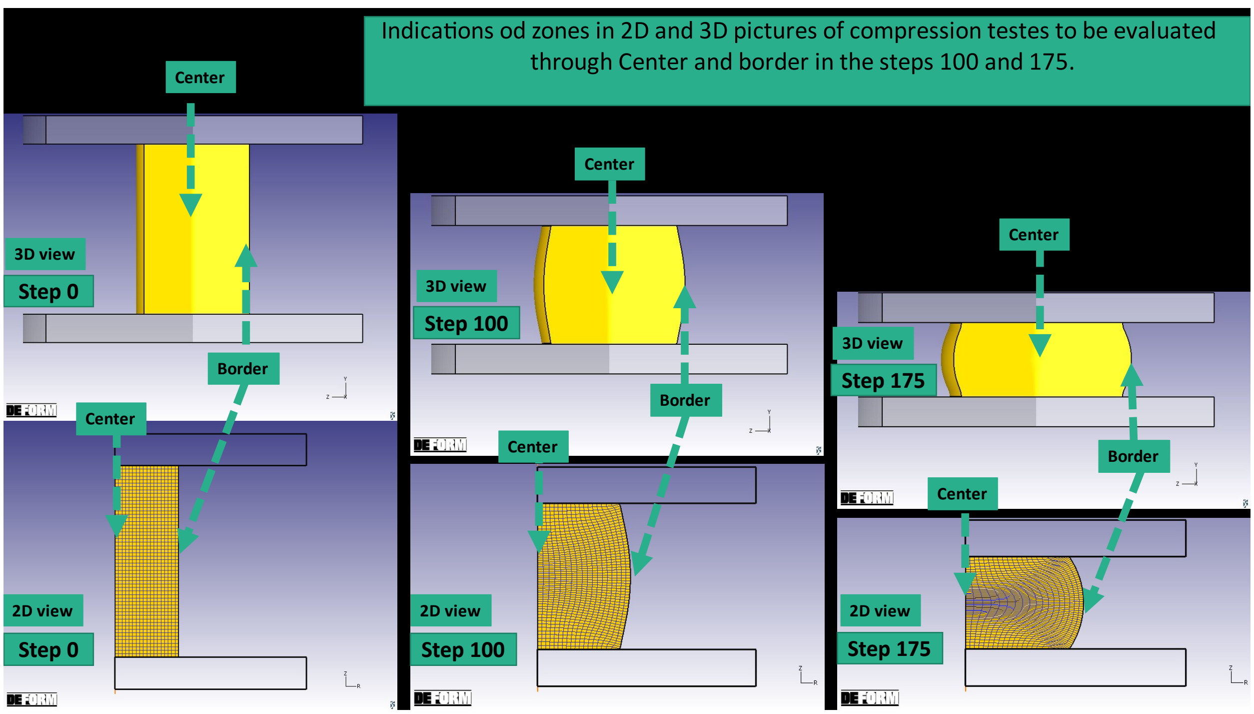
Cho, Seungchan et al. “Enhanced high-temperature compressive strength of TiC reinforced stainless steel matrix composites fabricated by liquid pressing infiltration process.” *Journal of Alloys and Compounds*, Vol. 817, 2020.

Yang, Xiaoyu et al. “Effect of carbon content on interfacial microstructure and mechanical properties of a vacuum hot-compressed bonding titanium-steel composite.” *Materials Science and Engineering: A*, Vol. 824, 2021.

APPENDIX B: Additional DEFORM Simulation Images

Comparisons and evaluations through Strain Rates, Strain and Stress
Materials: H13 annealed, H13 Hardened, INC625 + 5w%TiC, Pure INC625
and H13 HARDENED + (INC625 + 5w%TiC)

		DEFORM 2D - Temperature of compression					
Sample	STRAIN RATE	650°C	700°C	750°C	800°C	825°C	850°C
H15 mm x D10 mm	1s-1, 5s-1, 10s-1, and 20s-1						
Single	H13 ANNEALED	X	X	X	X		
Single	H13 HARDENED	X	X	X	X		
Single	INC625 + 5w%TiC			X	X	X	X
Single	Pure INC625			X	X	X	X
Multiple	H13 HARDENED + (INC625 + 5w%TiC)			X	X		



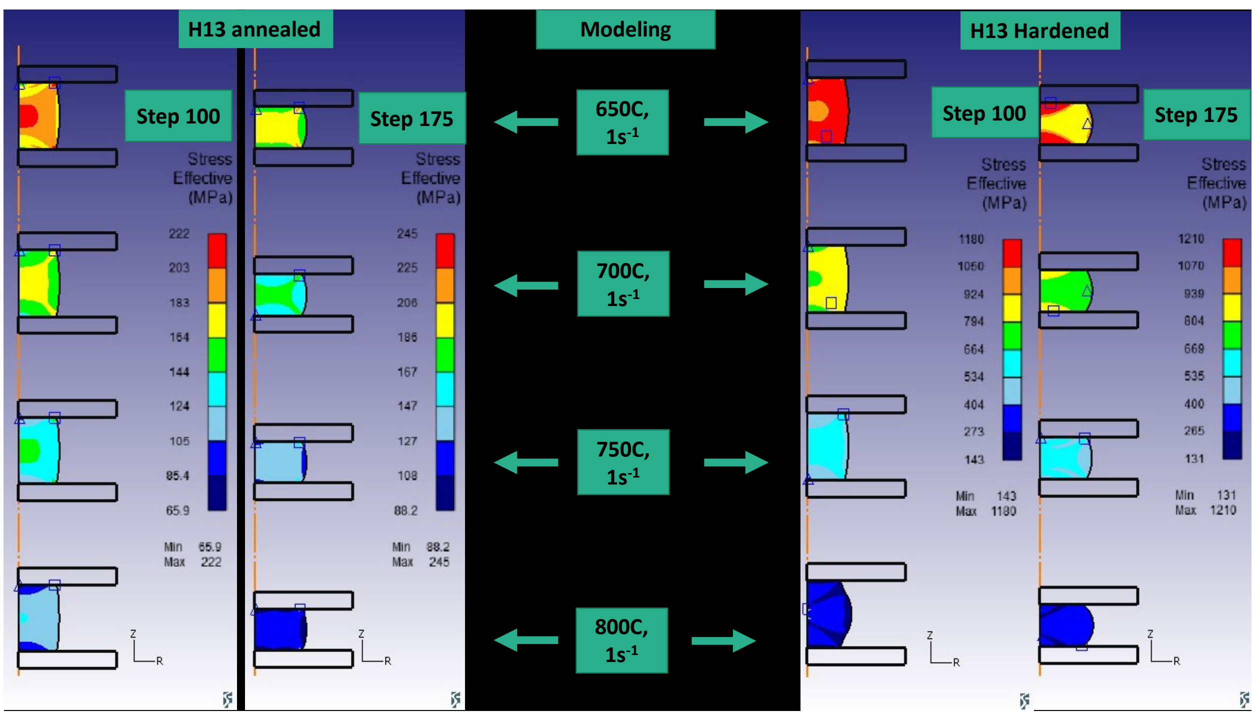
Slide 4

Example of model used to have a comparison between the development of different temperatures with same strain rate and appropriate comparison between two materials showing two models.

Main parameters of the modeling – DEFORM-2D:
Considering 200 steps of simulations, steps 100 and 175 were evaluated during the simulations of compression test (The flow stress curves came fromGleeble compression test).

Dimensions of billet tested: Diameter: 10 mm / Height: 15 mm.

Mesh information
Nodes: 1064
Elements: 990
Thickness elements: 4
Size ratio: 1



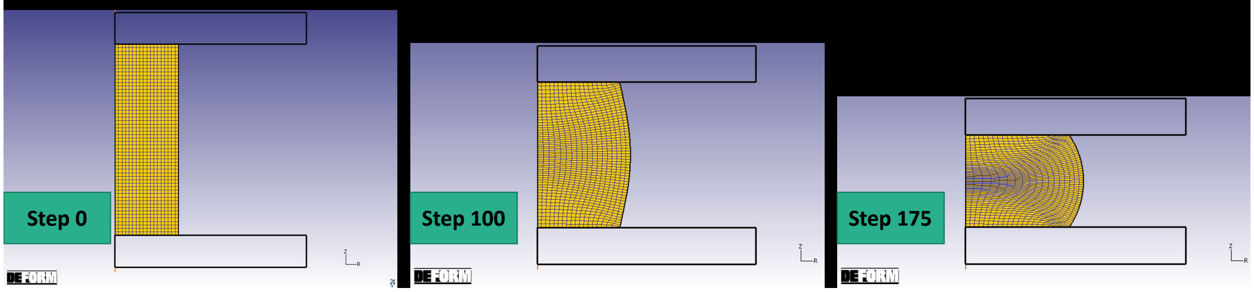
Slides 6 to 29

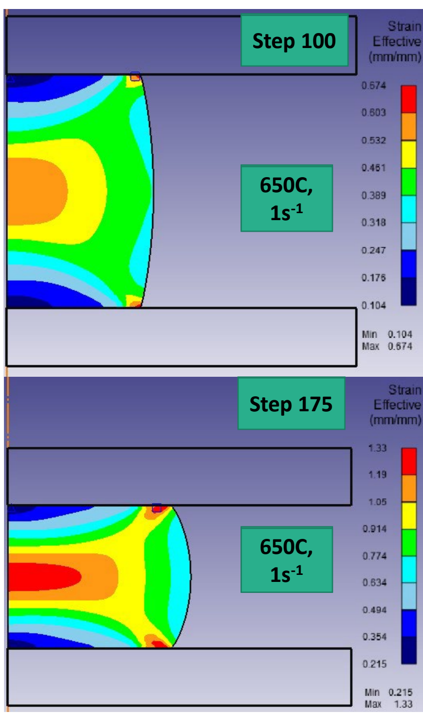
Material: H13 annealed;

Parameters to be evaluated: Strain-Effective (mm/mm), Strain Rate-Effective ((mm/mm)/s), and Stress-Effective (MPa);

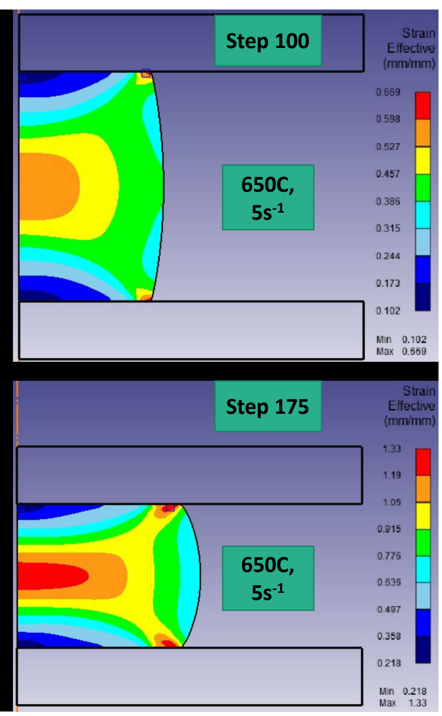
For the following slides, the temperatures used were 650 C, 700 C, 750 C and 800 C, and the strain rates used were $1s^{-1}$, $5s^{-1}$, $10s^{-1}$ and $20s^{-1}$. The flow stress curves came from Gleeble compression test).

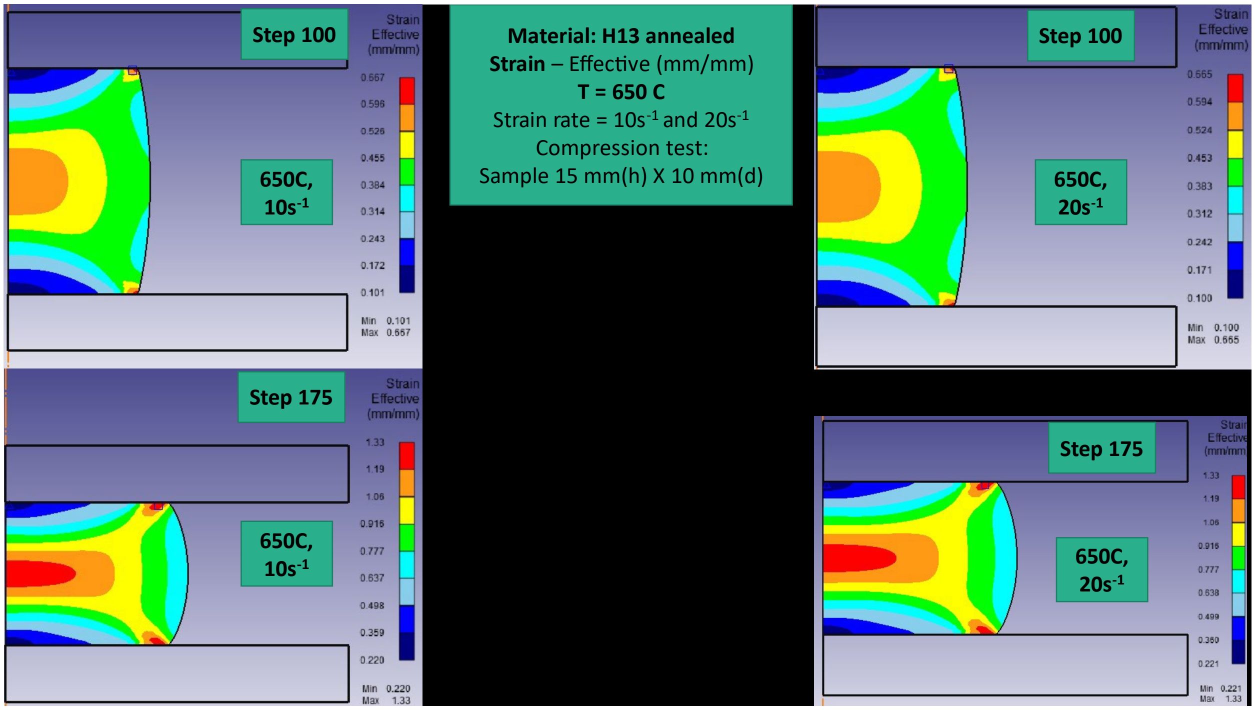
Considering 200 steps of simulation, the steps evaluated were step 100 and step 175, which are appropriate to check for the properties in specific point of the deformation.

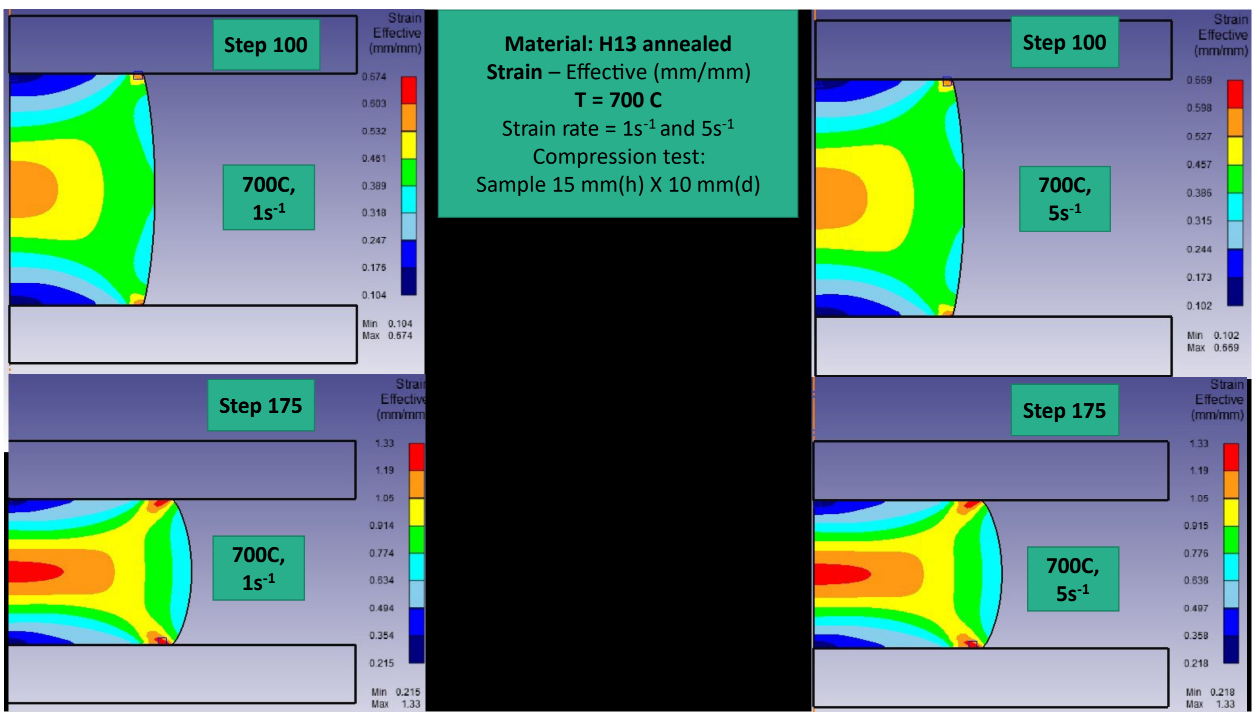


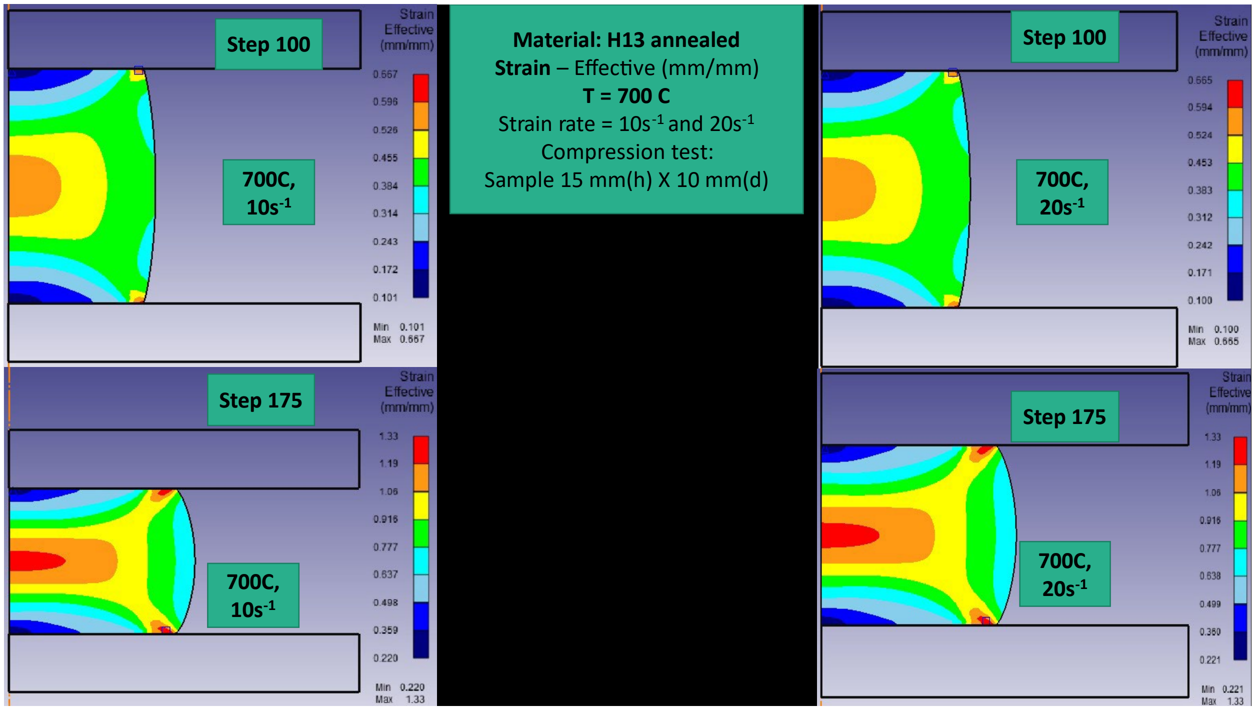


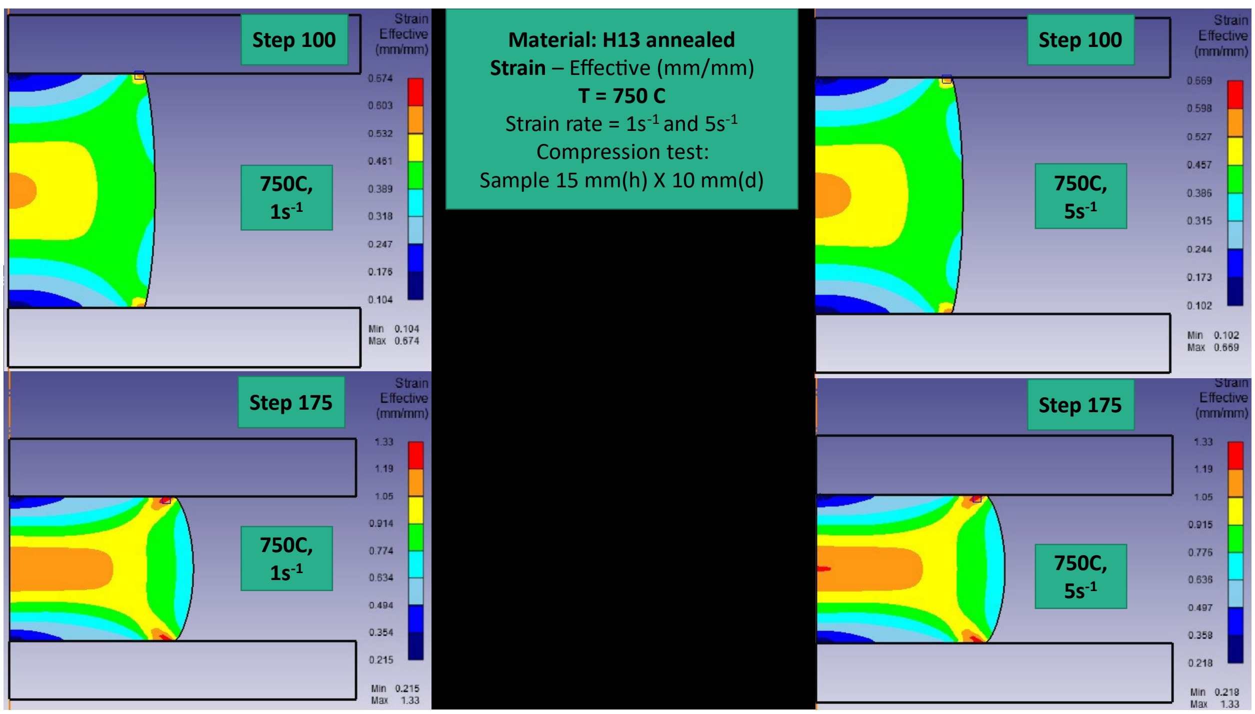
Material: H13 annealed
Strain – Effective (mm/mm)
T = 650 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)

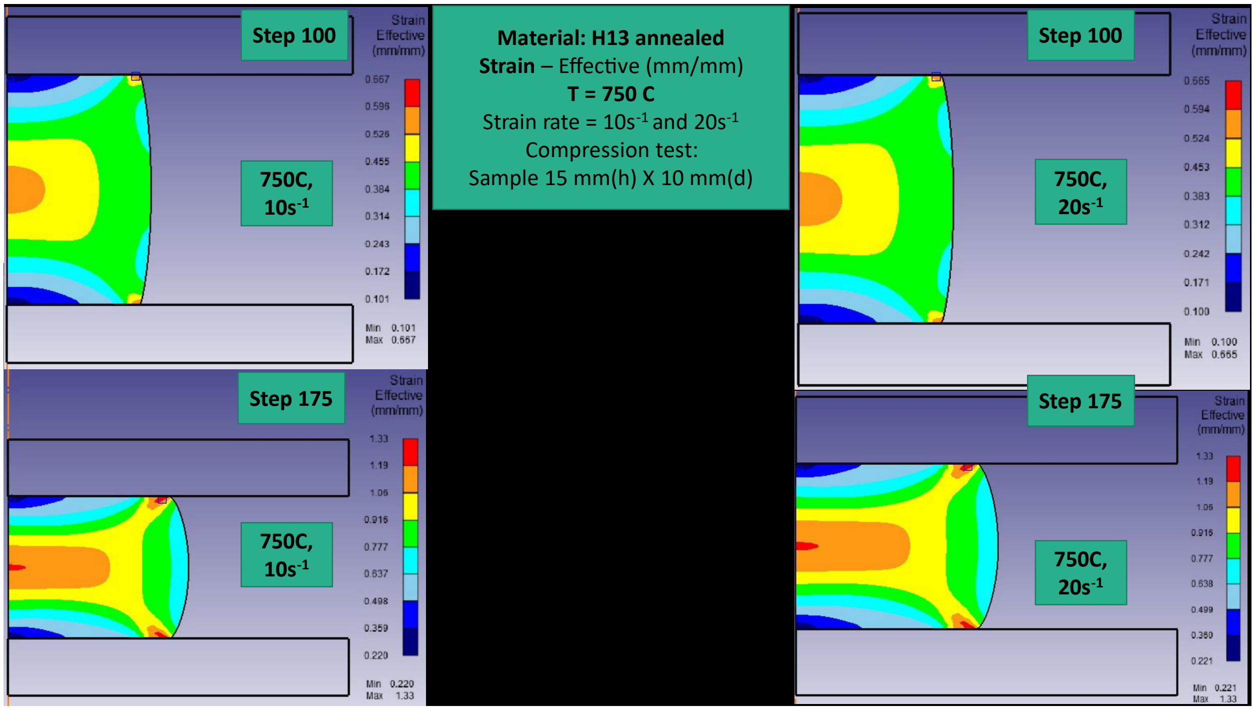


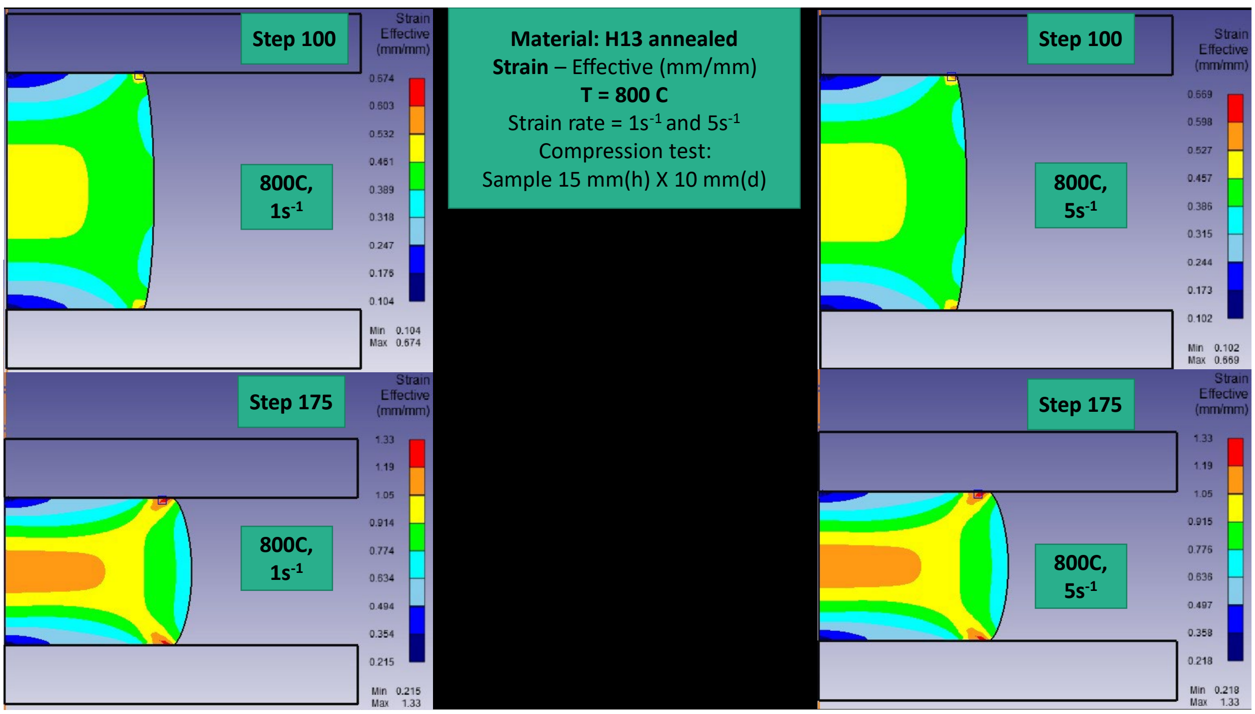

Material: H13 annealed
Strain – Effective (mm/mm)
T = 650 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 10s-1
Step 175
650C, 10s-1
Step 100
650C, 20s-1
Step 175
650C, 20s-1
Strain Effective (mm/mm)

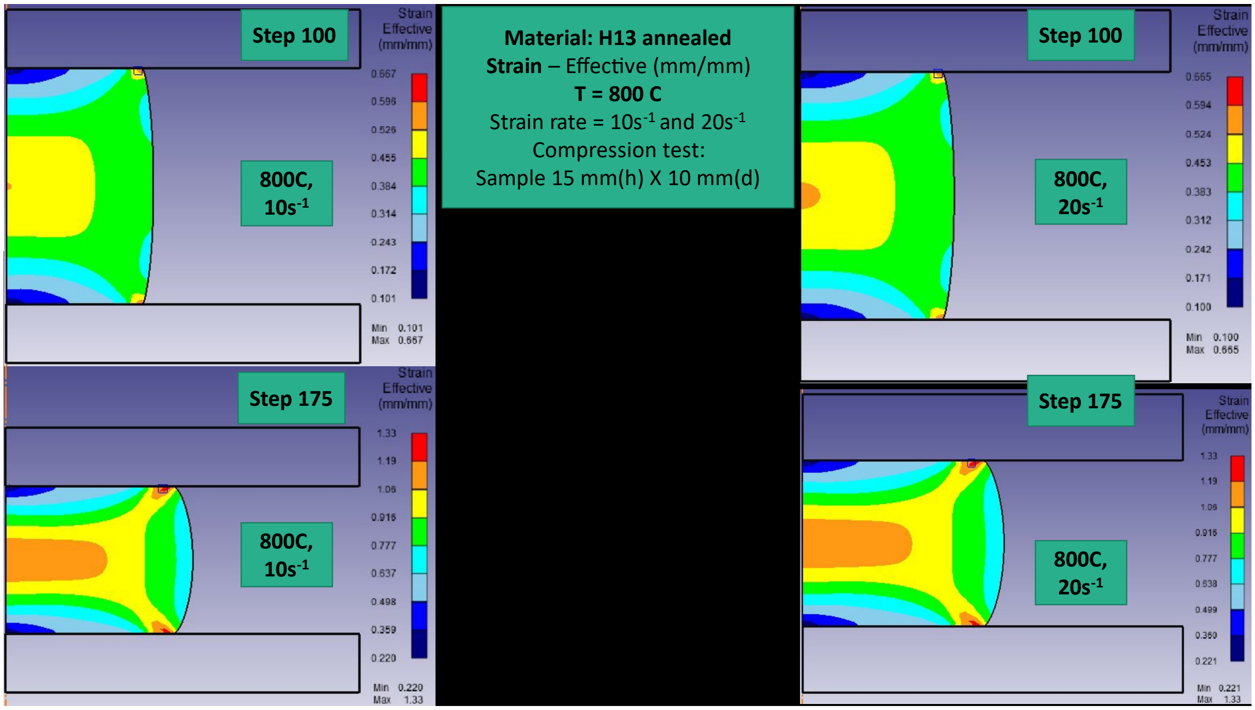

Material: H13 annealed
Strain – Effective (mm/mm)
T = 700 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 1s-1
Step 175
700C, 1s-1
Step 100
700C, 5s-1
Step 175
700C, 5s-1
Strain Effective (mm/mm)

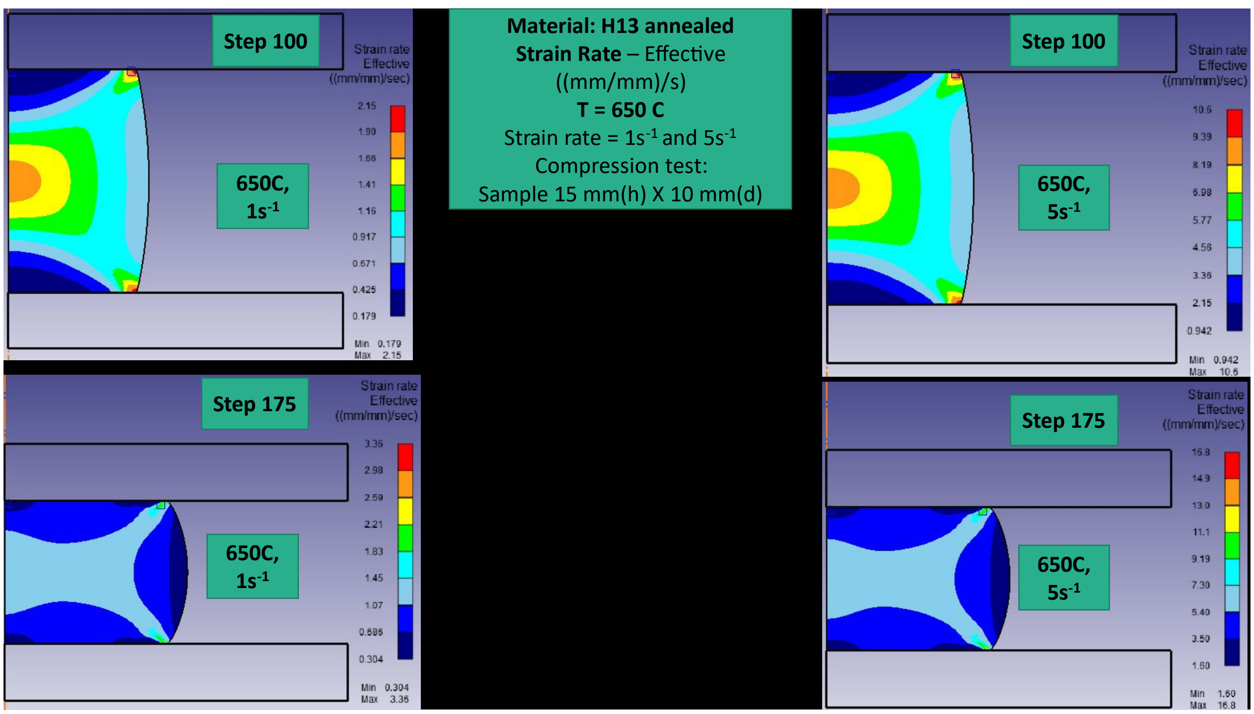

Material: H13 annealed
Strain – Effective (mm/mm)
T = 700 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 10s-1
Step 175
700C, 10s-1
Step 100
700C, 20s-1
Step 175
700C, 20s-1
Strain Effective (mm/mm)
Min 0.101 Max 0.667
Min 0.220 Max 1.33
Min 0.100 Max 0.665
Min 0.221 Max 1.33

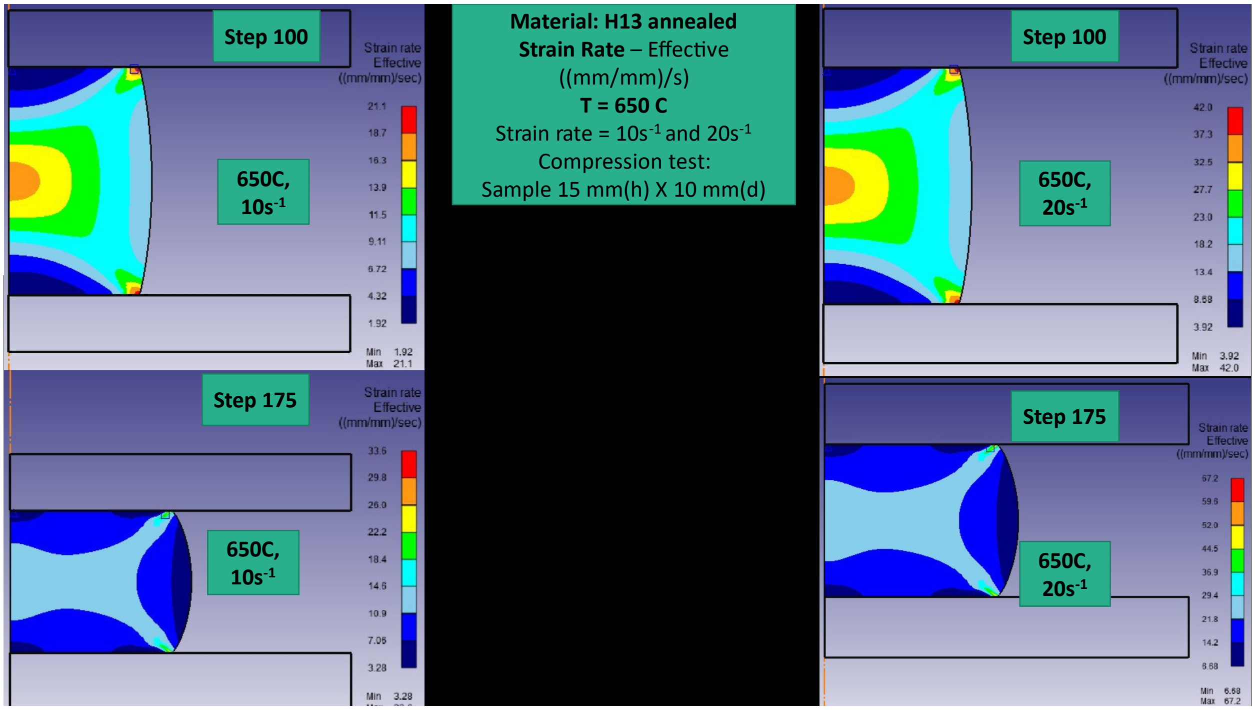

Material: H13 annealed
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 1s-1
Step 175
750C, 1s-1
Step 100
750C, 5s-1
Step 175
750C, 5s-1
Strain Effective (mm/mm)
Min 0.104 Max 0.674
Min 0.215 Max 1.33
Min 0.102 Max 0.669
Min 0.218 Max 1.33

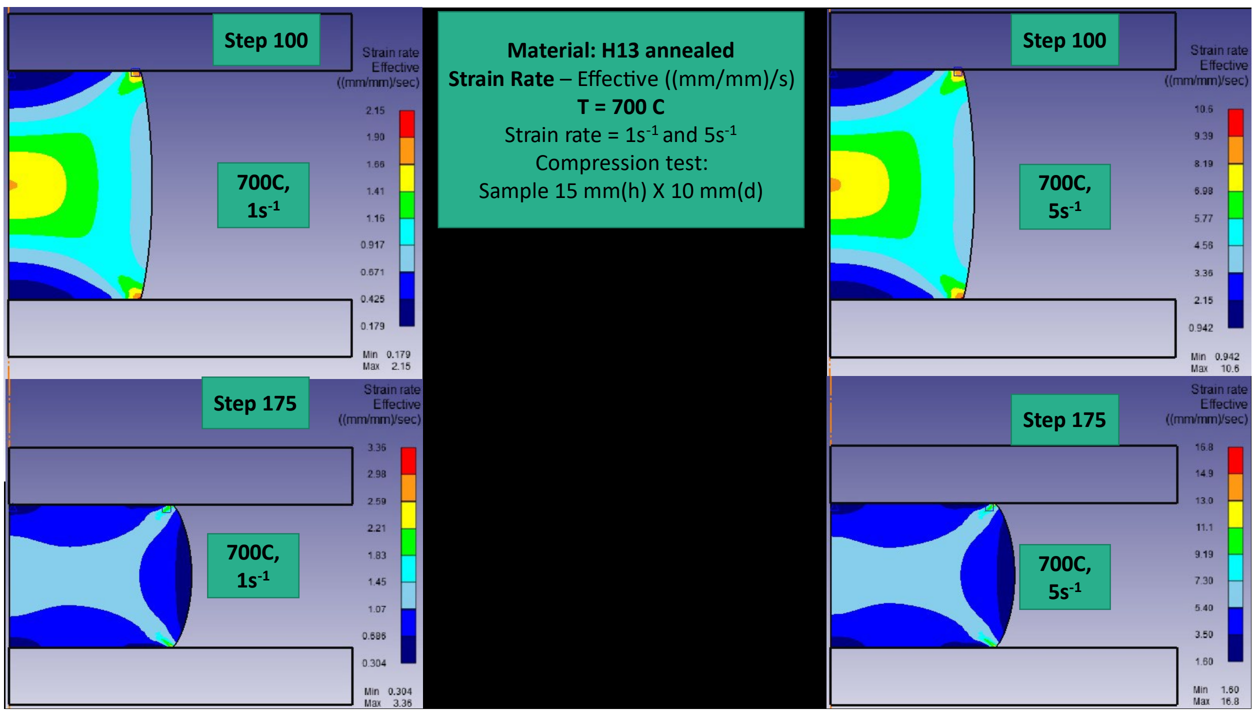

Material: H13 annealed
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Strain Effective (mm/mm)
0.667 0.596 0.526 0.455 0.384 0.314 0.243 0.172 0.101
Min 0.101 Max 0.667
Step 175
750C, 10s-1
Strain Effective (mm/mm)
1.33 1.19 1.06 0.916 0.777 0.637 0.498 0.359 0.220
Min 0.220 Max 1.33
Step 100
750C, 20s-1
Strain Effective (mm/mm)
0.665 0.594 0.524 0.453 0.383 0.312 0.242 0.171 0.100
Min 0.100 Max 0.665
Step 175
750C, 20s-1
Strain Effective (mm/mm)
1.33 1.19 1.06 0.916 0.777 0.638 0.499 0.360 0.221
Min 0.221 Max 1.33

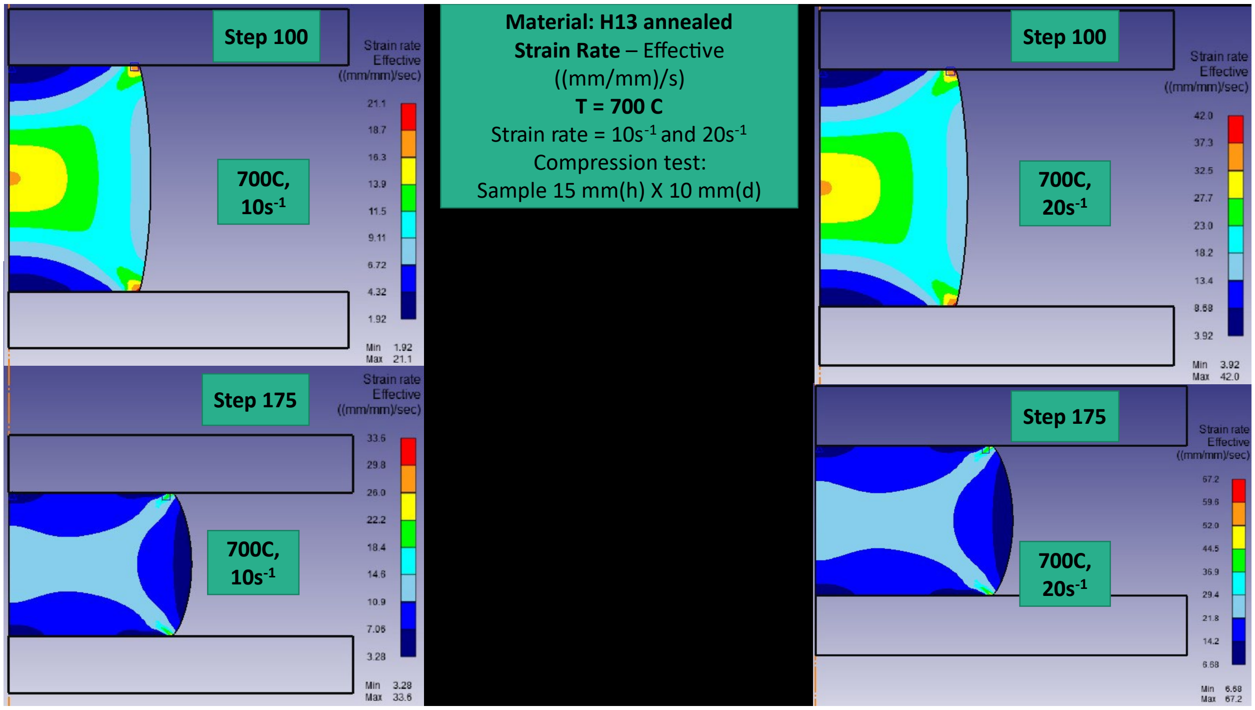

Material: H13 annealed
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Strain Effective (mm/mm)
0.674 0.603 0.532 0.461 0.389 0.318 0.247 0.176 0.104
Min 0.104 Max 0.674
Step 175
800C, 1s-1
Strain Effective (mm/mm)
1.33 1.19 1.05 0.914 0.774 0.634 0.494 0.354 0.215
Min 0.215 Max 1.33
Step 100
800C, 5s-1
Strain Effective (mm/mm)
0.669 0.598 0.527 0.457 0.386 0.315 0.244 0.173 0.102
Min 0.102 Max 0.669
Step 175
800C, 5s-1
Strain Effective (mm/mm)
1.33 1.19 1.05 0.915 0.776 0.636 0.497 0.358 0.218
Min 0.218 Max 1.33

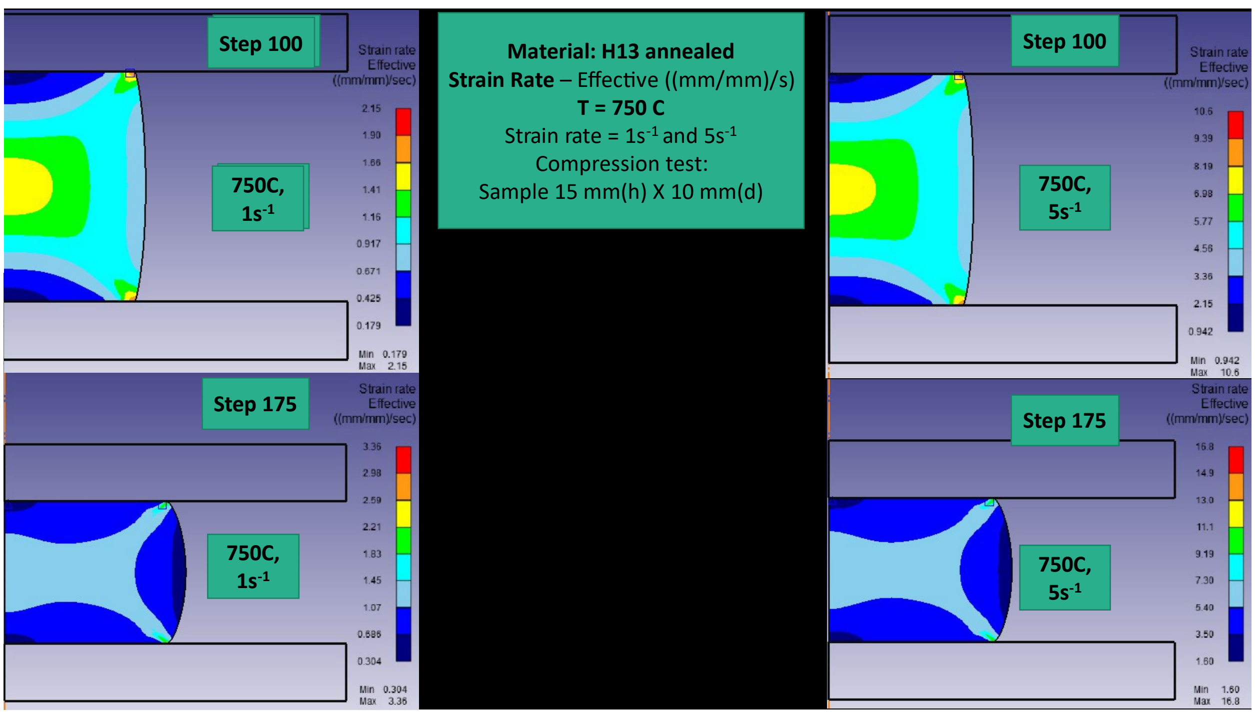

Material: H13 annealed
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain Effective (mm/mm)
0.667 0.596 0.526 0.455 0.384 0.314 0.243 0.172 0.101
Min 0.101 Max 0.667
800C, 10s-1
Step 100
Strain Effective (mm/mm)
0.665 0.594 0.524 0.453 0.383 0.312 0.242 0.171 0.100
Min 0.100 Max 0.665
800C, 20s-1
Step 175
Strain Effective (mm/mm)
1.33 1.19 1.06 0.916 0.777 0.637 0.498 0.359 0.220
Min 0.220 Max 1.33
800C, 10s-1
Step 175
Strain Effective (mm/mm)
1.33 1.19 1.06 0.916 0.777 0.638 0.499 0.360 0.221
Min 0.221 Max 1.33
800C, 20s-1

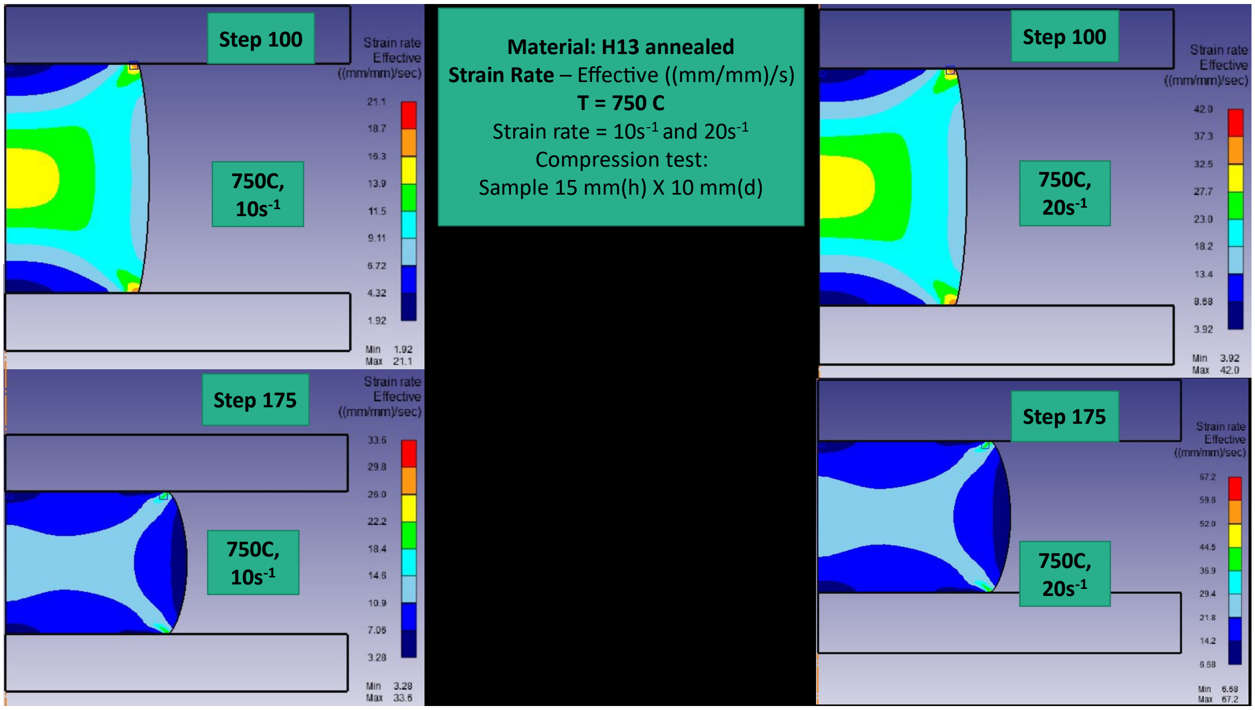

Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 650 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate Effective ((mm/mm)/sec)
2.15 1.90 1.66 1.41 1.16 0.917 0.671 0.425 0.179
Min 0.179 Max 2.15
650C, 1s-1
Step 100
Strain rate Effective ((mm/mm)/sec)
10.6 9.39 8.19 6.98 5.77 4.56 3.36 2.15 0.942
Min 0.942 Max 10.6
650C, 5s-1
Step 175
Strain rate Effective ((mm/mm)/sec)
3.36 2.98 2.59 2.21 1.83 1.45 1.07 0.686 0.304
Min 0.304 Max 3.36
650C, 1s-1
Step 175
Strain rate Effective ((mm/mm)/sec)
16.8 14.9 13.0 11.1 9.19 7.30 5.40 3.50 1.60
Min 1.60 Max 16.8
650C, 5s-1


Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 650 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 10s-1
Strain rate Effective ((mm/mm)/sec)
21.1
18.7
16.3
13.9
11.5
9.11
6.72
4.32
1.92
Min 1.92
Max 21.1
Step 175
650C, 10s-1
Strain rate Effective ((mm/mm)/sec)
33.6
29.8
26.0
22.2
18.4
14.6
10.9
7.06
3.28
Min 3.28
Step 100
650C, 20s-1
Strain rate Effective ((mm/mm)/sec)
42.0
37.3
32.5
27.7
23.0
18.2
13.4
8.68
3.92
Min 3.92
Max 42.0
Step 175
650C, 20s-1
Strain rate Effective ((mm/mm)/sec)
67.2
59.6
52.0
44.5
36.9
29.4
21.8
14.2
6.68
Min 6.68
Max 67.2

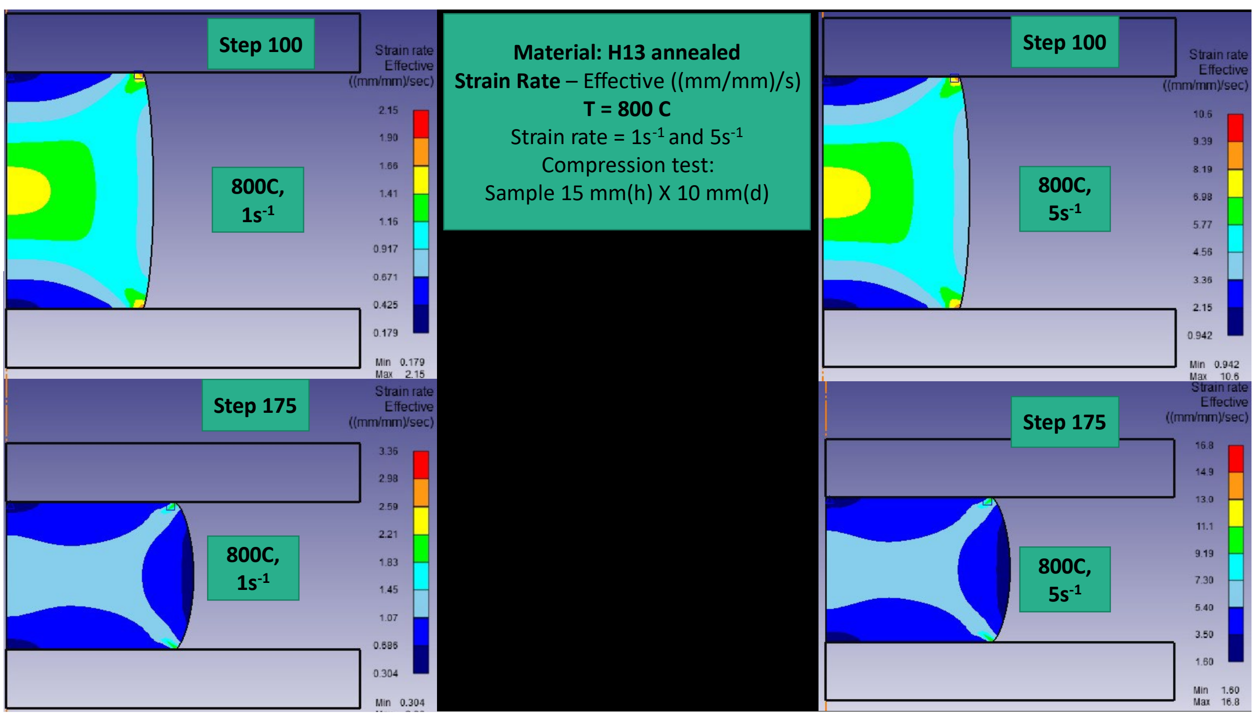

Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 700 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 1s-1
Strain rate Effective ((mm/mm)/sec)
2.15
1.90
1.66
1.41
1.16
0.917
0.671
0.425
0.179
Min 0.179
Max 2.15
Step 175
700C, 1s-1
Strain rate Effective ((mm/mm)/sec)
3.36
2.98
2.59
2.21
1.83
1.45
1.07
0.686
0.304
Min 0.304
Max 3.36
Step 100
700C, 5s-1
Strain rate Effective ((mm/mm)/sec)
10.6
9.39
8.19
6.98
5.77
4.56
3.36
2.15
0.942
Min 0.942
Max 10.6
Step 175
700C, 5s-1
Strain rate Effective ((mm/mm)/sec)
16.8
14.9
13.0
11.1
9.19
7.30
5.40
3.50
1.60
Min 1.60
Max 16.8


Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 700 C
Strain rate = 10s^{-1} and 20s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate Effective ((mm/mm)/sec)
21.1 18.7 16.3 13.9 11.5 9.11 6.72 4.32 1.92
Min 1.92 Max 21.1
700C, 10s^{-1}
Step 175
Strain rate Effective ((mm/mm)/sec)
33.6 29.8 26.0 22.2 18.4 14.6 10.9 7.06 3.28
Min 3.28 Max 33.6
700C, 10s^{-1}
Step 100
Strain rate Effective ((mm/mm)/sec)
42.0 37.3 32.5 27.7 23.0 18.2 13.4 8.68 3.92
Min 3.92 Max 42.0
700C, 20s^{-1}
Step 175
Strain rate Effective ((mm/mm)/sec)
67.2 59.6 52.0 44.5 36.9 29.4 21.8 14.2 6.68
Min 6.68 Max 67.2
700C, 20s^{-1}

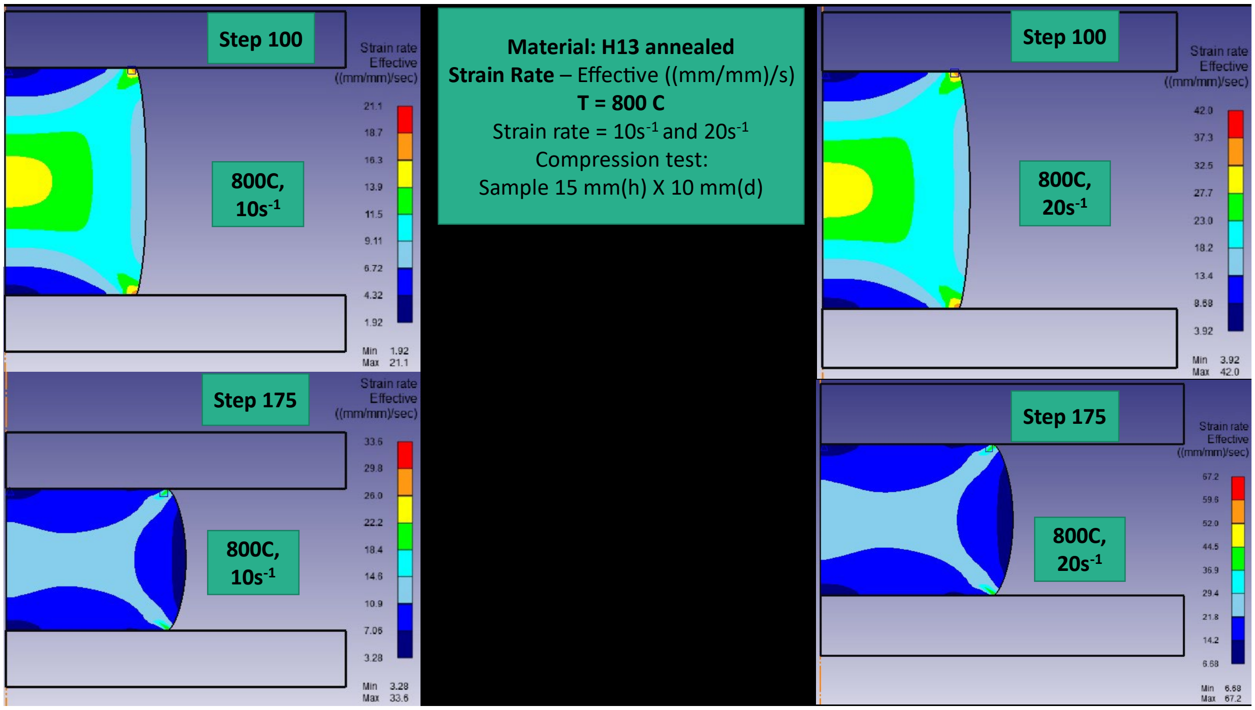

Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 1s^{-1} and 5s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate Effective ((mm/mm)/sec)
2.15 1.90 1.66 1.41 1.16 0.917 0.671 0.425 0.179
Min 0.179 Max 2.15
750C, 1s^{-1}
Step 175
Strain rate Effective ((mm/mm)/sec)
3.36 2.98 2.59 2.21 1.83 1.45 1.07 0.686 0.304
Min 0.304 Max 3.36
750C, 1s^{-1}
Step 100
Strain rate Effective ((mm/mm)/sec)
10.6 9.39 8.19 6.98 5.77 4.56 3.36 2.15 0.942
Min 0.942 Max 10.6
750C, 5s^{-1}
Step 175
Strain rate Effective ((mm/mm)/sec)
16.8 14.9 13.0 11.1 9.19 7.30 5.40 3.50 1.60
Min 1.60 Max 16.8
750C, 5s^{-1}

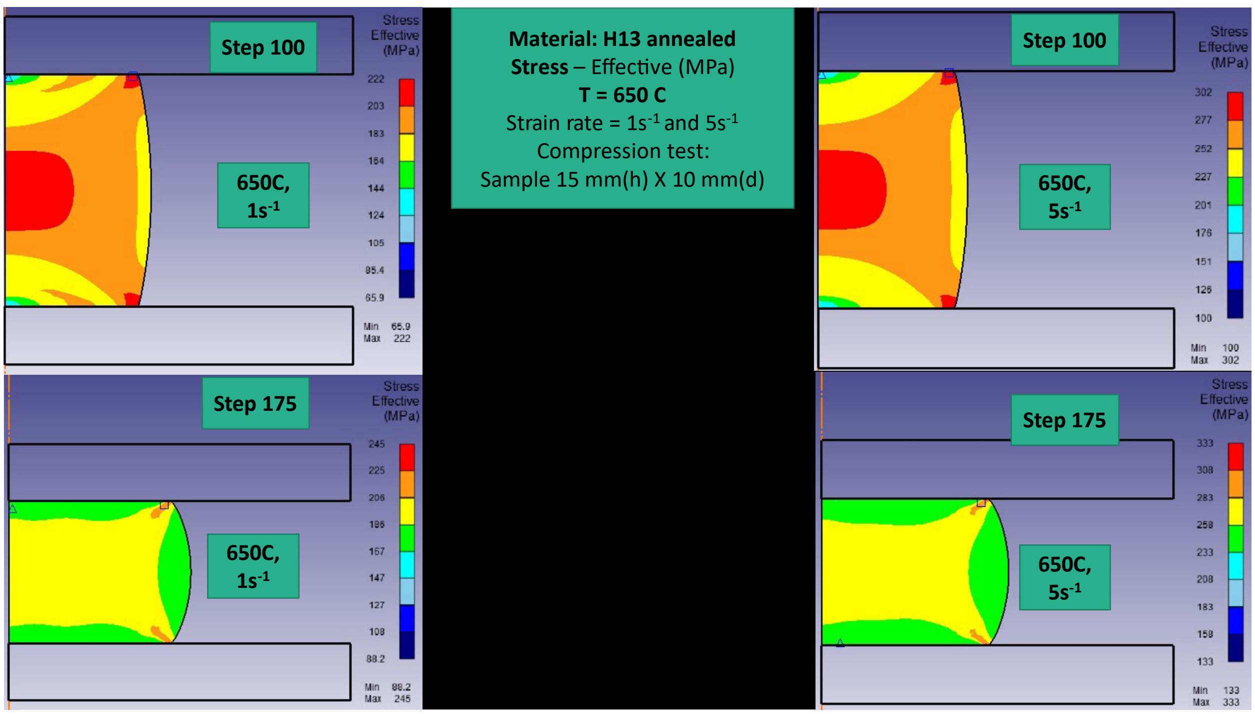


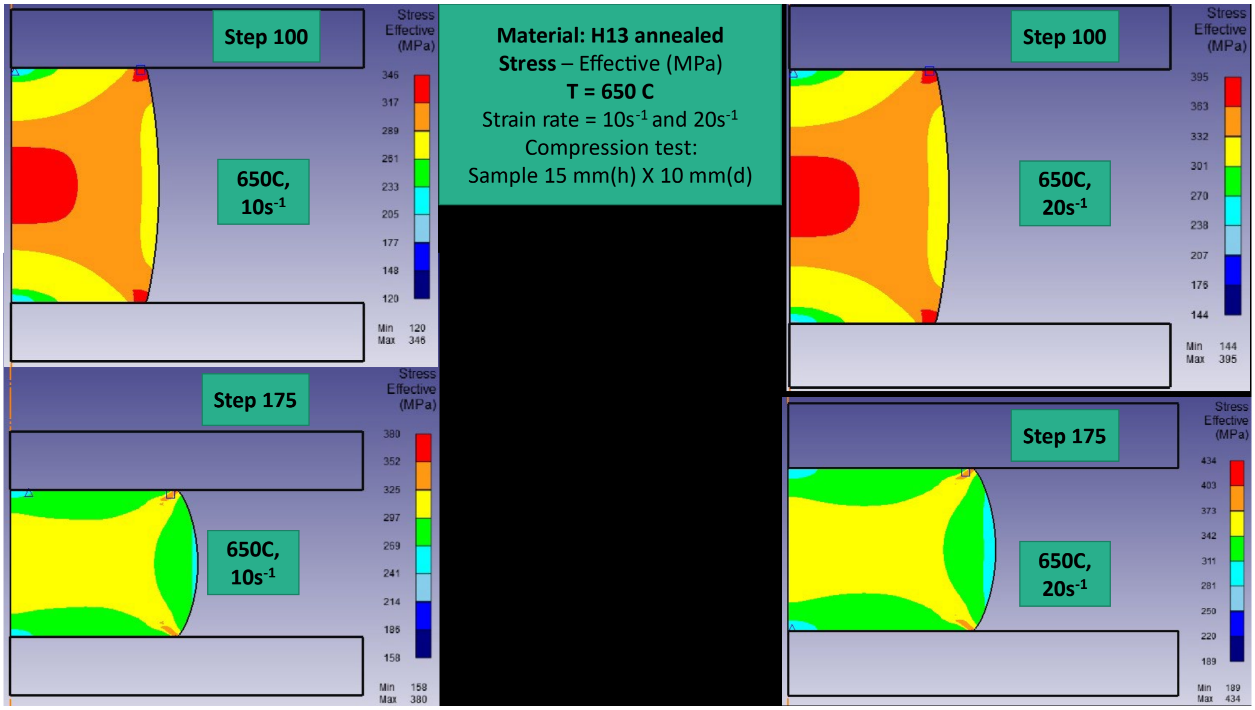
Step 100
750C, 10s-1
Step 175
750C, 10s-1
Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 20s-1
Step 175
750C, 20s-1
Strain rate Effective ((mm/mm)/sec)

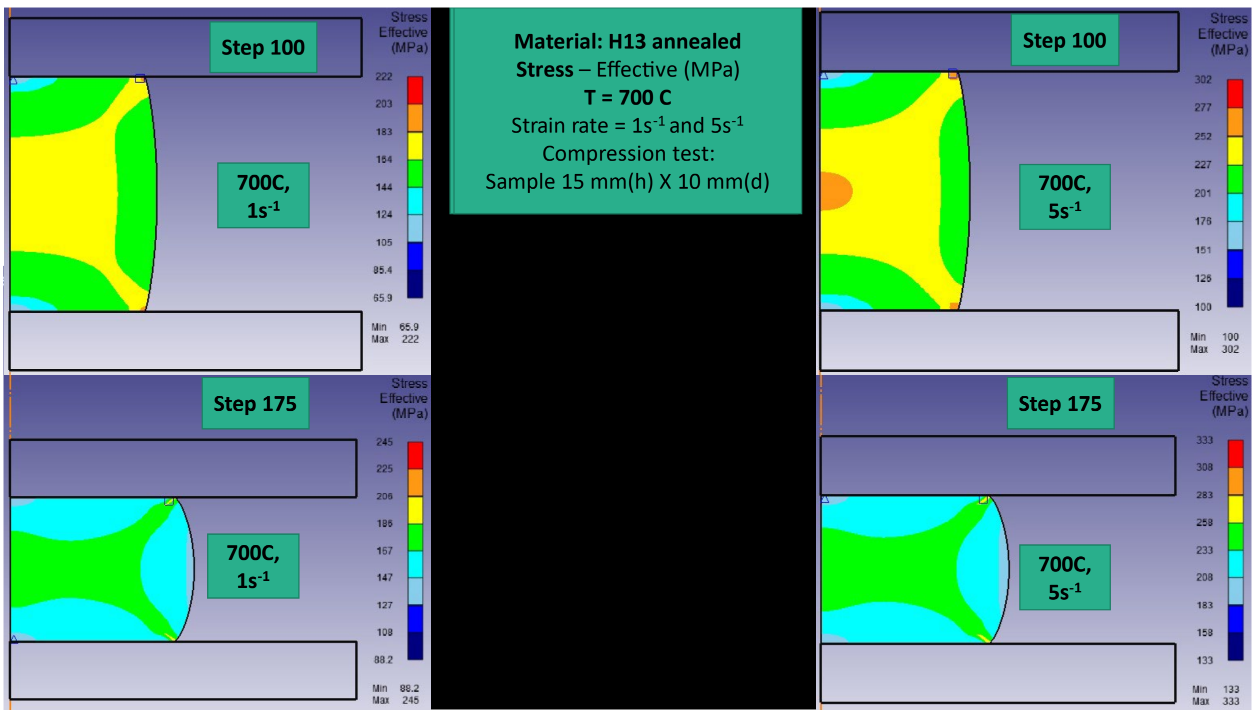


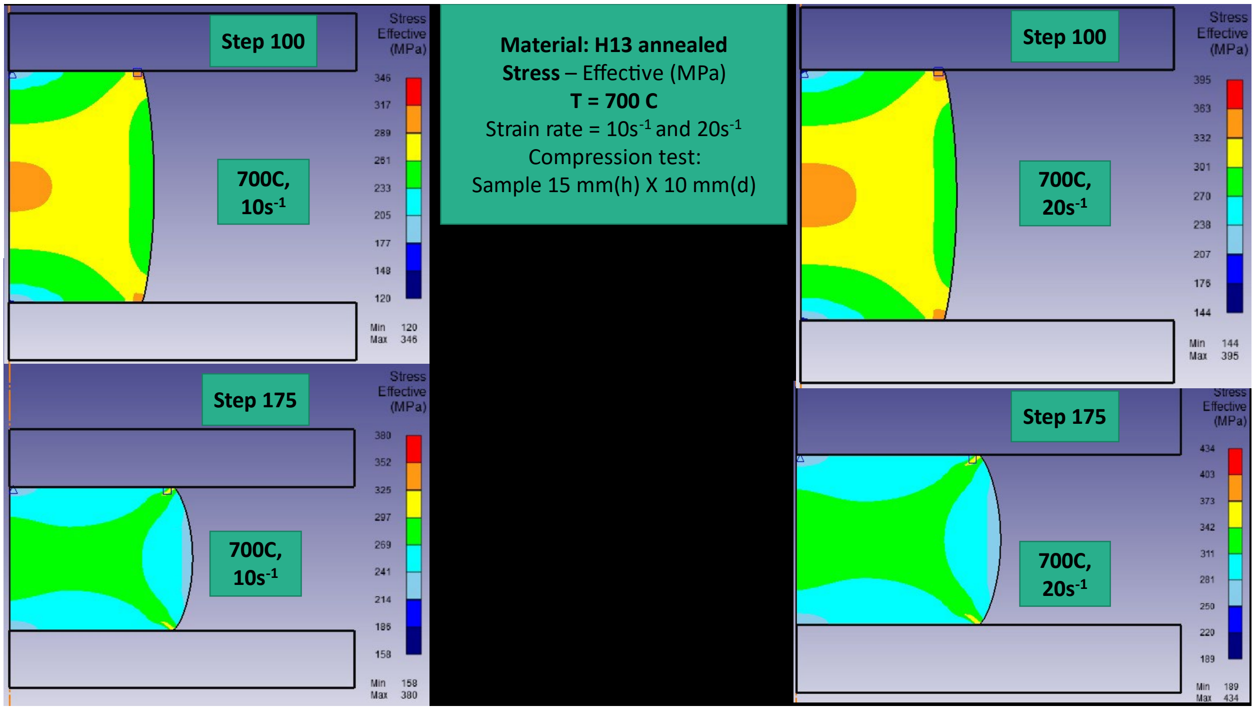
Step 100
800C, 1s-1
Step 175
800C, 1s-1
Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 5s-1
Step 175
800C, 5s-1
Strain rate Effective ((mm/mm)/sec)

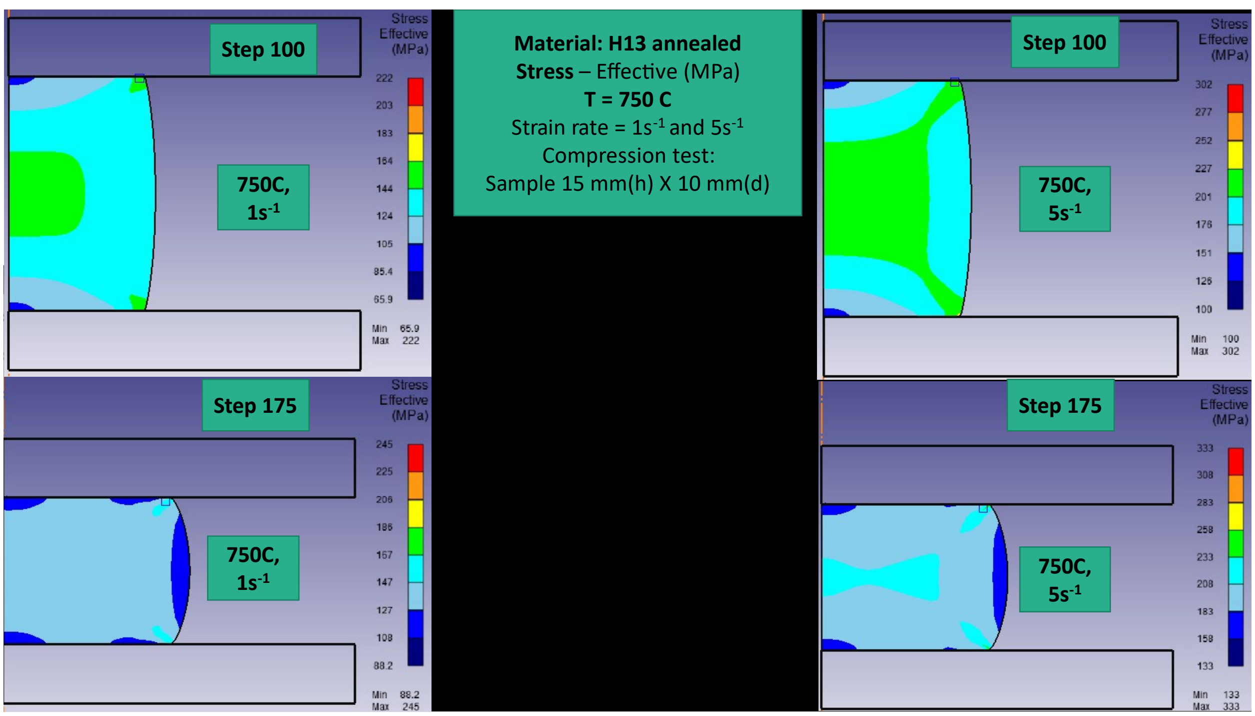

Material: H13 annealed
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Strain rate Effective ((mm/mm)/sec)
21.1 18.7 16.3 13.9 11.5 9.11 6.72 4.32 1.92
Min 1.92 Max 21.1
Step 175
800C, 10s-1
Strain rate Effective ((mm/mm)/sec)
33.6 29.8 26.0 22.2 18.4 14.6 10.9 7.06 3.28
Min 3.28 Max 33.6
Step 100
800C, 20s-1
Strain rate Effective ((mm/mm)/sec)
42.0 37.3 32.5 27.7 23.0 18.2 13.4 8.68 3.92
Min 3.92 Max 42.0
Step 175
800C, 20s-1
Strain rate Effective ((mm/mm)/sec)
Min 6.68 Max 67.2

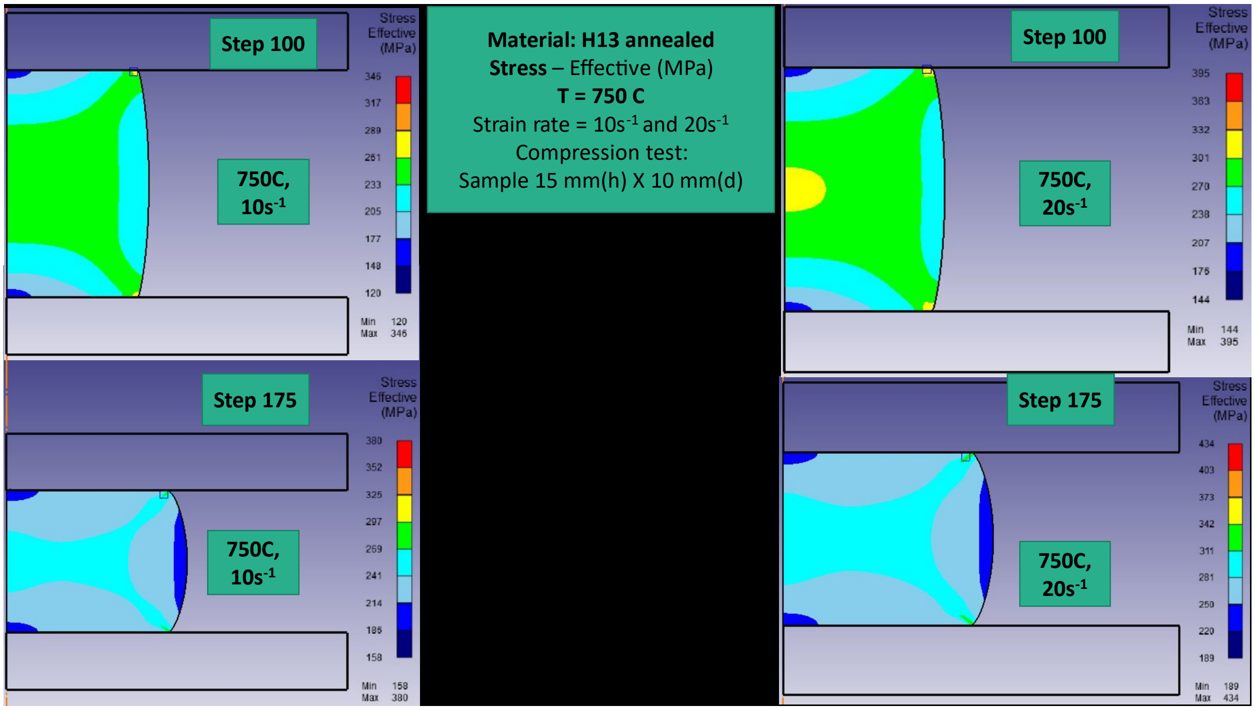

Material: H13 annealed
Stress – Effective (MPa)
T = 650 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 1s-1
Stress Effective (MPa)
222 203 183 164 144 124 105 85.4 65.9
Min 65.9 Max 222
Step 175
650C, 1s-1
Stress Effective (MPa)
245 225 206 186 167 147 127 108 88.2
Min 88.2 Max 245
Step 100
650C, 5s-1
Stress Effective (MPa)
302 277 252 227 201 176 151 126 100
Min 100 Max 302
Step 175
650C, 5s-1
Stress Effective (MPa)
333 308 283 258 233 208 183 158 133
Min 133 Max 333


Material: H13 annealed
Stress – Effective (MPa)
T = 650 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 10s-1
Stress Effective (MPa)
346 317 289 261 233 205 177 148 120
Min 120 Max 346
Step 175
650C, 10s-1
Stress Effective (MPa)
380 352 325 297 269 241 214 186 158
Min 158 Max 380
Step 100
650C, 20s-1
Stress Effective (MPa)
395 363 332 301 270 238 207 176 144
Min 144 Max 395
Step 175
650C, 20s-1
Stress Effective (MPa)
434 403 373 342 311 281 250 220 189
Min 189 Max 434

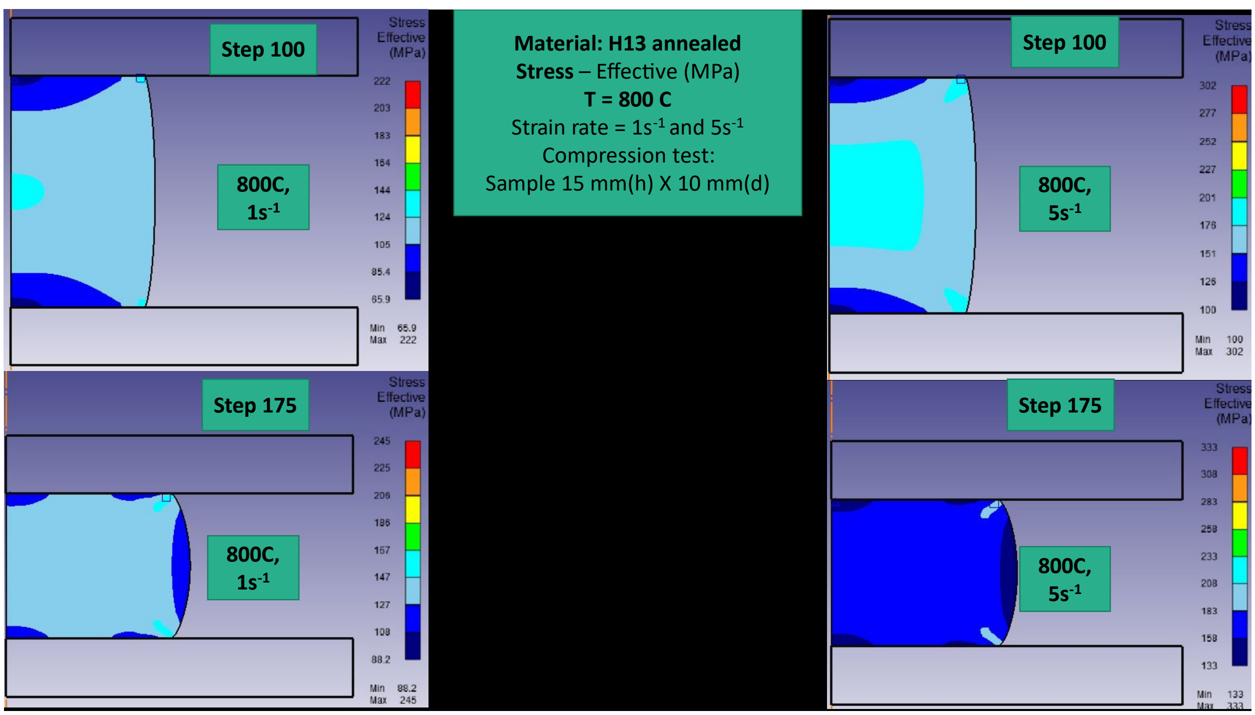

Material: H13 annealed
Stress – Effective (MPa)
T = 700 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 1s-1
Stress Effective (MPa)
222 203 183 164 144 124 105 85.4 65.9
Min 65.9 Max 222
Step 175
700C, 1s-1
Stress Effective (MPa)
245 225 206 186 167 147 127 108 88.2
Min 88.2 Max 245
Step 100
700C, 5s-1
Stress Effective (MPa)
302 277 252 227 201 176 151 126 100
Min 100 Max 302
Step 175
700C, 5s-1
Stress Effective (MPa)
333 308 283 258 233 208 183 158 133
Min 133 Max 333


Material: H13 annealed
Stress – Effective (MPa)
T = 700 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 10s-1
Step 175
700C, 10s-1
Step 100
700C, 20s-1
Step 175
700C, 20s-1
Stress Effective (MPa)

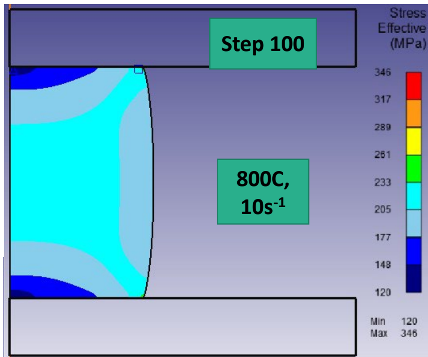

Material: H13 annealed
Stress – Effective (MPa)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 1s-1
Step 175
750C, 1s-1
Step 100
750C, 5s-1
Step 175
750C, 5s-1
Stress Effective (MPa)



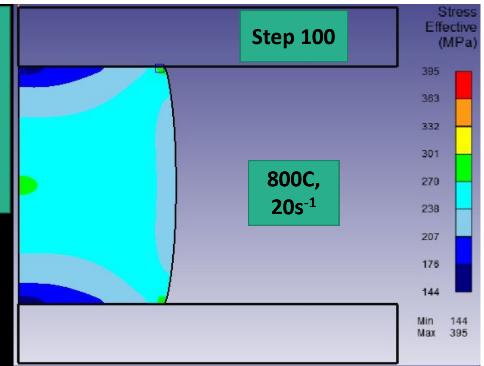
Material: H13 annealed
Stress – Effective (MPa)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Step 175
750C, 10s-1
Step 100
750C, 20s-1
Step 175
750C, 20s-1
Stress Effective (MPa)

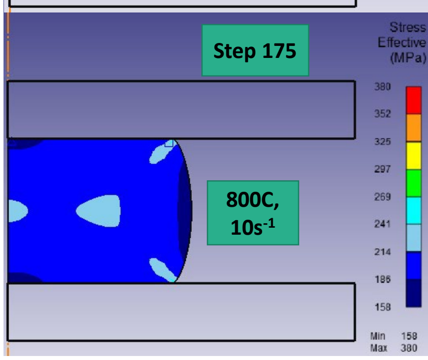


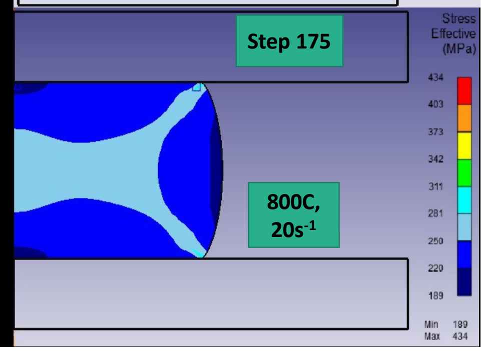
Material: H13 annealed
Stress – Effective (MPa)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Step 175
800C, 1s-1
Step 100
800C, 5s-1
Step 175
800C, 5s-1
Stress Effective (MPa)



Material: H13 annealed
Stress – Effective (MPa)
T = 800 C
Strain rate = 10s^{-1} and 20s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)







Material: H13 annealed Steps of the simulations 100 of 200 and 175 of 200

Strain Rate – Effective ((mm/mm)/s)

T= 650 C	1 S^{-1} Center	1 S^{-1} Border	5 S^{-1} Center	5 S^{-1} Border	10 S^{-1} Center	10 S^{-1} Border	20 S^{-1} Center	20 S^{-1} Border
Step 100	1.9	0.92	9.39	4.56	18.7	9.11	37.3	18.2
Step 175	1.45	0.68	7.3	3.5	15.5	7.05	29.4	14.2
T= 700 C								
Step 100	1.65	0.91	8.19	4.56	16.3	9.11	32.5	18.2
Step 175	1.45	1.07	7.3	2.52	14.5	7.06	29.4	14.2
T= 750 C								
Step 100	1.66	0.91	8.19	4.56	16.3	9.11	32.5	18.2
Step 175	1.45	1.07	7.3	3.5	14.6	7.06	29.4	14.2
T= 800 C								
Step 100	1.66	0.91	8.19	4.56	16.3	9.11	32.5	18.2
Step 175	1.45	0.69	7.3	3.5	14.6	7.06	29.4	14.2

Strain – Effective (mm/mm)

T= 650 C	1 S^{-1} Center	1 S^{-1} Border	5 S^{-1} Center	5 S^{-1} Border	10 S^{-1} Center	10 S^{-1} Border	20 S^{-1} Center	20 S^{-1} Border
Step 100	0.6	0.45	0.59	0.45	0.59	0.45	0.59	0.45
Step 175	1.33	0.77	1.33	0.77	1.33	0.77	1.33	0.77
T= 700 C								
Step 100	0.6	0.45	0.59	0.45	0.59	0.45	0.59	0.45
Step 175	1.33	0.77	1.33	0.77	1.33	0.77	1.33	0.77
T= 750 C								
Step 100	0.6	0.46	0.66	0.45	0.59	0.45	0.59	0.45
Step 175	1.19	0.77	1.33	0.77	1.33	0.77	1.33	0.77
T= 800 C								
Step 100	0.53	0.46	0.66	0.45	0.52	0.45	0.59	0.45
Step 175	1.19	0.77	1.19	0.77	1.19	0.77	1.19	0.77

Stress – Effective (MPa)

T= 650 C	1 S^{-1} Center	1 S^{-1} Border	5 S^{-1} Center	5 S^{-1} Border	10 S^{-1} Center	10 S^{-1} Border	20 S^{-1} Center	20 S^{-1} Border
Step 100	222	183	302	252	345	289	395	332
Step 175	205	185	283	258	325	297	373	311
T= 700 C								
Step 100	183	154	277	227	317	251	383	301
Step 175	185	157	258	233	297	269	342	311
T= 750 C								
Step 100	164	144	227	201	261	233	332	270
Step 175	147	127	233	183	269	214	311	250
T= 800 C								
Step 100	144	124	201	176	233	205	301	238
Step 175	127	108	183	158	241	214	281	220

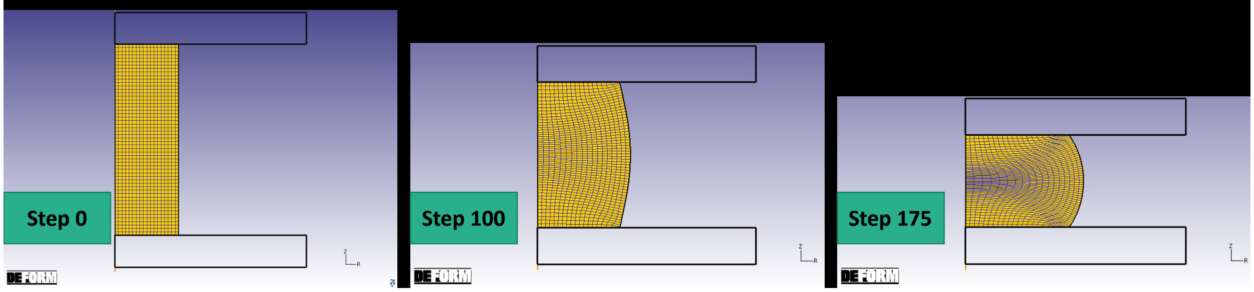
Slides 32 to 55

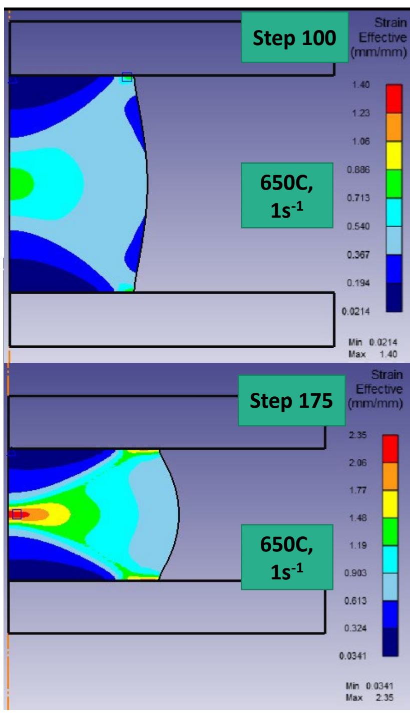
Material: H13 Hardened;

Parameters to be evaluated: Strain-Effective (mm/mm), Strain Rate-Effective ((mm/mm)/s), and Stress-Effective (MPa);

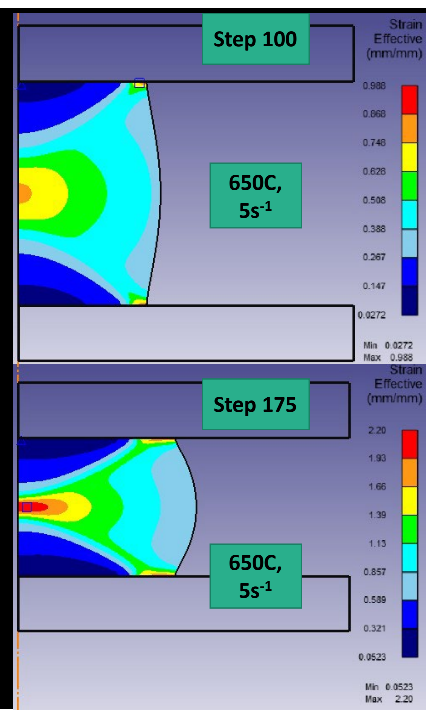
For the following slides, the temperatures used were 650 C, 700 C, 750 C and 800 C, and the strain rates used were $1s^{-1}$, $5s^{-1}$, $10s^{-1}$ and $20s^{-1}$. The flow stress curves came from Gleeble compression test).

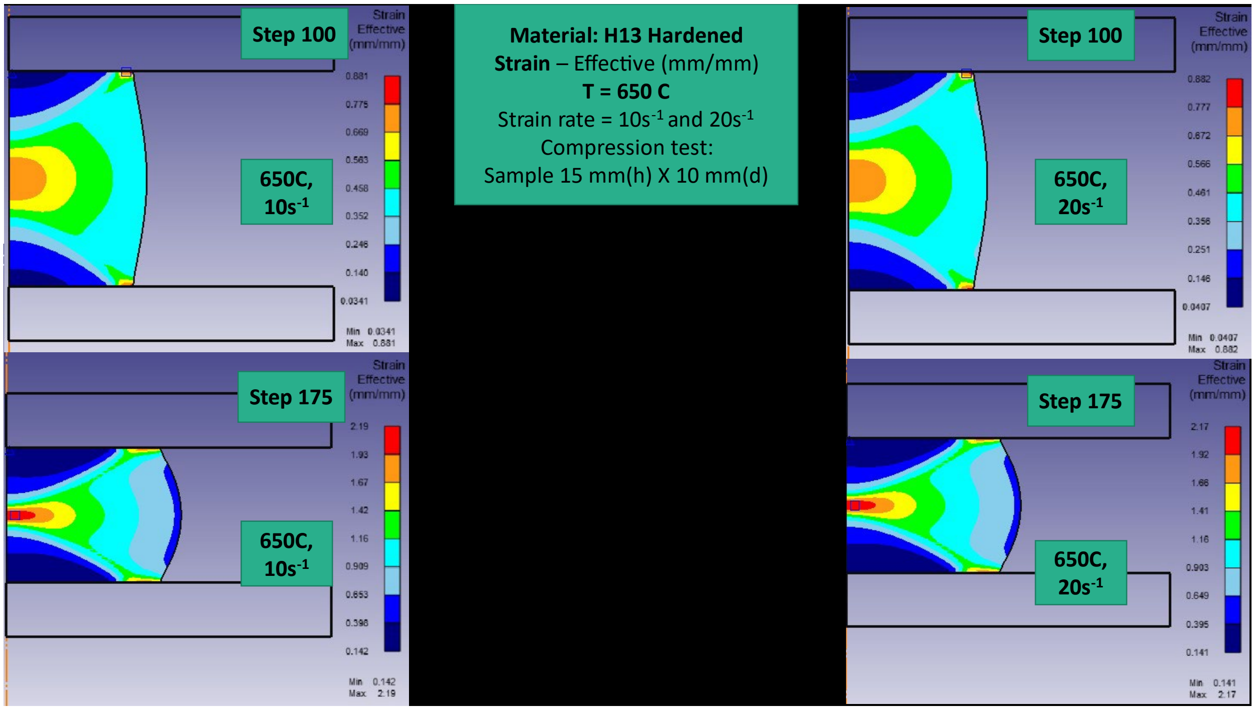
Considering 200 steps of simulation, the steps evaluated were step 100 and step 175, which are appropriate to check for the properties in specific point of the deformation.

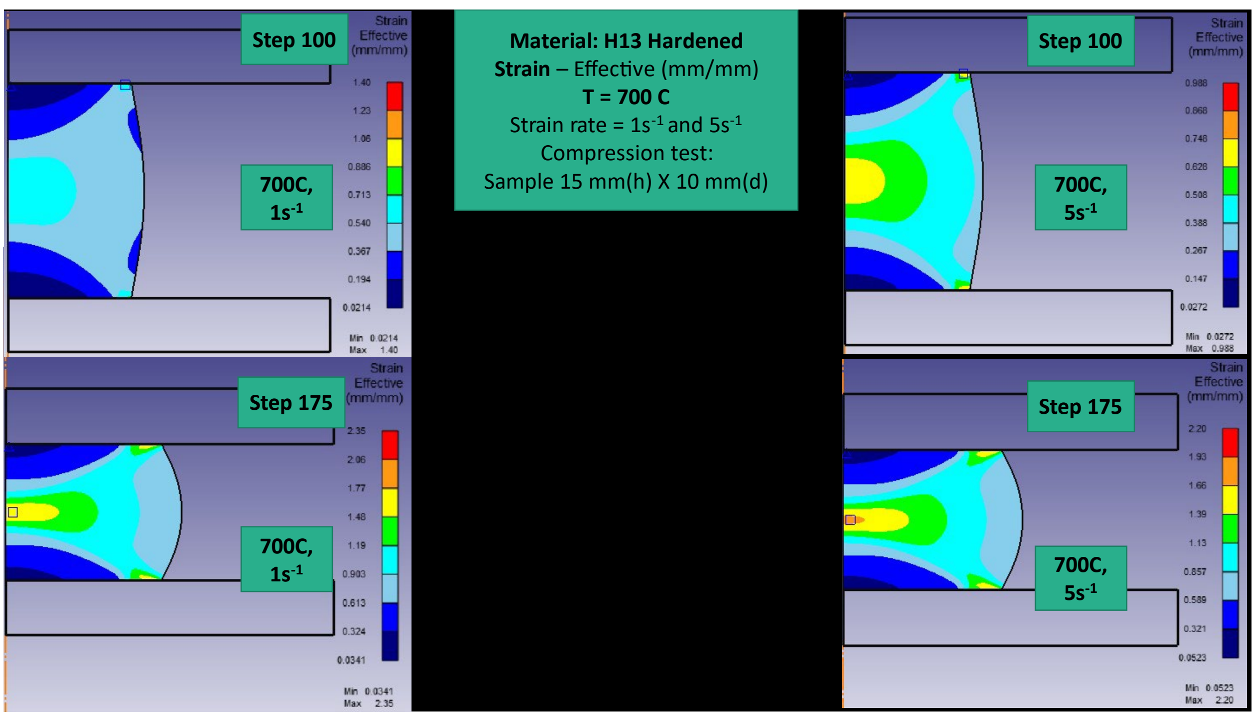


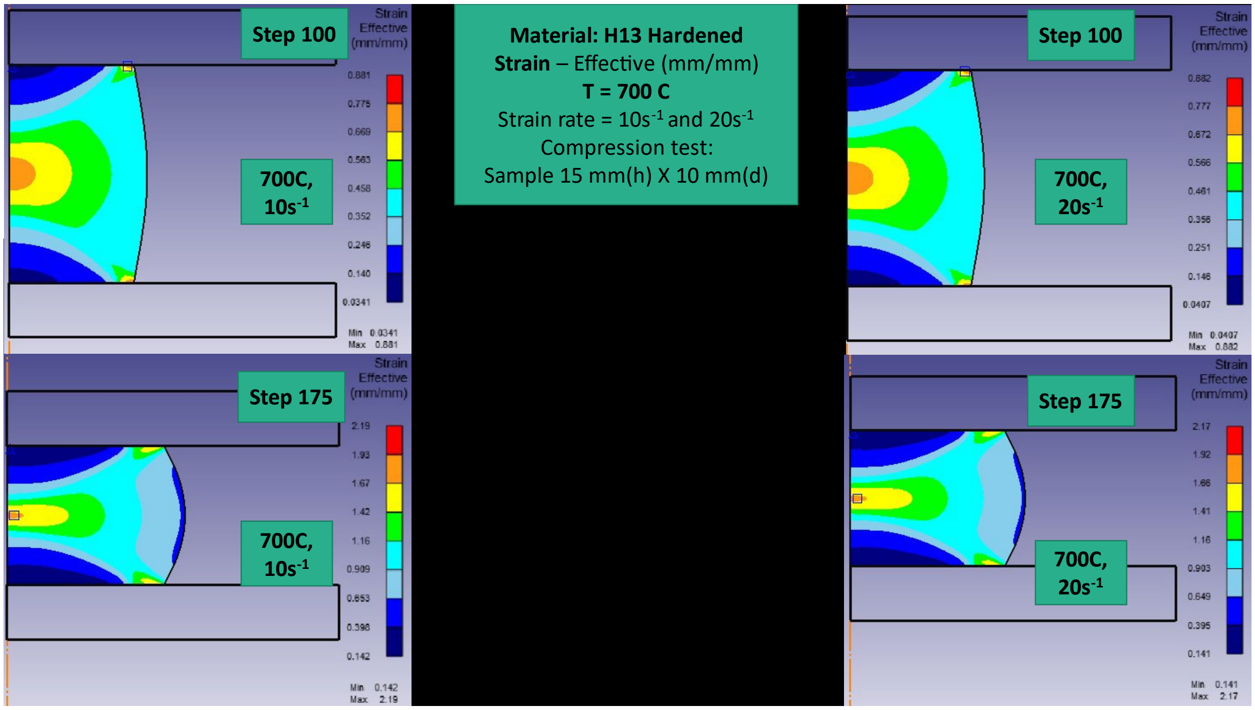


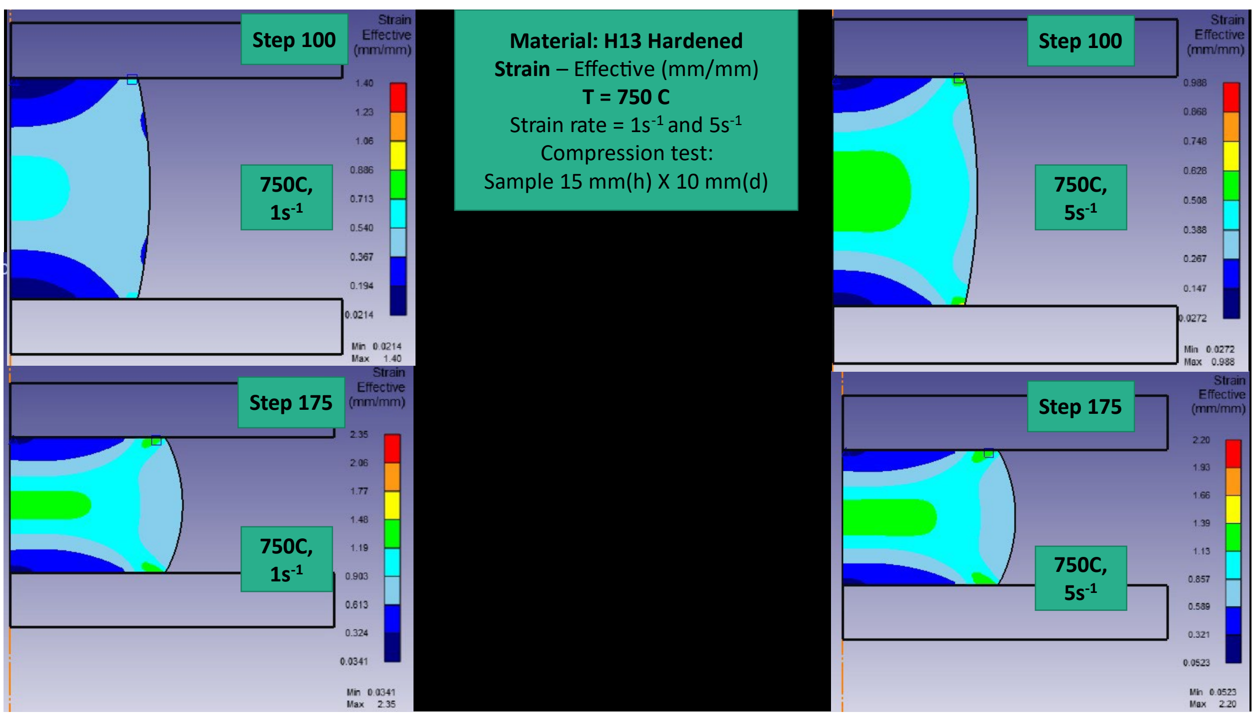
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 650 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)

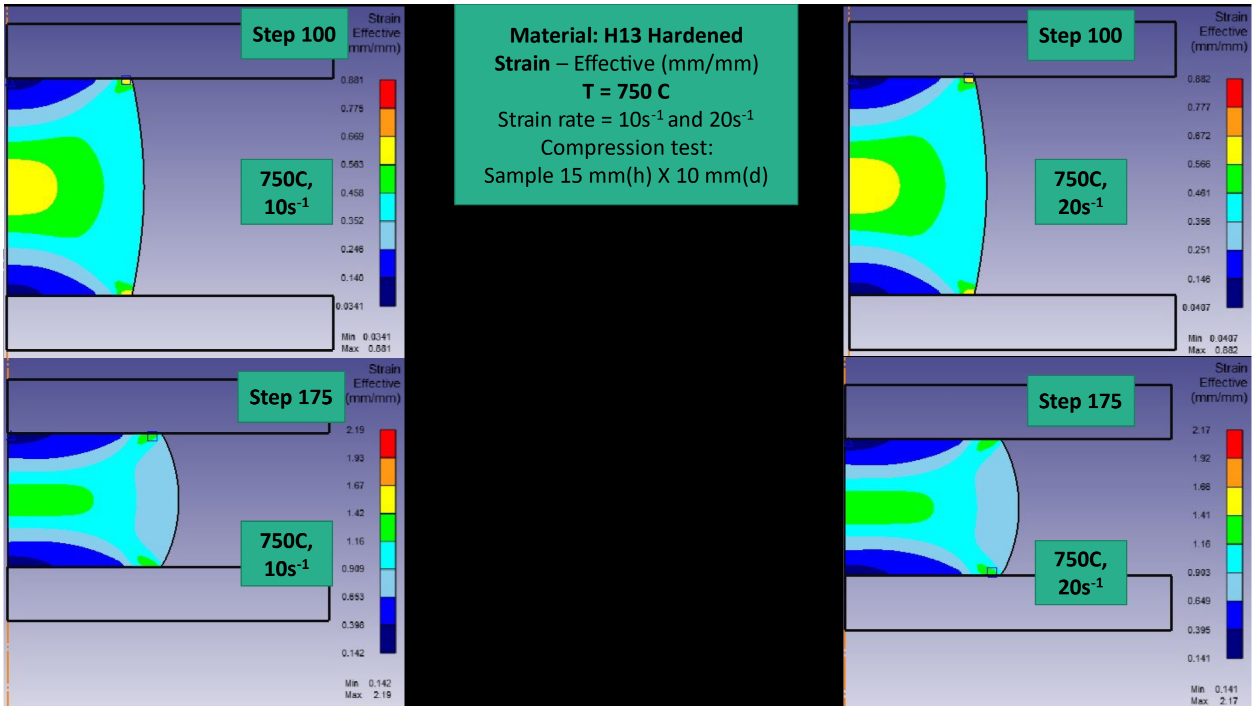



Step 100
650C, $10s^{-1}$
Step 175
650C, $10s^{-1}$
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 650 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, $20s^{-1}$
Step 175
650C, $20s^{-1}$
Strain
Effective
(mm/mm)

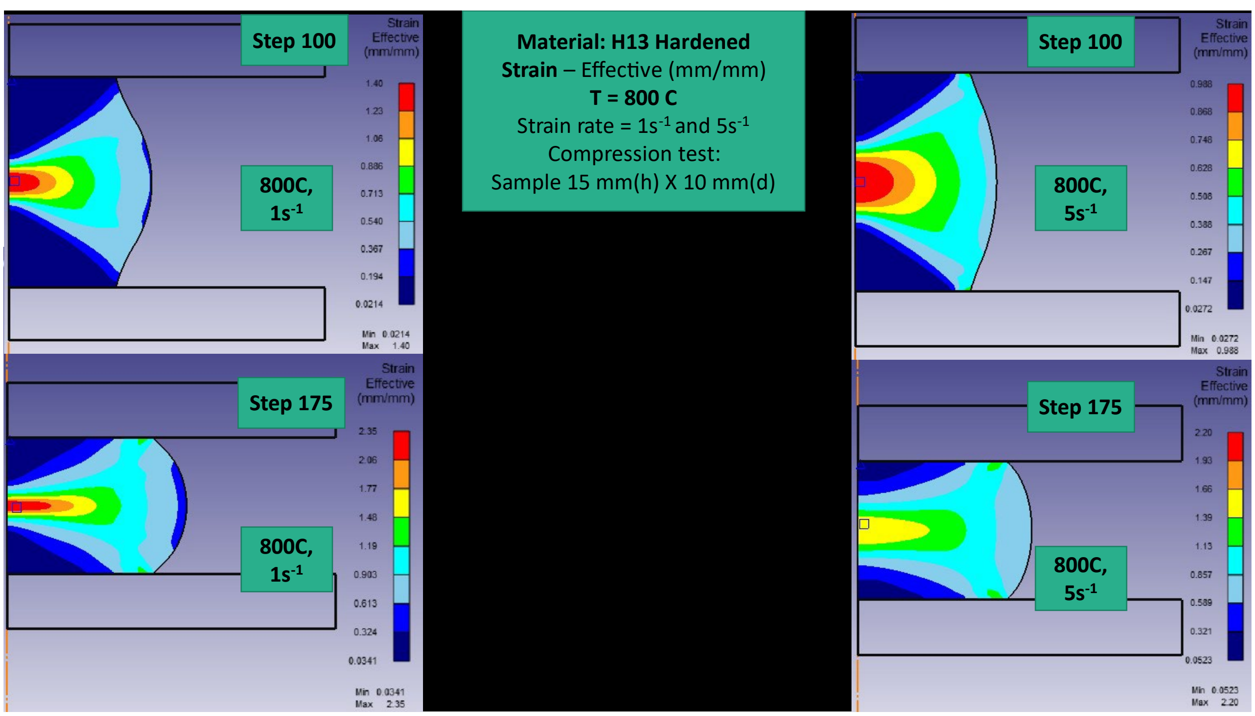

Step 100
700C, $1s^{-1}$
Step 175
700C, $1s^{-1}$
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 700 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, $5s^{-1}$
Step 175
700C, $5s^{-1}$
Strain
Effective
(mm/mm)


Step 100
Strain
Effective
(mm/mm)
700C, 10s-1
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 700 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 20s-1
Step 175
700C, 10s-1
Step 175
700C, 20s-1

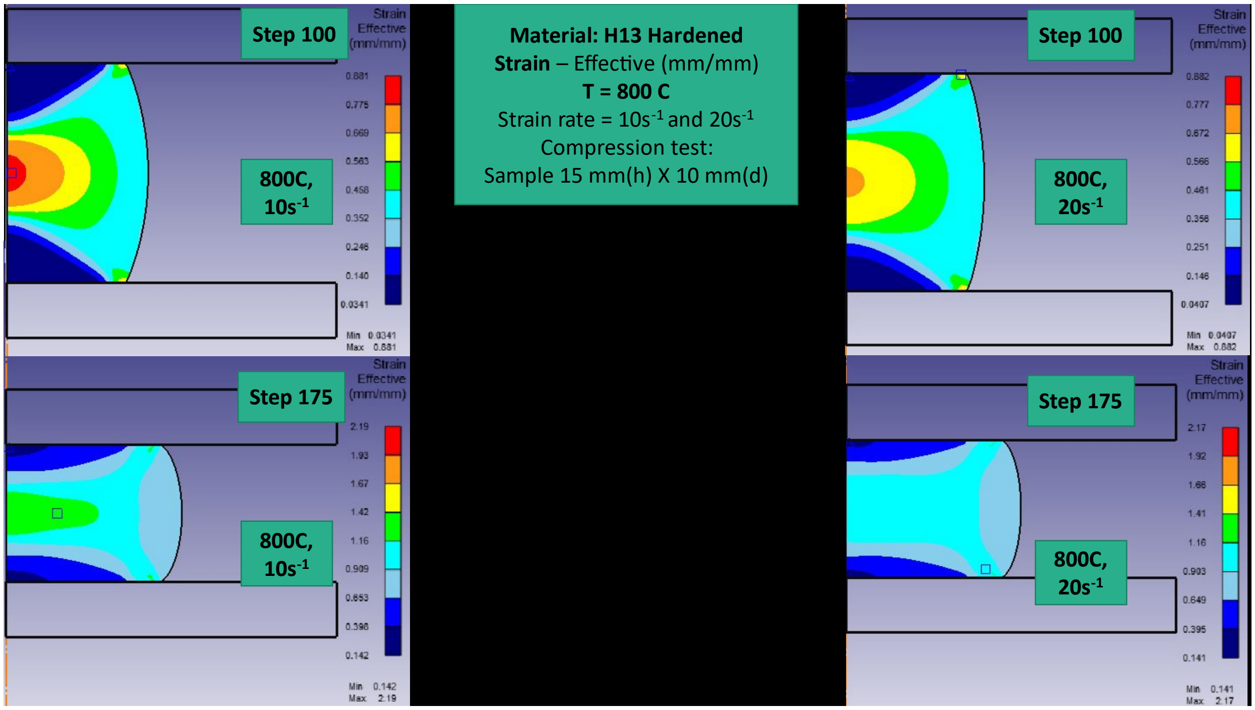

Step 100
Strain
Effective
(mm/mm)
750C, 1s-1
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 5s-1
Step 175
750C, 1s-1
Step 175
750C, 5s-1



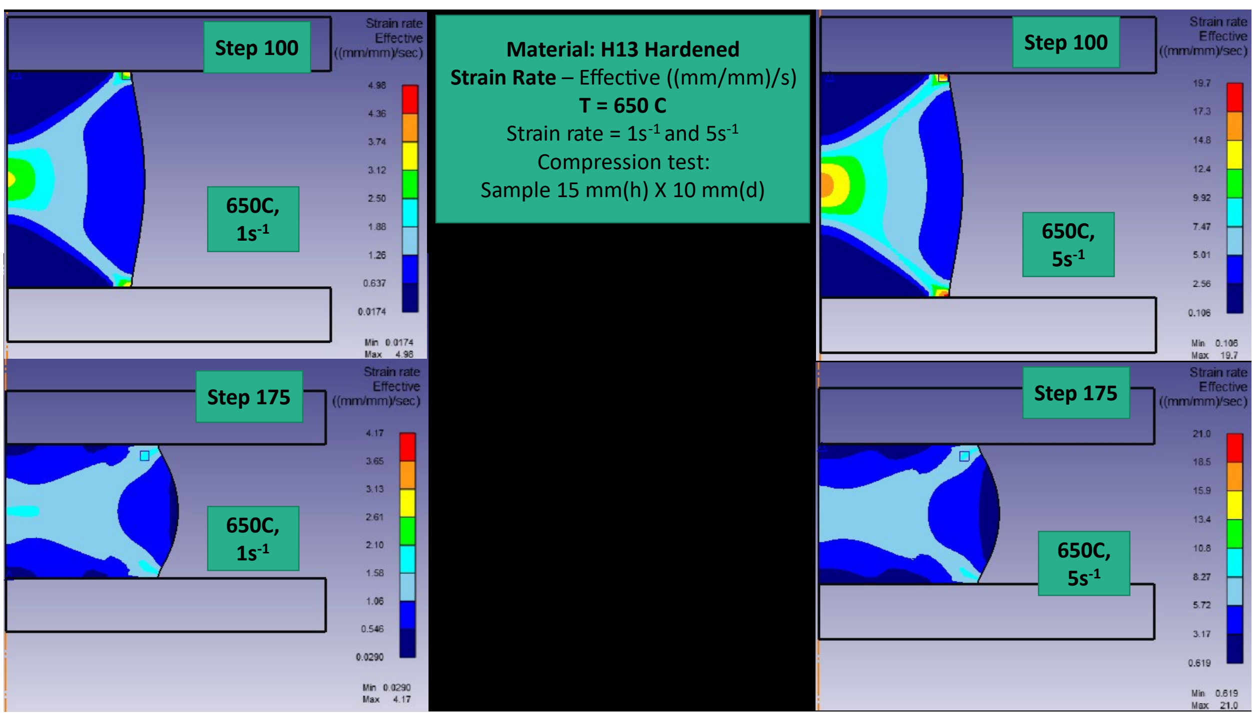
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Step 175
750C, 10s-1
Step 100
750C, 20s-1
Step 175
750C, 20s-1
Strain Effective (mm/mm)



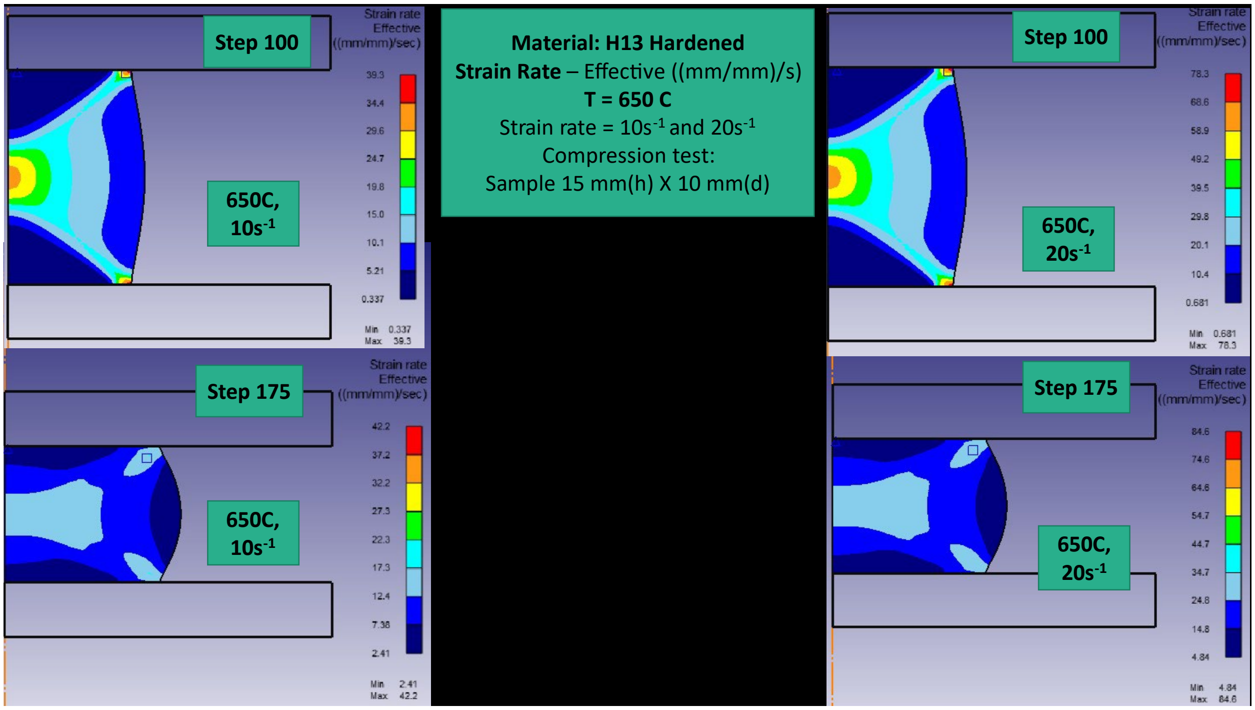
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Step 175
800C, 1s-1
Step 100
800C, 5s-1
Step 175
800C, 5s-1
Strain Effective (mm/mm)

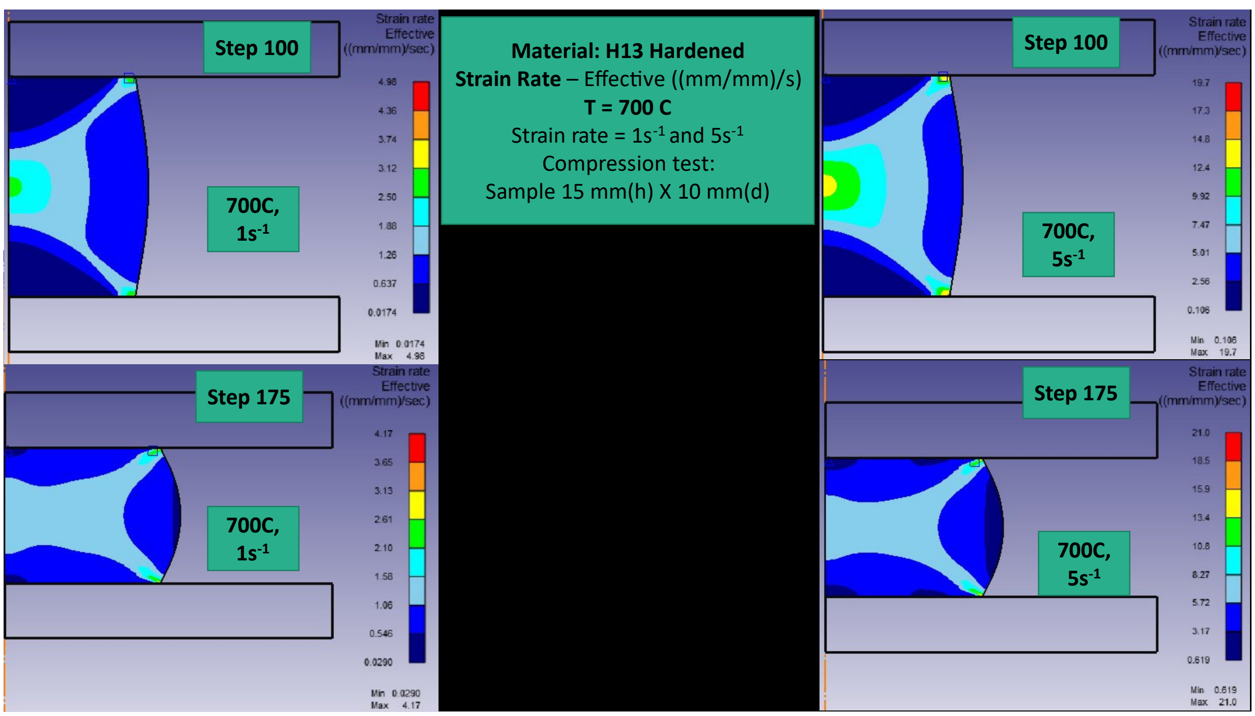


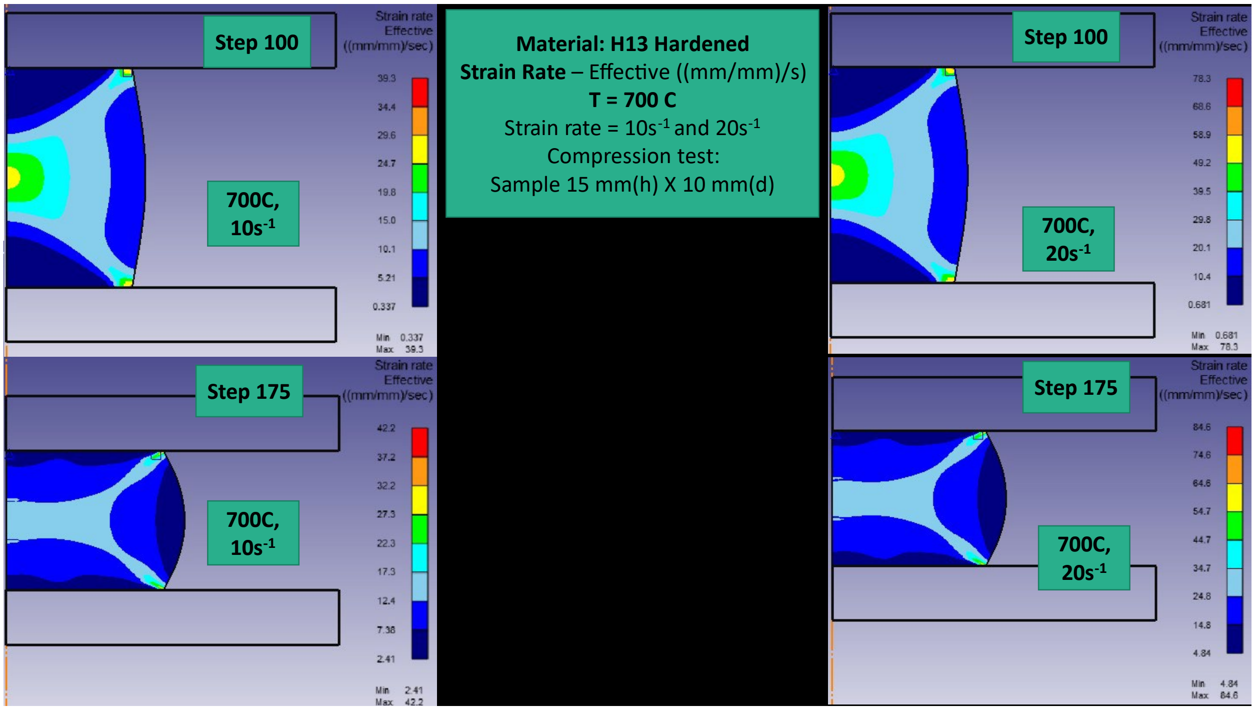
Material: H13 Hardened
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Strain Effective (mm/mm)
0.881 0.775 0.669 0.563 0.458 0.352 0.246 0.140 0.0341
Min 0.0341 Max 0.881
Step 100
800C, 20s-1
Strain Effective (mm/mm)
0.882 0.777 0.672 0.566 0.461 0.356 0.251 0.146 0.0407
Min 0.0407 Max 0.882
Step 175
800C, 10s-1
Strain Effective (mm/mm)
2.19 1.93 1.67 1.42 1.16 0.909 0.653 0.398 0.142
Min 0.142 Max 2.19
Step 175
800C, 20s-1
Strain Effective (mm/mm)
2.17 1.92 1.66 1.41 1.16 0.903 0.649 0.395 0.141
Min 0.141 Max 2.17

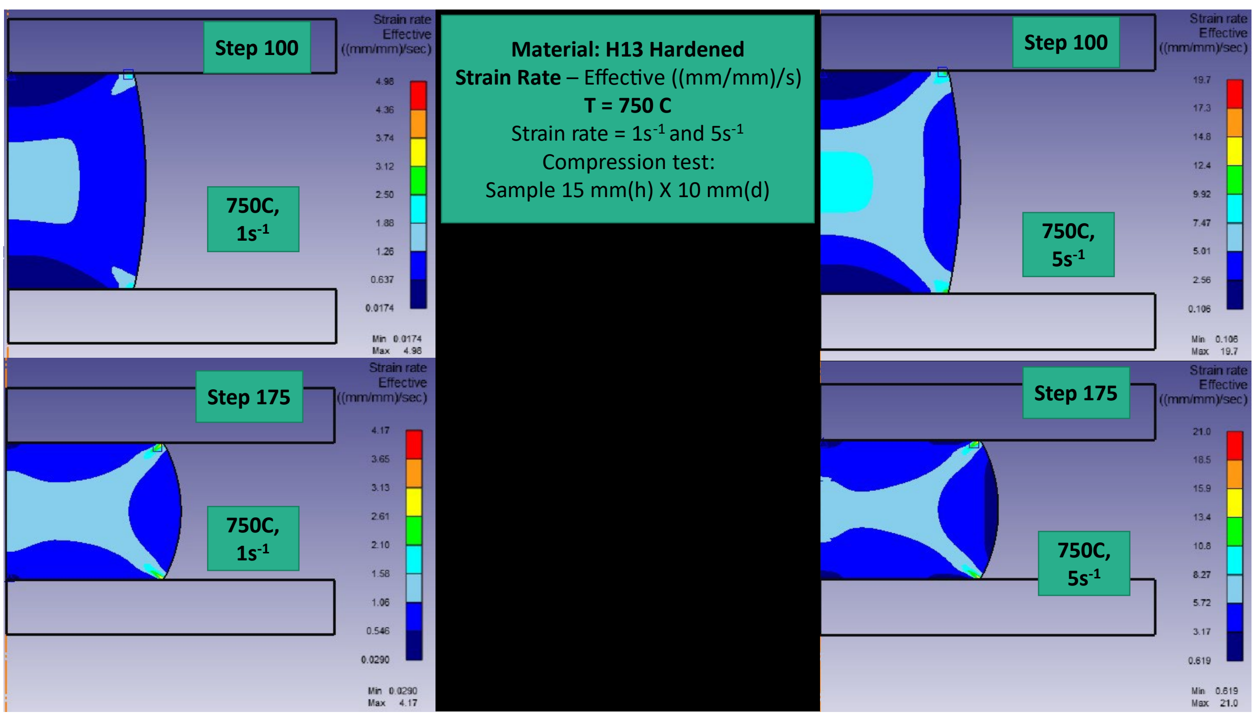


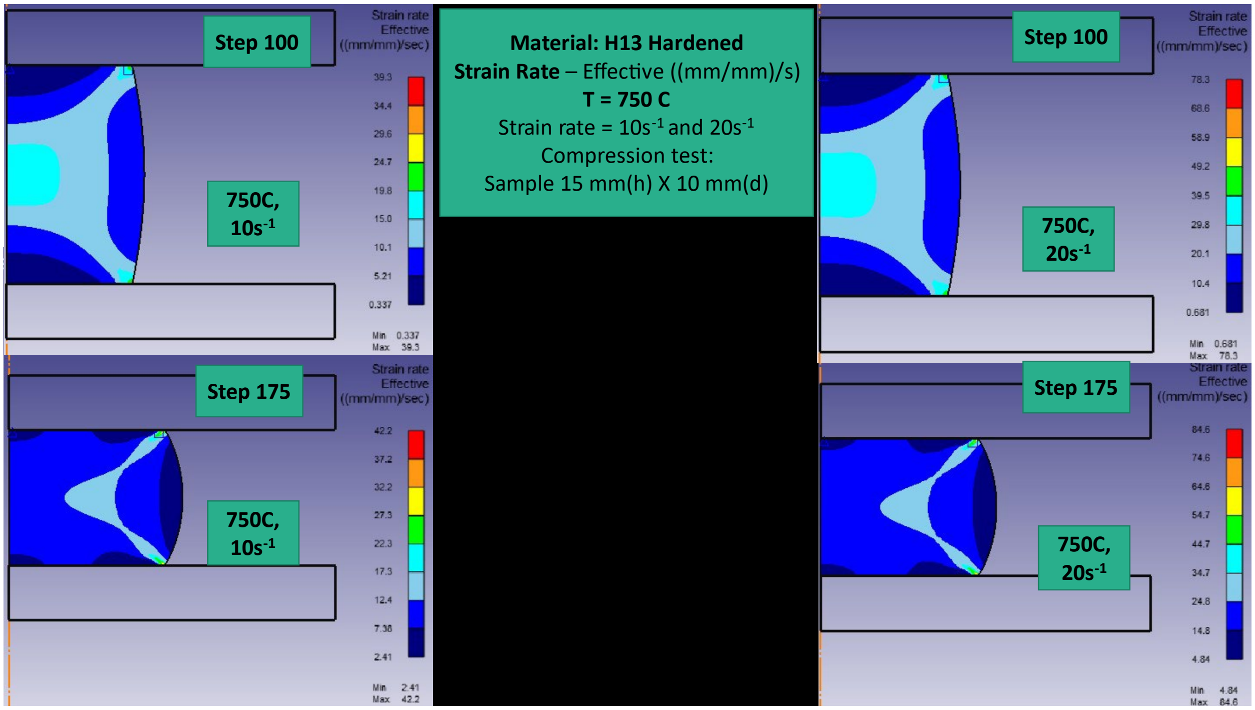
Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 650 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 1s-1
Strain rate Effective ((mm/mm)/sec)
4.98 4.36 3.74 3.12 2.50 1.88 1.26 0.637 0.0174
Min 0.0174 Max 4.98
Step 100
650C, 5s-1
Strain rate Effective ((mm/mm)/sec)
19.7 17.3 14.8 12.4 9.92 7.47 5.01 2.56 0.106
Min 0.106 Max 19.7
Step 175
650C, 1s-1
Strain rate Effective ((mm/mm)/sec)
4.17 3.65 3.13 2.61 2.10 1.58 1.06 0.546 0.0290
Min 0.0290 Max 4.17
Step 175
650C, 5s-1
Strain rate Effective ((mm/mm)/sec)
21.0 18.5 15.9 13.4 10.8 8.27 5.72 3.17 0.619
Min 0.619 Max 21.0

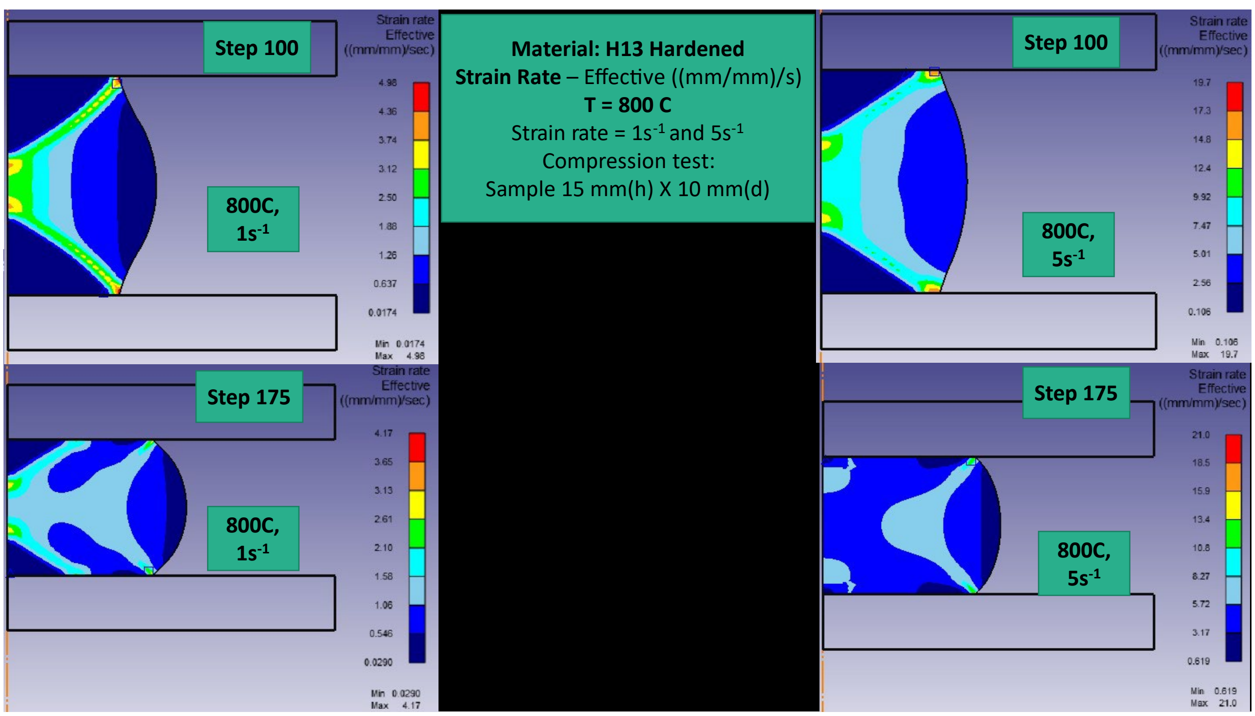

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 650 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, 10s-1
Step 175
650C, 10s-1
Step 100
650C, 20s-1
Step 175
650C, 20s-1
Strain rate
Effective
((mm/mm)/sec)

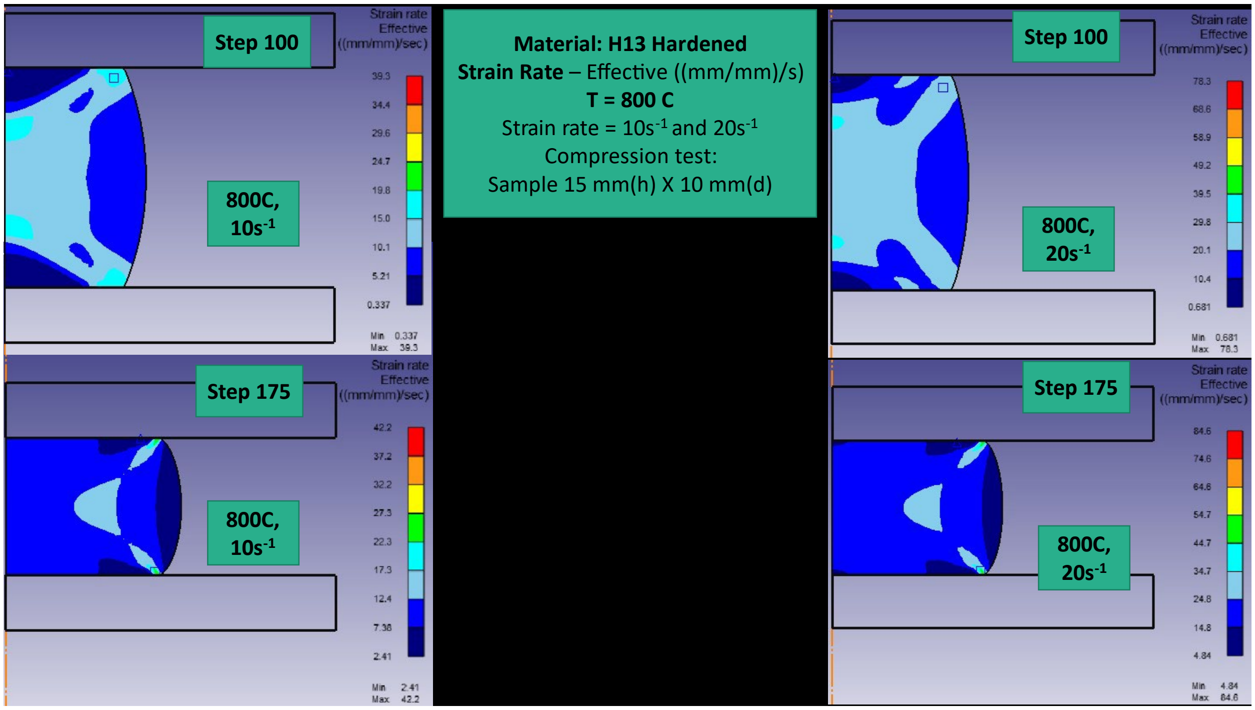

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 700 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 1s-1
Step 175
700C, 1s-1
Step 100
700C, 5s-1
Step 175
700C, 5s-1
Strain rate
Effective
((mm/mm)/sec)

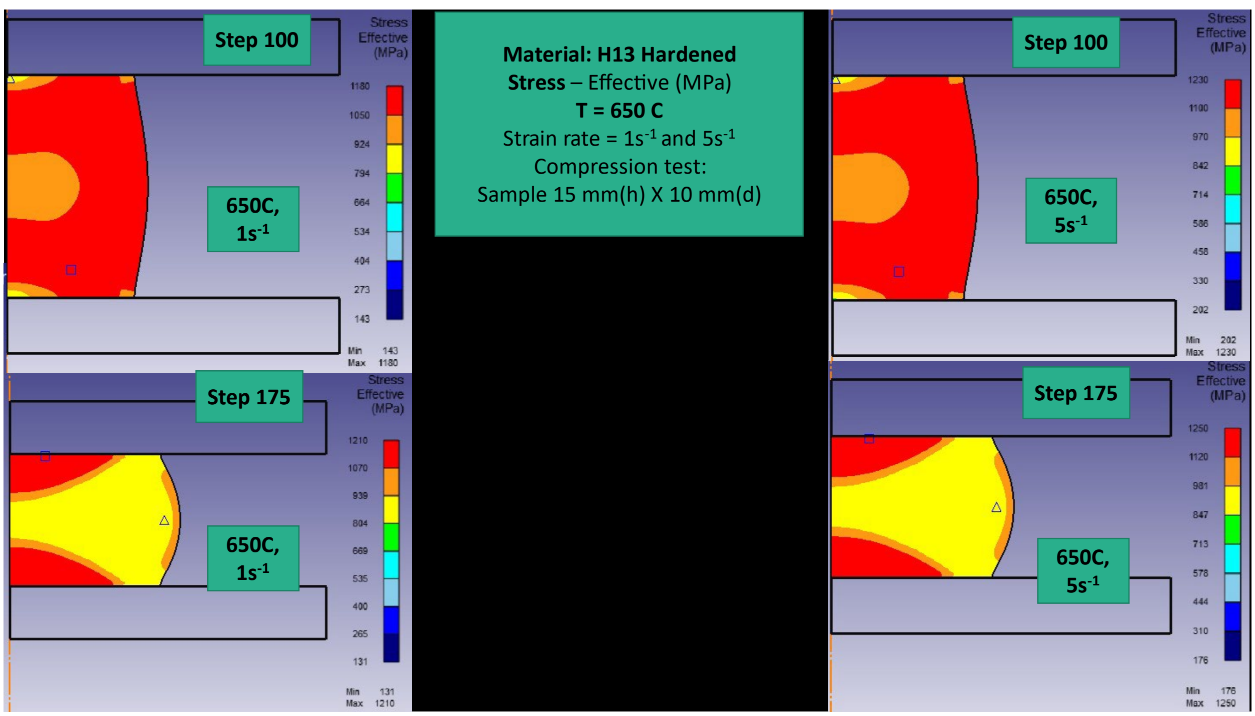

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 700 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 10s-1
Strain rate Effective ((mm/mm)/sec)
39.3 34.4 29.6 24.7 19.8 15.0 10.1 5.21 0.337
Min 0.337 Max 39.3
Step 175
700C, 10s-1
Strain rate Effective ((mm/mm)/sec)
42.2 37.2 32.2 27.3 22.3 17.3 12.4 7.36 2.41
Min 2.41 Max 42.2
Step 100
700C, 20s-1
Strain rate Effective ((mm/mm)/sec)
78.3 68.6 58.9 49.2 39.5 29.8 20.1 10.4 0.681
Min 0.681 Max 78.3
Step 175
700C, 20s-1
Strain rate Effective ((mm/mm)/sec)
84.6 74.6 64.6 54.7 44.7 34.7 24.8 14.8 4.84
Min 4.84 Max 84.6

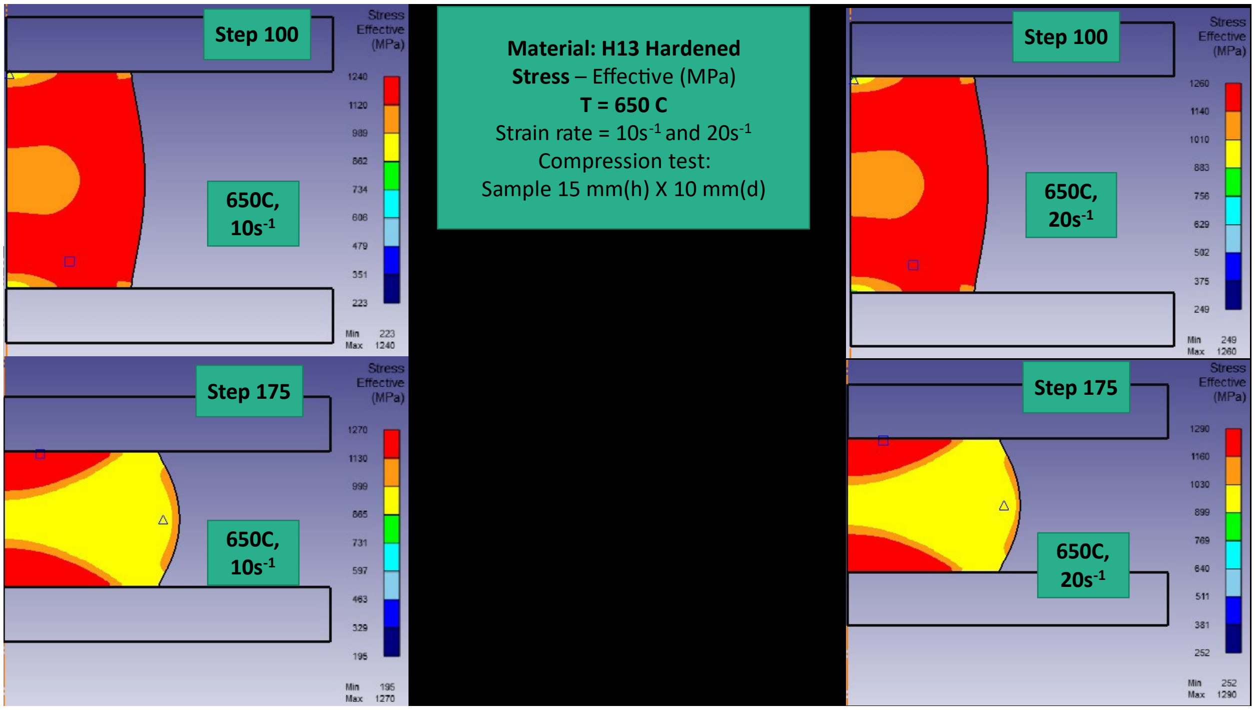

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 1s-1
Strain rate Effective ((mm/mm)/sec)
4.98 4.36 3.74 3.12 2.50 1.88 1.26 0.637 0.0174
Min 0.0174 Max 4.98
Step 175
750C, 1s-1
Strain rate Effective ((mm/mm)/sec)
4.17 3.65 3.13 2.61 2.10 1.58 1.06 0.546 0.0290
Min 0.0290 Max 4.17
Step 100
750C, 5s-1
Strain rate Effective ((mm/mm)/sec)
19.7 17.3 14.8 12.4 9.92 7.47 5.01 2.56 0.106
Min 0.106 Max 19.7
Step 175
750C, 5s-1
Strain rate Effective ((mm/mm)/sec)
21.0 18.5 15.9 13.4 10.8 8.27 5.72 3.17 0.619
Min 0.619 Max 21.0

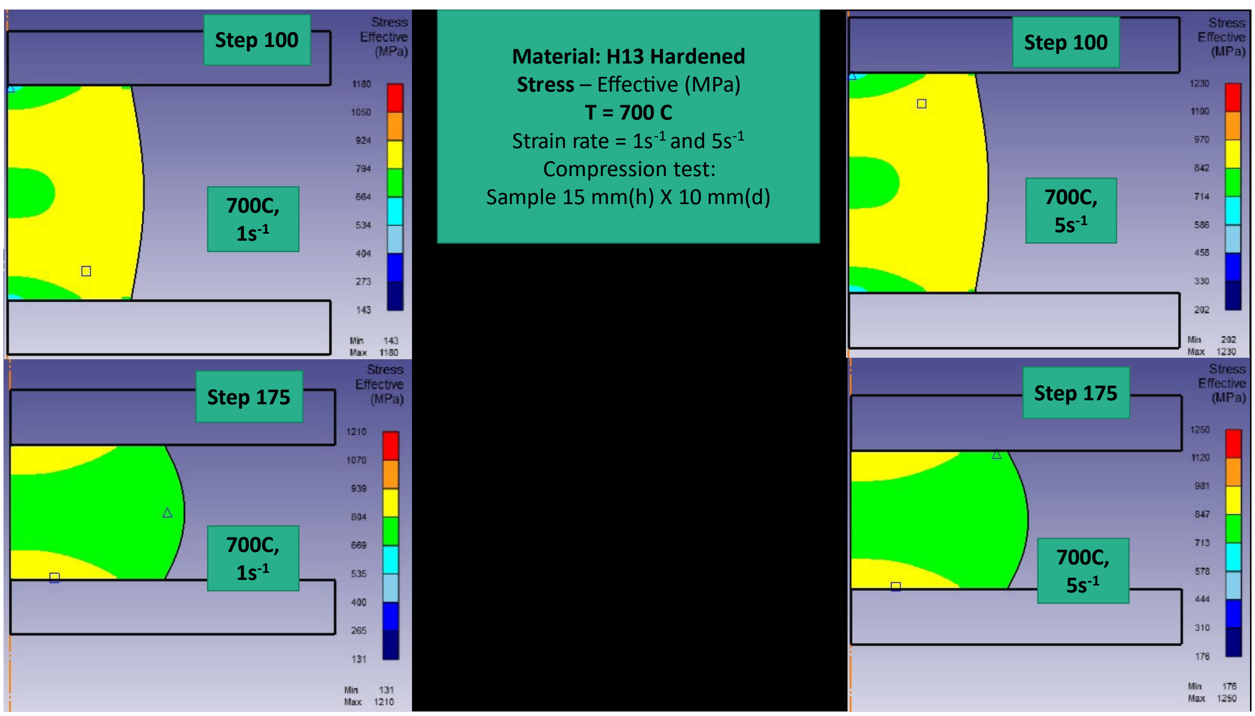

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Step 175
750C, 10s-1
Step 100
750C, 20s-1
Step 175
750C, 20s-1
Strain rate Effective ((mm/mm)/sec)

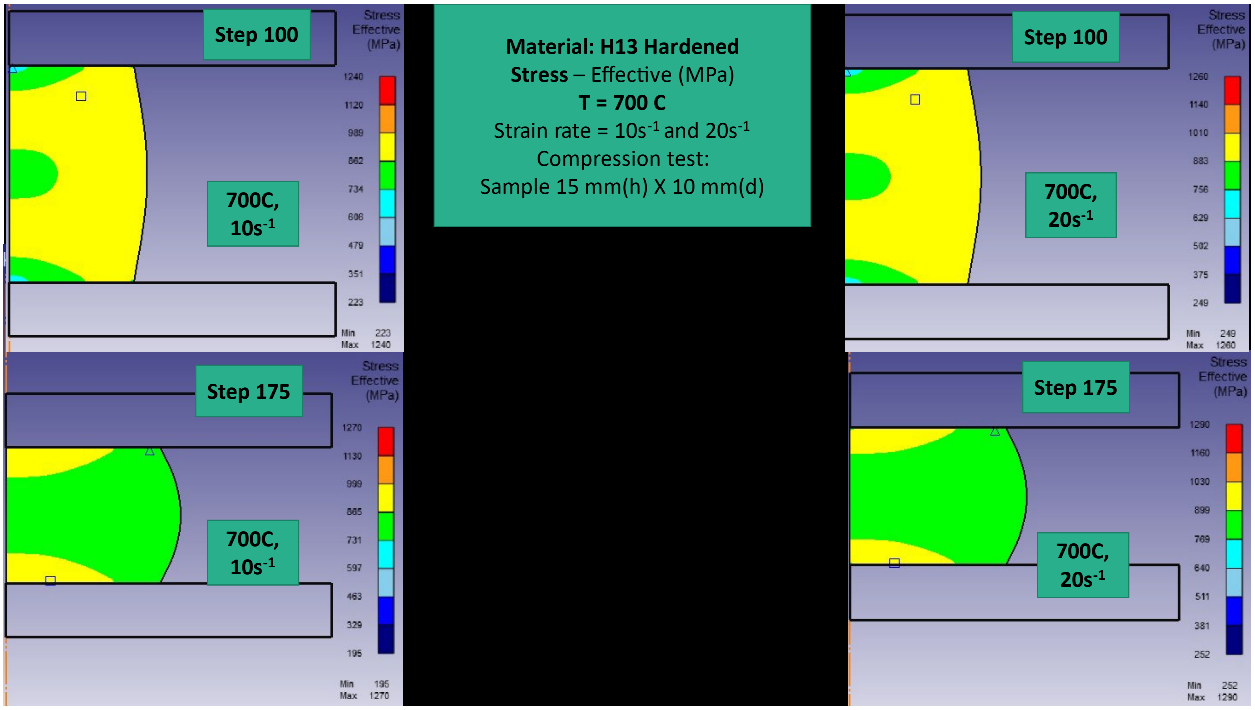

Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Step 175
800C, 1s-1
Step 100
800C, 5s-1
Step 175
800C, 5s-1
Strain rate Effective ((mm/mm)/sec)

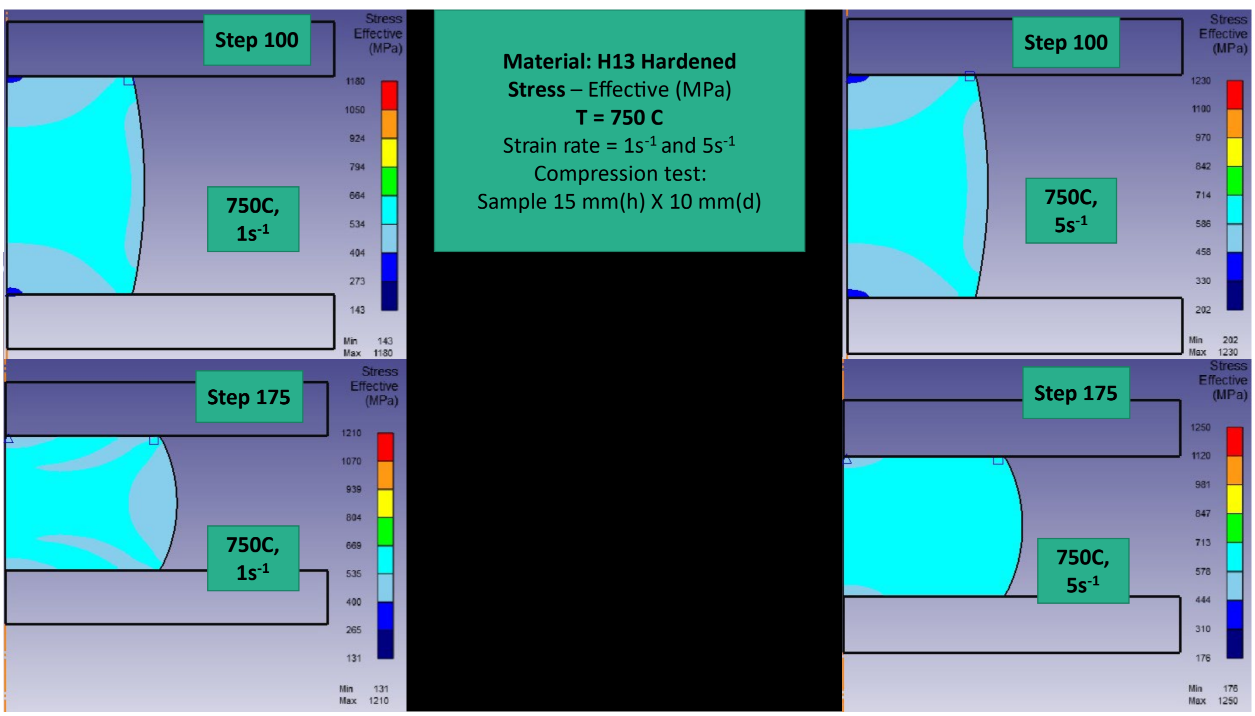

Step 100
Strain rate
Effective
((mm/mm)/sec)
800C,
10s-1
Material: H13 Hardened
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C,
20s-1
Step 175
800C,
10s-1
Step 175
800C,
20s-1

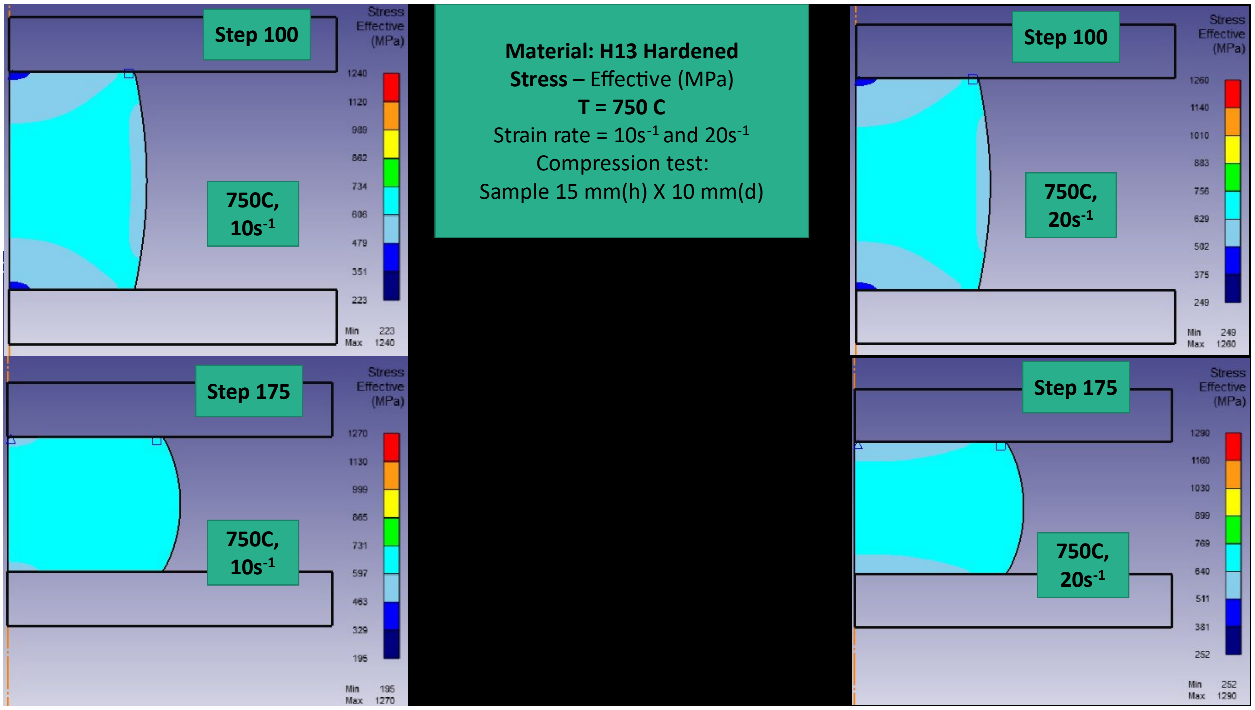

Step 100
Stress
Effective
(MPa)
650C,
1s-1
Material: H13 Hardened
Stress – Effective (MPa)
T = 650 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C,
5s-1
Step 175
650C,
1s-1
Step 175
650C,
5s-1

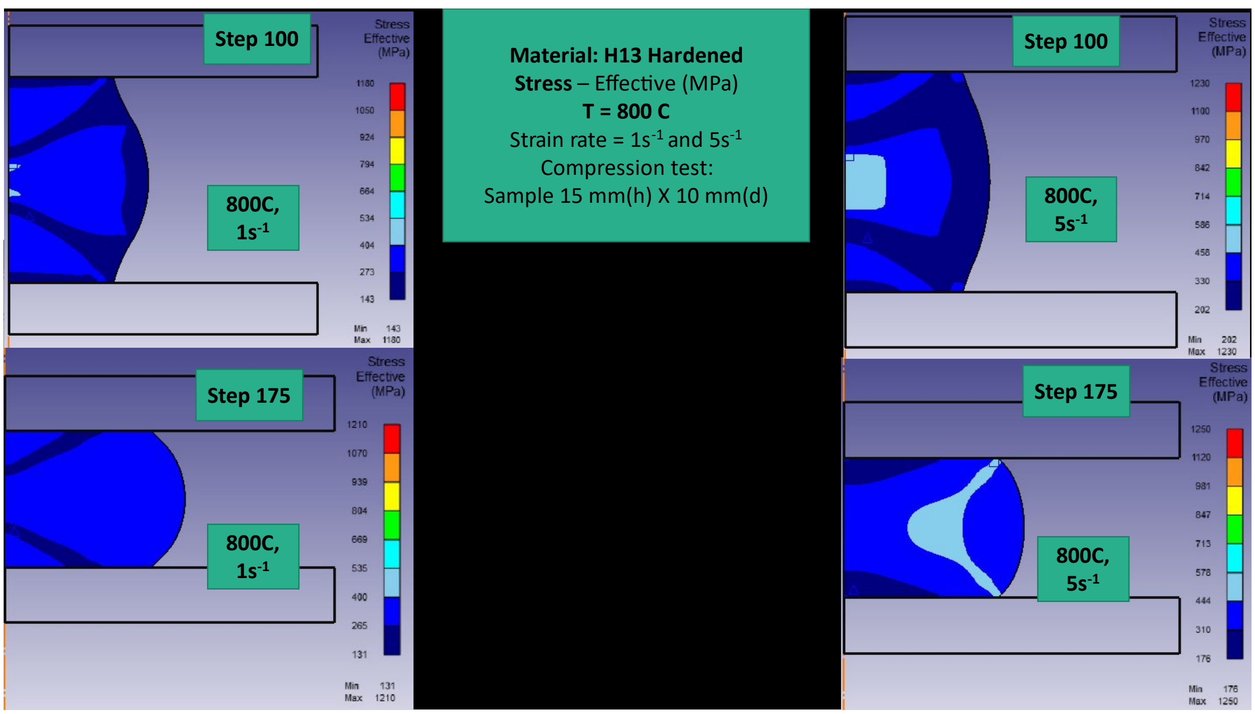

Step 100
650C, $10s^{-1}$
Step 175
650C, $10s^{-1}$
Material: H13 Hardened
Stress – Effective (MPa)
T = 650 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
650C, $20s^{-1}$
Step 175
650C, $20s^{-1}$
Stress Effective (MPa)

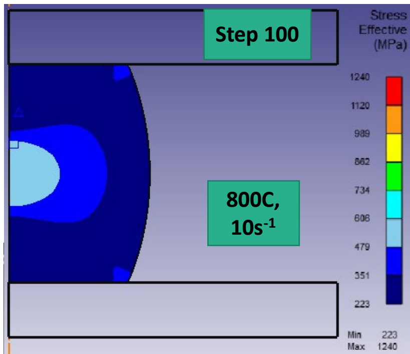

Step 100
700C, $1s^{-1}$
Step 175
700C, $1s^{-1}$
Material: H13 Hardened
Stress – Effective (MPa)
T = 700 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, $5s^{-1}$
Step 175
700C, $5s^{-1}$
Stress Effective (MPa)


Step 100
Stress Effective (MPa)
700C, 10s-1
Material: H13 Hardened
Stress – Effective (MPa)
T = 700 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
700C, 20s-1
Step 175
700C, 10s-1
Step 175
700C, 20s-1

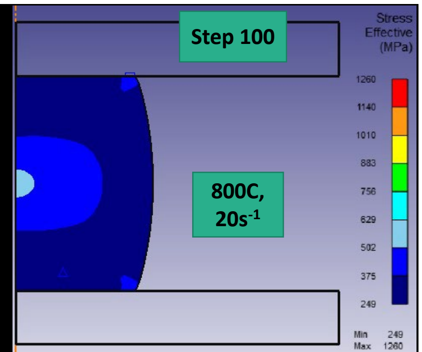

Step 100
Stress Effective (MPa)
750C, 1s-1
Material: H13 Hardened
Stress – Effective (MPa)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 5s-1
Step 175
750C, 1s-1
Step 175
750C, 5s-1

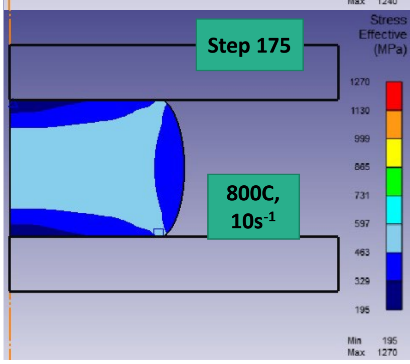

Step 100
750C, 10s-1
Material: H13 Hardened
Stress – Effective (MPa)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 20s-1
Step 175
750C, 10s-1
Step 175
750C, 20s-1
Stress Effective (MPa)

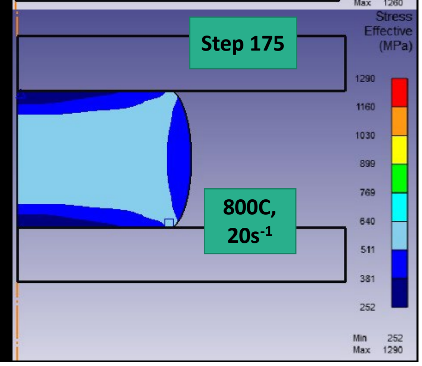

Step 100
800C, 1s-1
Material: H13 Hardened
Stress – Effective (MPa)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 5s-1
Step 175
800C, 1s-1
Step 175
800C, 5s-1
Stress Effective (MPa)



Material: H13 Hardened
Stress – Effective (MPa)
T = 800 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)







Material: H13 Hardened
Steps of the simulations 100 of 200 and 175 of 200

Strain Rate – Effective ((mm/mm)/s)

T= 650 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	1.9	0.92	9.39	4.56	18.7	9.11	37.3	18.2
Step 175	1.45	0.68	7.3	3.5	15.5	7.05	29.4	14.2
T= 700 C								
Step 100	1.65	0.91	8.19	4.56	16.3	9.11	32.5	18.2
Step 175	1.45	1.07	7.3	2.52	14.5	7.06	29.4	14.2
T= 750 C								
Step 100	1.88	1.26	9.92	5.01	19.8	10.1	39.8	20.1
Step 175	1.58	1.06	8.27	5.72	12.4	7.38	24.8	14.8
T= 800 C								
Step 100	3.12	0.63	9.92	5.01	15	10.1	29.8	20.1
Step 175	1.58	1.06	5.72	3.17	12.4	7.36	24.8	14.8

Strain – Effective (mm/mm)

T= 650 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	0.88	0.54	0.85	0.38	0.77	0.45	0.77	0.45
Step 175	2.35	0.9	2.2	0.85	2.19	0.7	2.17	0.7
T= 700 C								
Step 100	0.7	0.54	0.74	0.4	0.77	0.45	0.77	0.45
Step 175	1.77	0.7	1.9	0.85	1.9	0.9	1.75	0.9
T= 750 C								
Step 100	0.7	0.5	0.62	0.38	0.66	0.45	0.66	0.45
Step 175	1.48	0.9	1.39	0.85	1.42	0.9	1.42	0.9
T= 800 C								
Step 100	1.4	0.53	0.98	0.4	0.88	0.45	0.77	0.46
Step 175	2.35	0.65	1.65	0.85	1.4	0.9	1.16	0.9

Stress – Effective (MPa)

T= 650 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	1050	1180	1100	1230	1120	1240	1140	1260
Step 175	939	1070	981	1120	1000	1130	1030	1160
T= 700 C								
Step 100	764	924	842	970	862	989	883	1010
Step 175	804	804	847	847	865	865	899	899
T= 750 C								
Step 100	664	534	714	586	734	608	756	629
Step 175	669	535	713	713	731	731	769	769
T= 800 C								
Step 100	404	273	536	456	734	479	629	502
Step 175	400	400	444	444	597	463	640	531

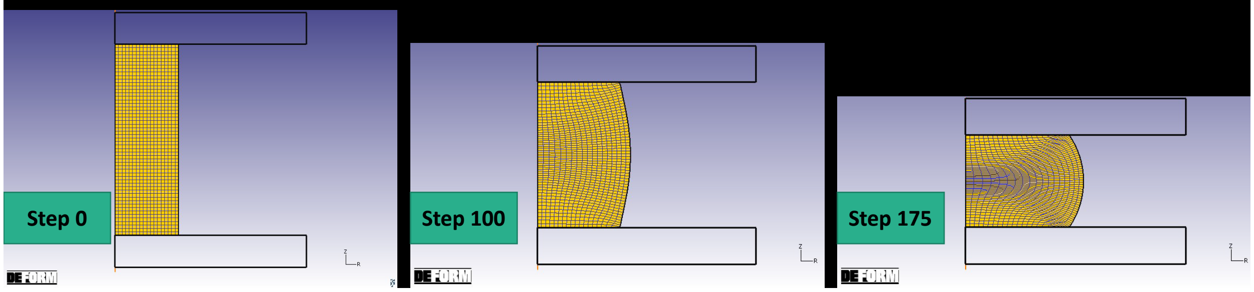
Slides 58 to 75

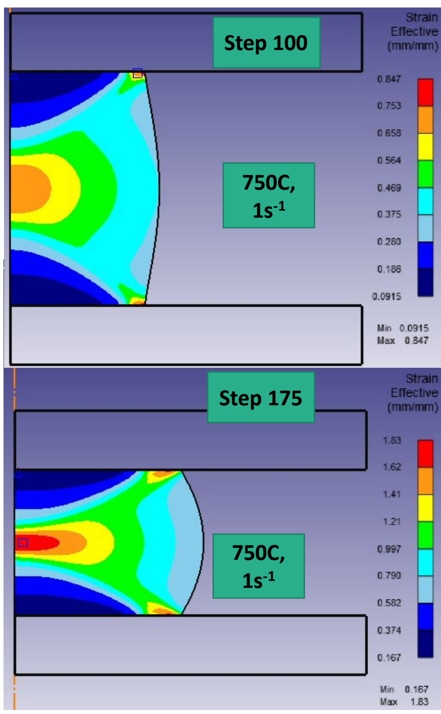
Material: INC625 + 5w%TiC;

Parameters to be evaluated: Strain-Effective (mm/mm), Strain Rate-Effective ((mm/mm)/s), and Stress-Effective (MPa);

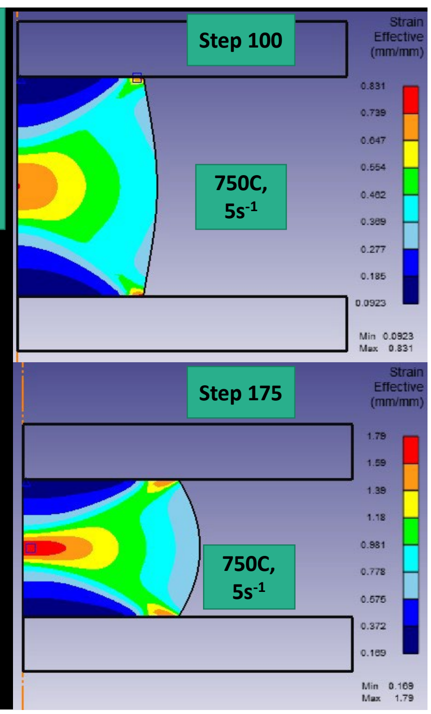
For the following slides, the temperatures used were 750 C , 800 C and 850 C, and the strain rates used were $1s^{-1}$, $5s^{-1}$, $10s^{-1}$ and $20s^{-1}$. The flow stress curves came from Gleeble -compression test.

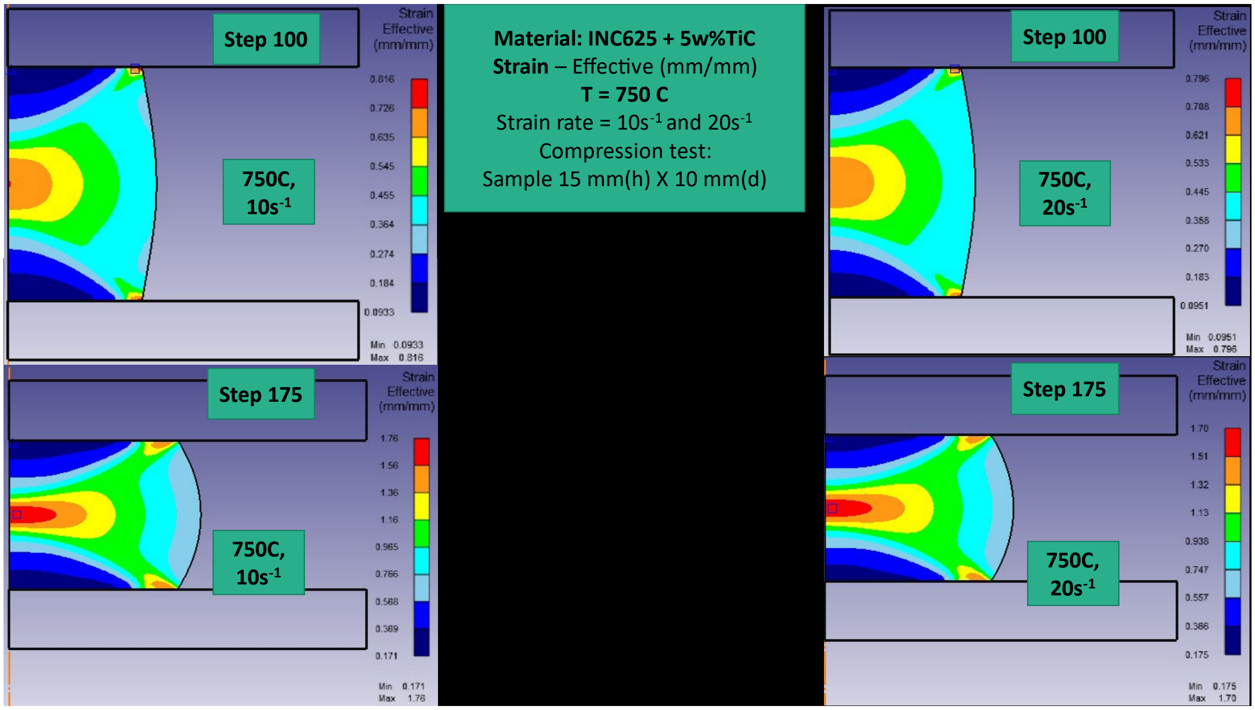
Considering 200 steps of simulation, the steps evaluated were step 100 and step 175, which are appropriate to check for the properties in specific point of the deformation.

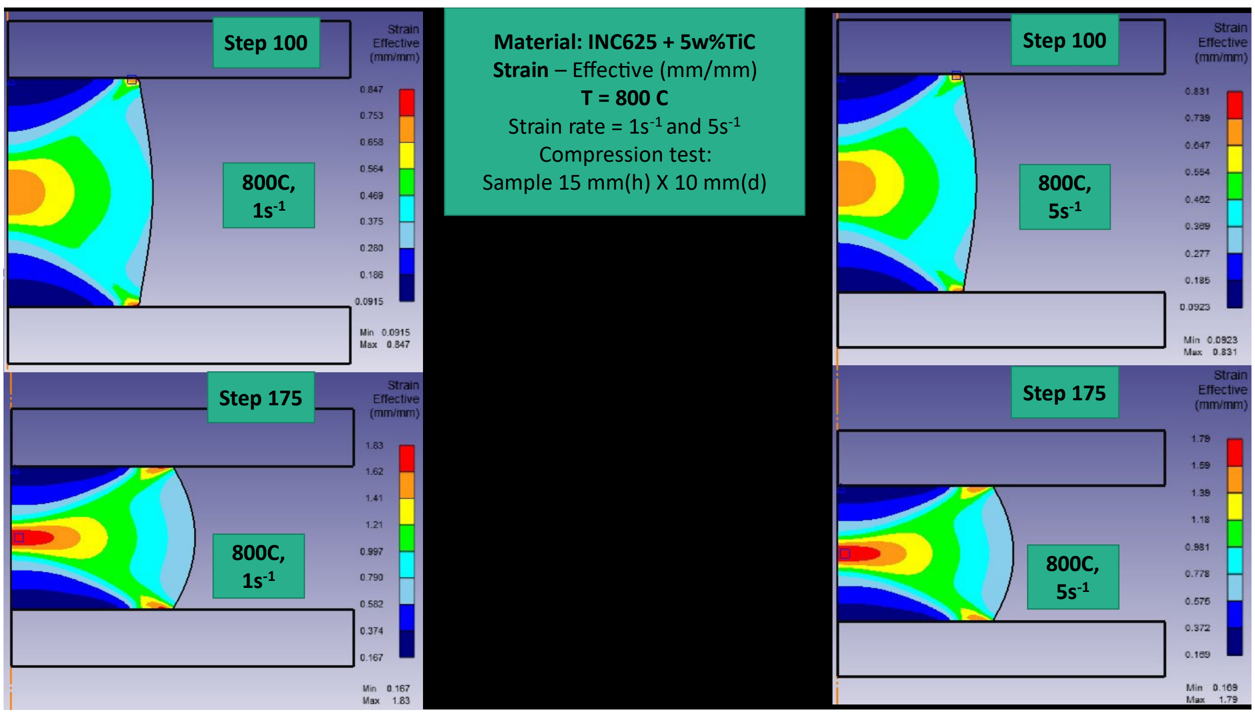


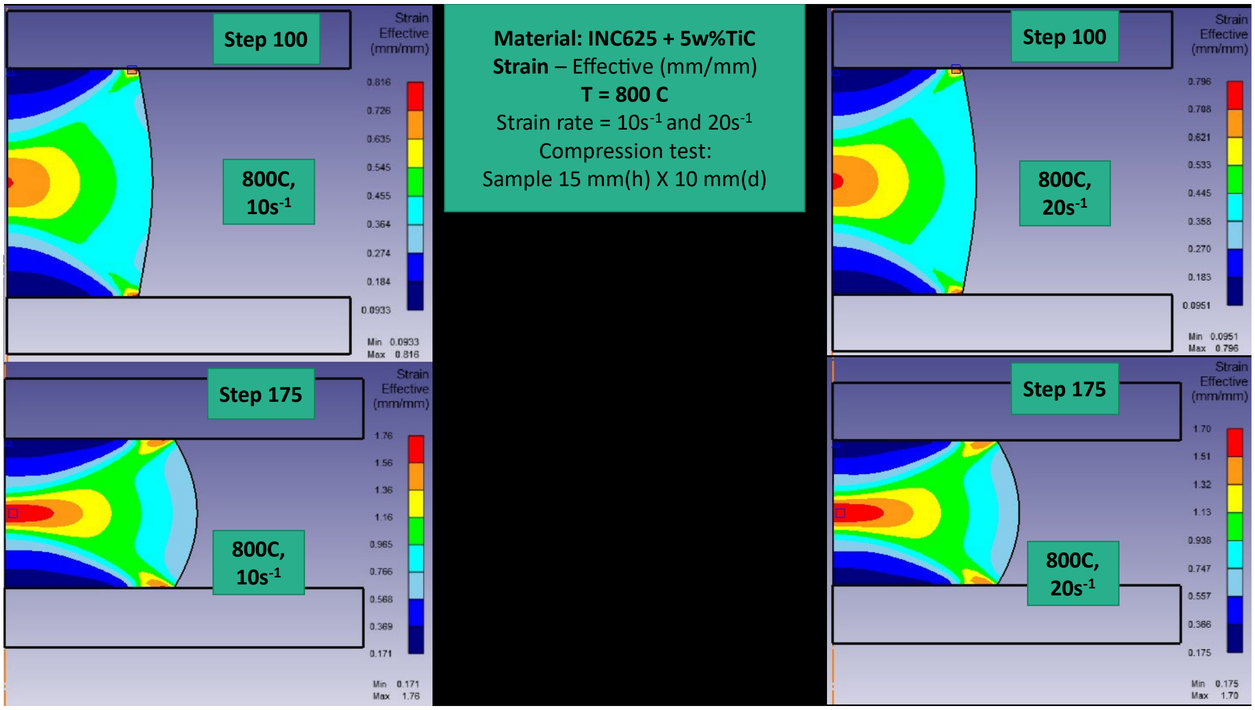


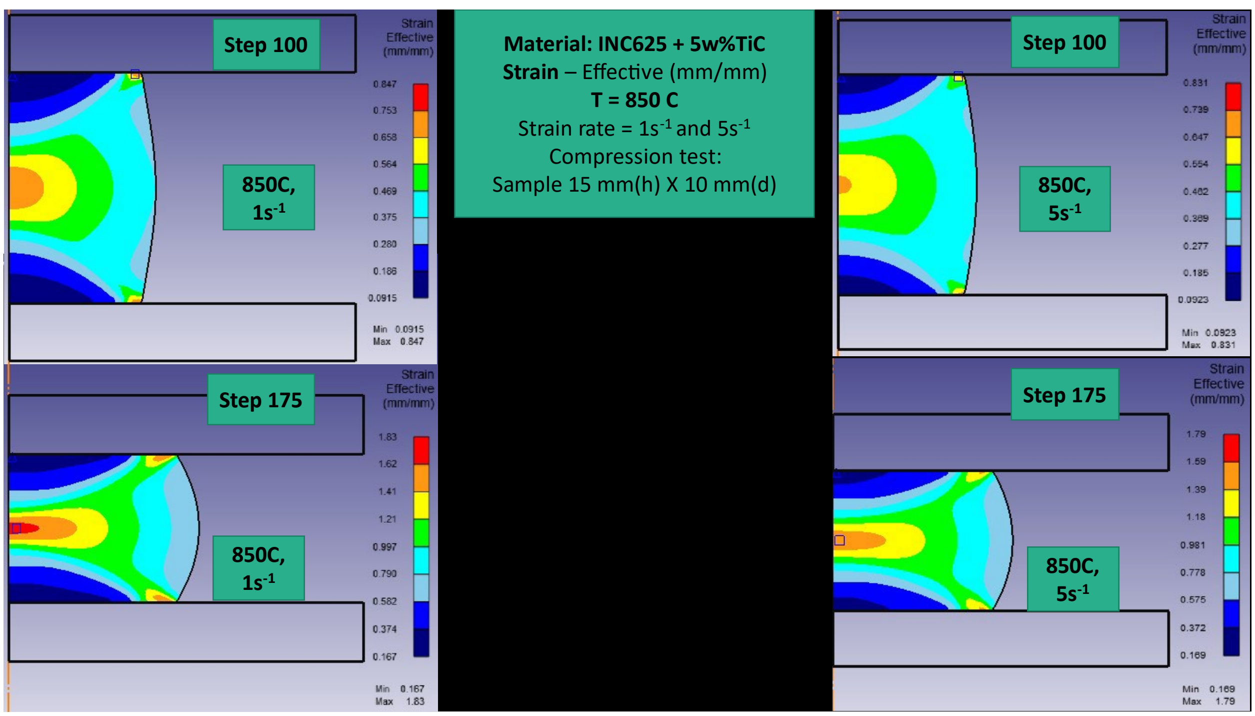
Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 750 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)

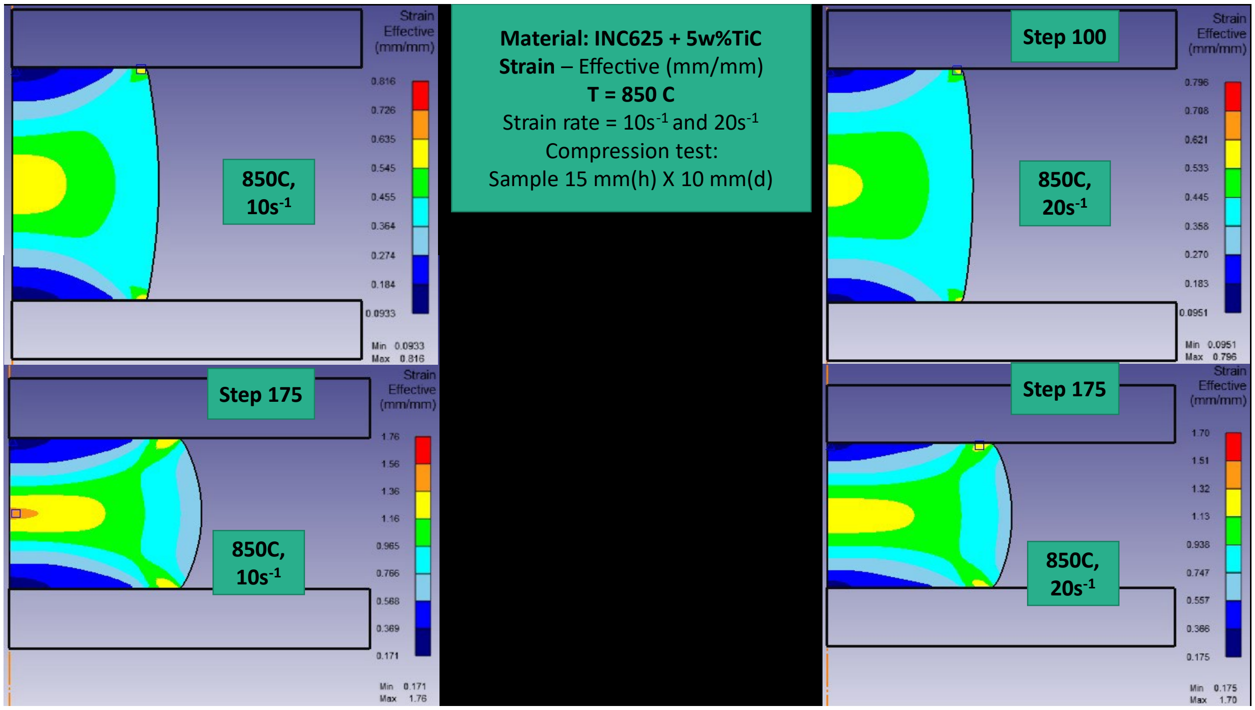


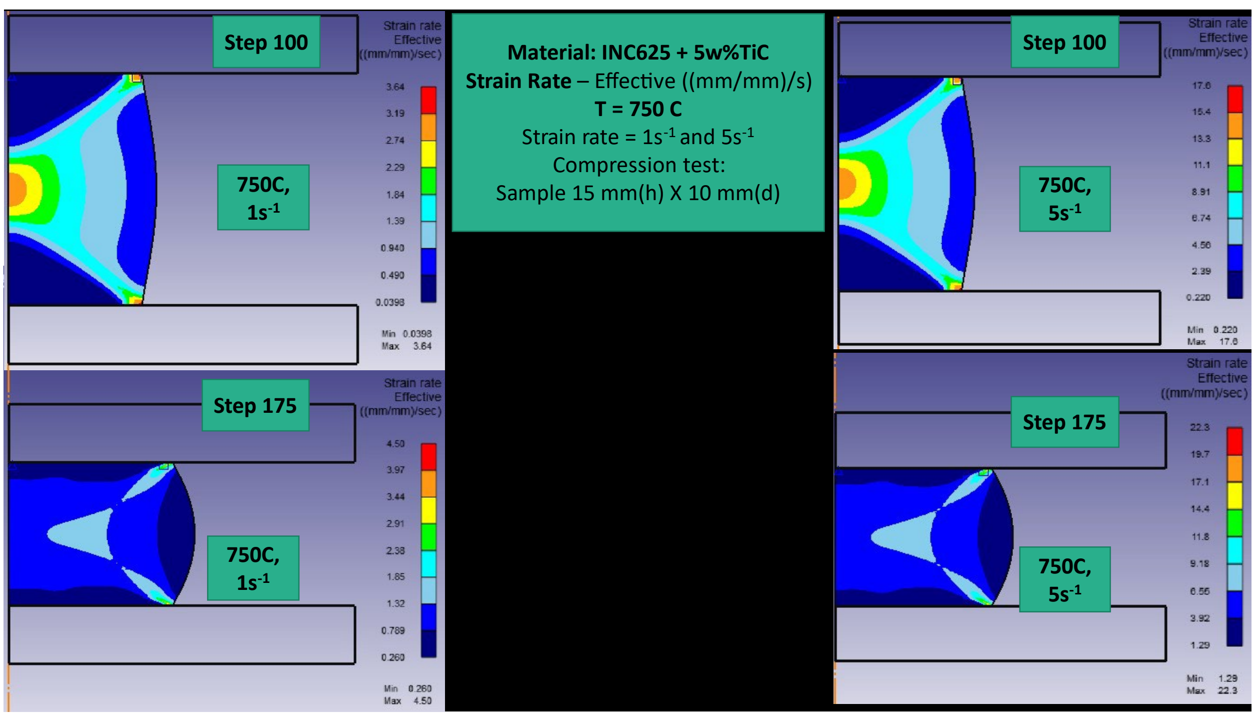

Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Strain Effective (mm/mm)
0.816 0.726 0.635 0.545 0.455 0.364 0.274 0.184 0.0933
Min 0.0933 Max 0.816
Step 175
750C, 10s-1
Strain Effective (mm/mm)
1.76 1.56 1.36 1.16 0.965 0.766 0.568 0.369 0.171
Min 0.171 Max 1.76
Step 100
750C, 20s-1
Strain Effective (mm/mm)
0.796 0.708 0.621 0.533 0.445 0.358 0.270 0.183 0.0951
Min 0.0951 Max 0.796
Step 175
750C, 20s-1
Strain Effective (mm/mm)
1.70 1.51 1.32 1.13 0.938 0.747 0.557 0.366 0.175
Min 0.175 Max 1.70

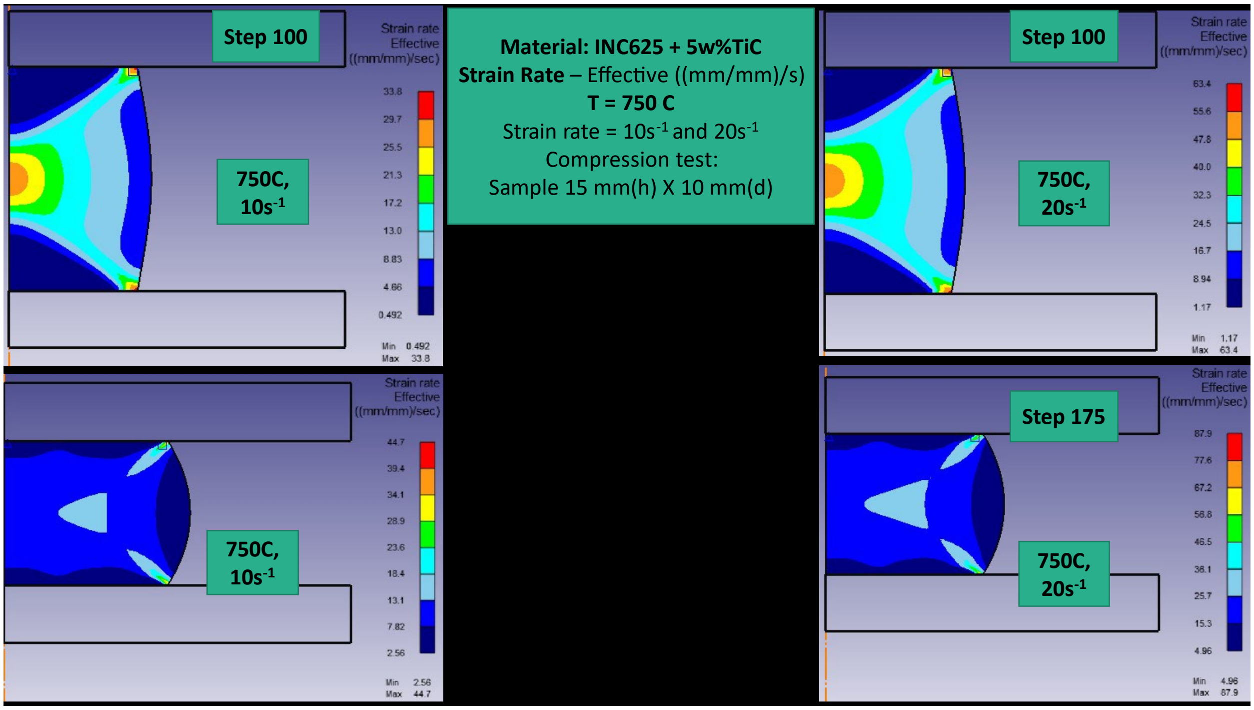

Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Strain Effective (mm/mm)
0.847 0.753 0.658 0.564 0.469 0.375 0.280 0.186 0.0915
Min 0.0915 Max 0.847
Step 175
800C, 1s-1
Strain Effective (mm/mm)
1.83 1.62 1.41 1.21 0.997 0.790 0.582 0.374 0.167
Min 0.167 Max 1.83
Step 100
800C, 5s-1
Strain Effective (mm/mm)
0.831 0.739 0.647 0.554 0.462 0.369 0.277 0.185 0.0923
Min 0.0923 Max 0.831
Step 175
800C, 5s-1
Strain Effective (mm/mm)
1.79 1.59 1.38 1.18 0.981 0.778 0.575 0.372 0.169
Min 0.169 Max 1.79

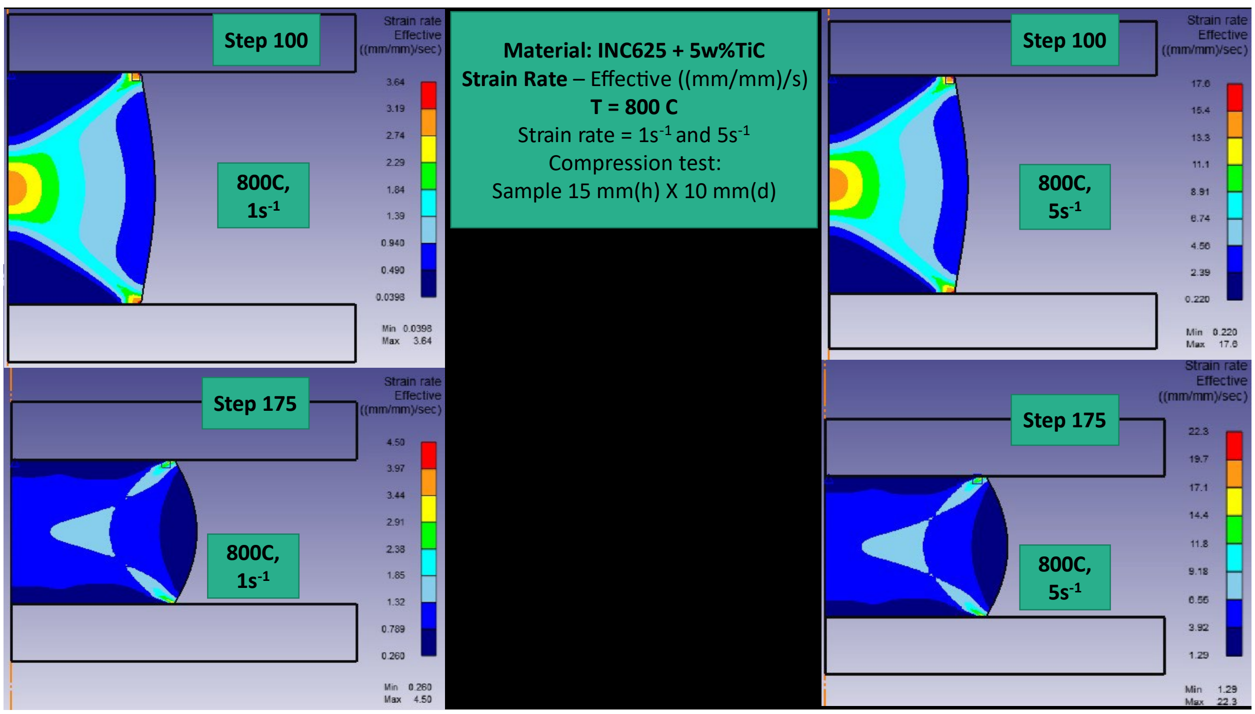

Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Strain Effective (mm/mm)
0.816
0.726
0.635
0.545
0.455
0.364
0.274
0.184
0.0933
Min 0.0933
Max 0.816
Step 175
800C, 10s-1
Strain Effective (mm/mm)
1.76
1.56
1.36
1.16
0.965
0.766
0.568
0.369
0.171
Min 0.171
Max 1.76
Step 100
800C, 20s-1
Strain Effective (mm/mm)
0.796
0.708
0.621
0.533
0.445
0.358
0.270
0.183
0.0951
Min 0.0951
Max 0.796
Step 175
800C, 20s-1
Strain Effective (mm/mm)
1.70
1.51
1.32
1.13
0.938
0.747
0.557
0.366
0.175
Min 0.175
Max 1.70

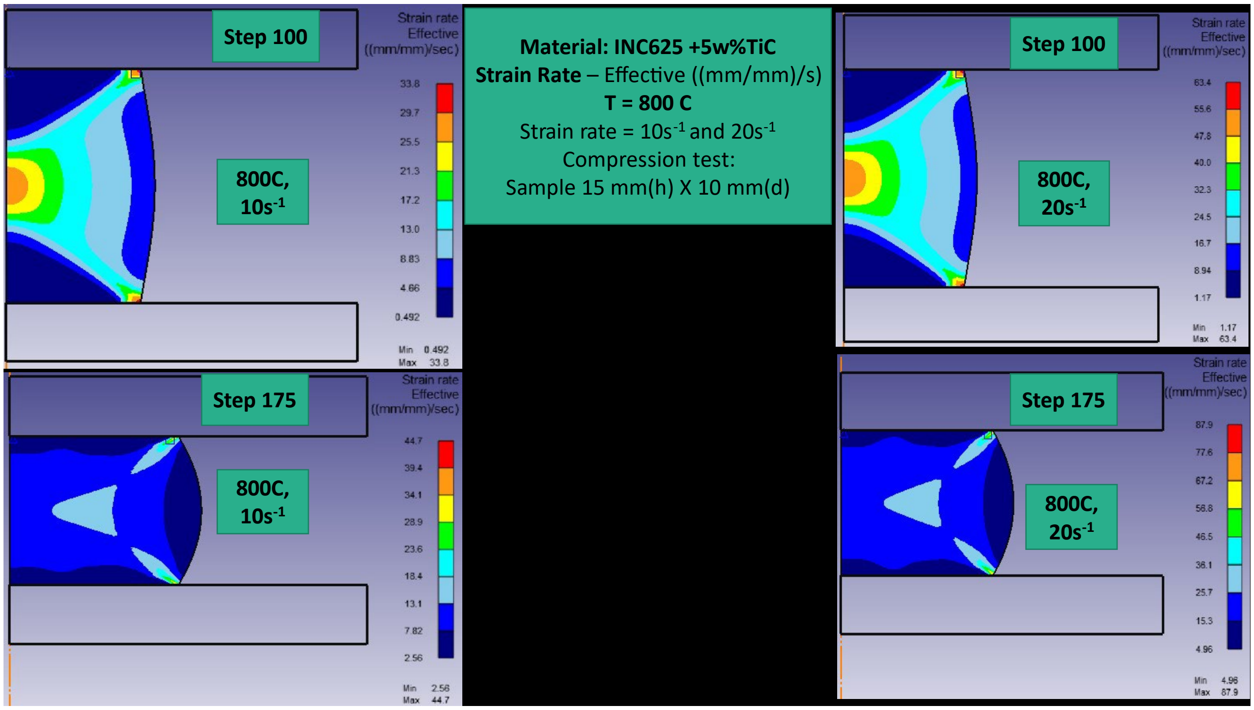

Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 850 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 1s-1
Strain Effective (mm/mm)
0.847
0.753
0.658
0.564
0.469
0.375
0.280
0.186
0.0915
Min 0.0915
Max 0.847
Step 175
850C, 1s-1
Strain Effective (mm/mm)
1.83
1.62
1.41
1.21
0.997
0.790
0.582
0.374
0.167
Min 0.167
Max 1.83
Step 100
850C, 5s-1
Strain Effective (mm/mm)
0.831
0.739
0.647
0.554
0.462
0.369
0.277
0.185
0.0923
Min 0.0923
Max 0.831
Step 175
850C, 5s-1
Strain Effective (mm/mm)
1.79
1.59
1.39
1.18
0.981
0.778
0.575
0.372
0.169
Min 0.169
Max 1.79

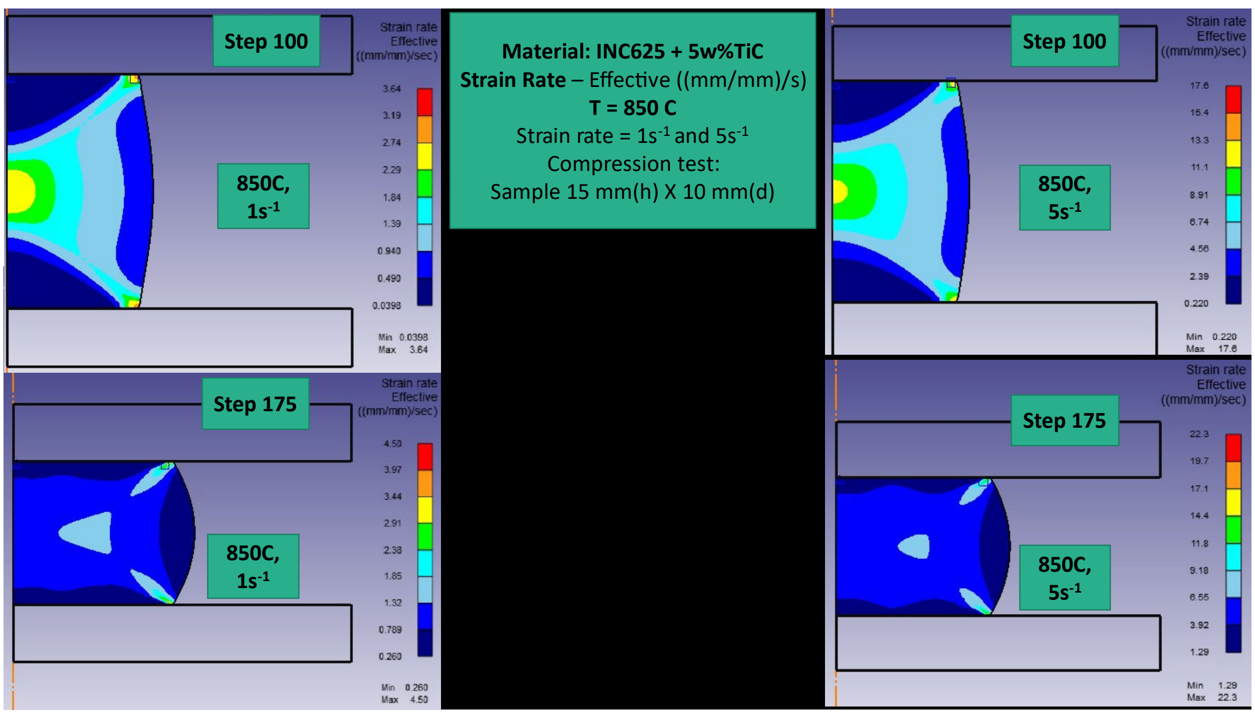

Material: INC625 + 5w%TiC
Strain – Effective (mm/mm)
T = 850 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Strain Effective (mm/mm)
850C, 10s-1
Step 100
850C, 20s-1
Step 175
850C, 10s-1
Step 175
850C, 20s-1
Min 0.0933 Max 0.816
Min 0.0951 Max 0.796
Min 0.171 Max 1.76
Min 0.175 Max 1.70

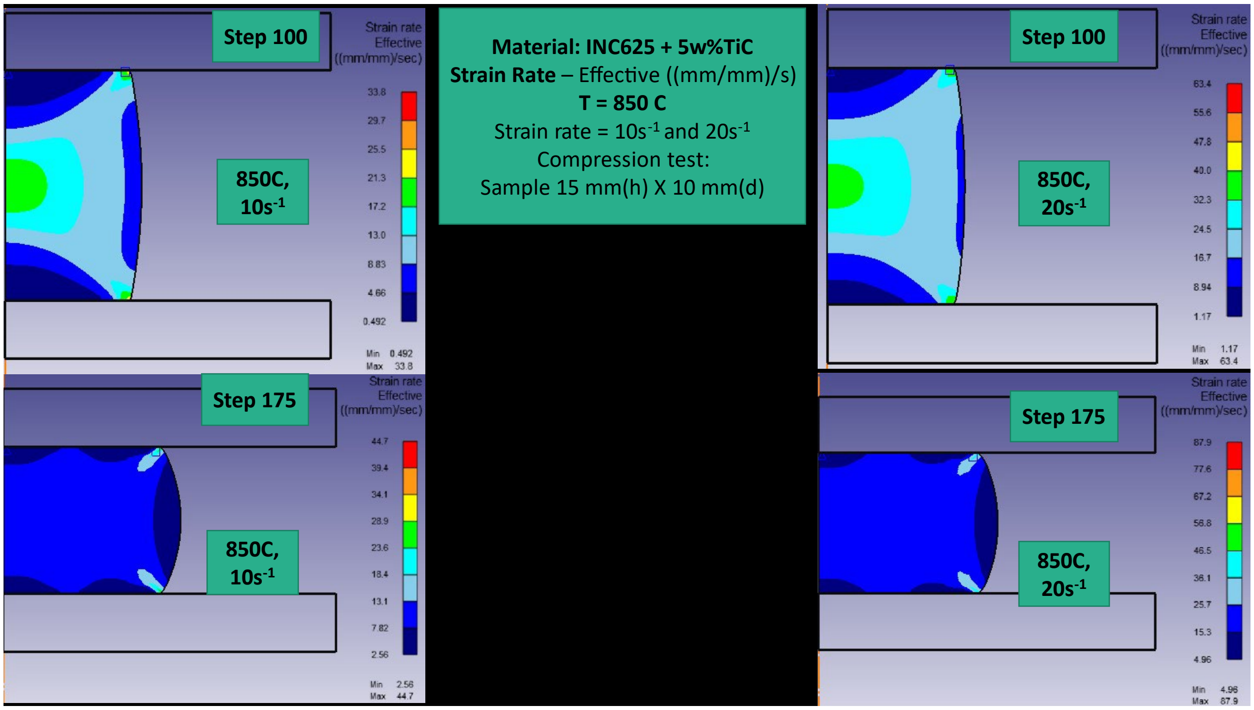

Material: INC625 + 5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Strain rate Effective ((mm/mm)/sec)
Step 100
750C, 1s-1
Step 100
750C, 5s-1
Step 175
750C, 1s-1
Step 175
750C, 5s-1
Min 0.0398 Max 3.64
Min 0.220 Max 17.0
Min 0.260 Max 4.50
Min 1.29 Max 22.3

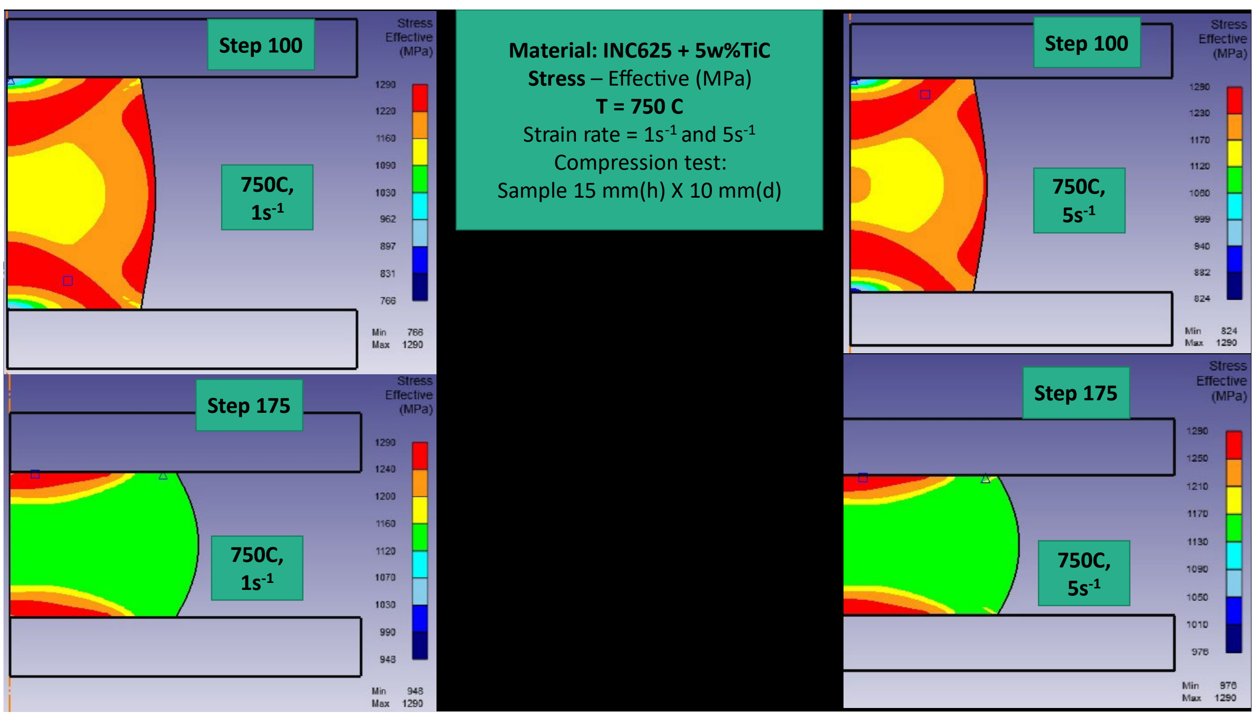

Step 100
Strain rate Effective ((mm/mm)/sec)
750C, $10s^{-1}$
Material: INC625 + 5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate Effective ((mm/mm)/sec)
750C, $20s^{-1}$
Strain rate Effective ((mm/mm)/sec)
750C, $10s^{-1}$
Step 175
Strain rate Effective ((mm/mm)/sec)
750C, $20s^{-1}$

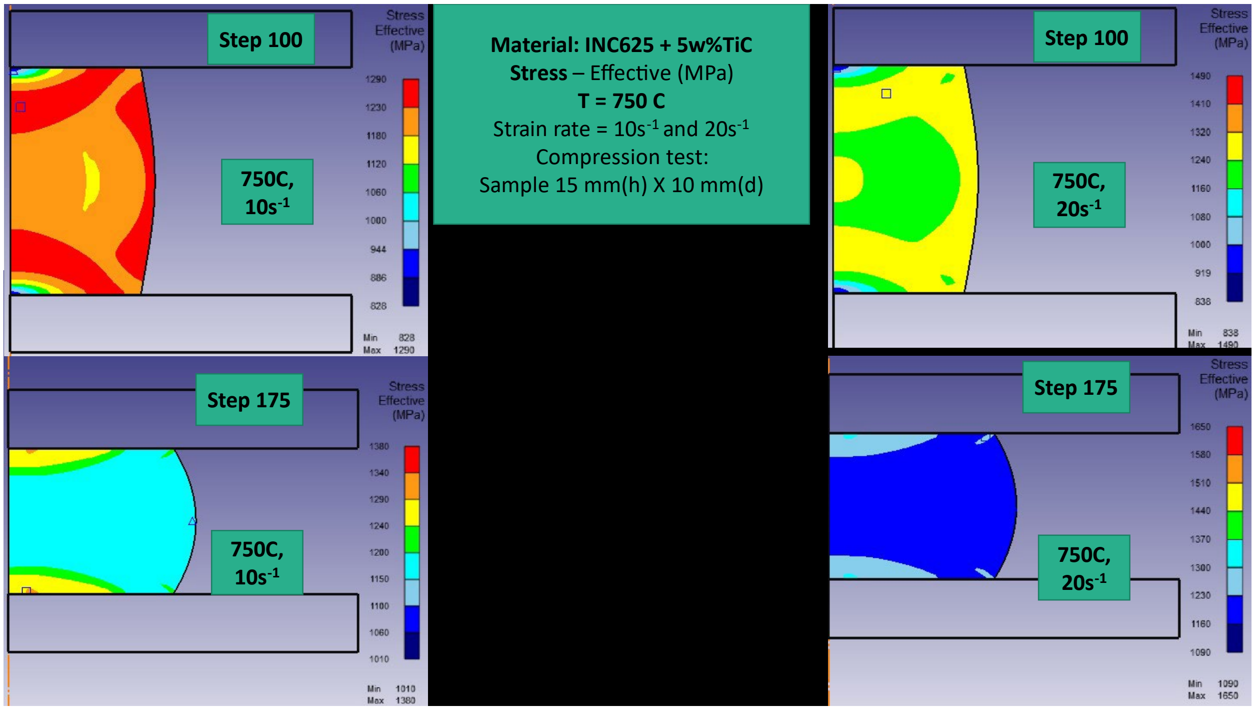

Step 100
Strain rate Effective ((mm/mm)/sec)
800C, $1s^{-1}$
Material: INC625 + 5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate Effective ((mm/mm)/sec)
800C, $5s^{-1}$
Step 175
Strain rate Effective ((mm/mm)/sec)
800C, $1s^{-1}$
Step 175
Strain rate Effective ((mm/mm)/sec)
800C, $5s^{-1}$

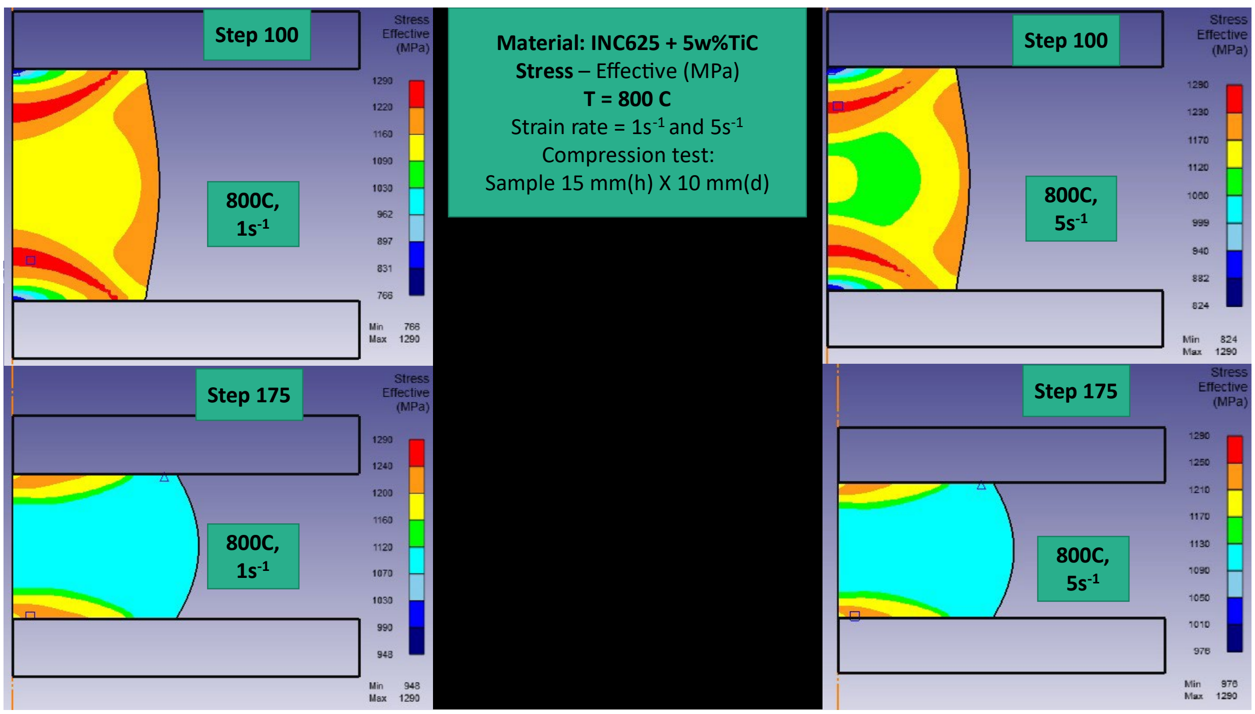

Step 100
Strain rate
Effective
((mm/mm)/sec)
33.8
29.7
25.5
21.3
17.2
13.0
8.83
4.66
0.492
Min 0.492
Max 33.8
800C,
10s-1
Material: INC625 +5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate
Effective
((mm/mm)/sec)
63.4
55.6
47.8
40.0
32.3
24.5
16.7
8.94
1.17
Min 1.17
Max 63.4
800C,
20s-1
Step 175
Strain rate
Effective
((mm/mm)/sec)
44.7
39.4
34.1
28.9
23.6
18.4
13.1
7.82
2.56
Min 2.56
Max 44.7
800C,
10s-1
Step 175
Strain rate
Effective
((mm/mm)/sec)
87.9
77.6
67.2
56.8
46.5
36.1
25.7
15.3
4.96
Min 4.96
Max 87.9
800C,
20s-1

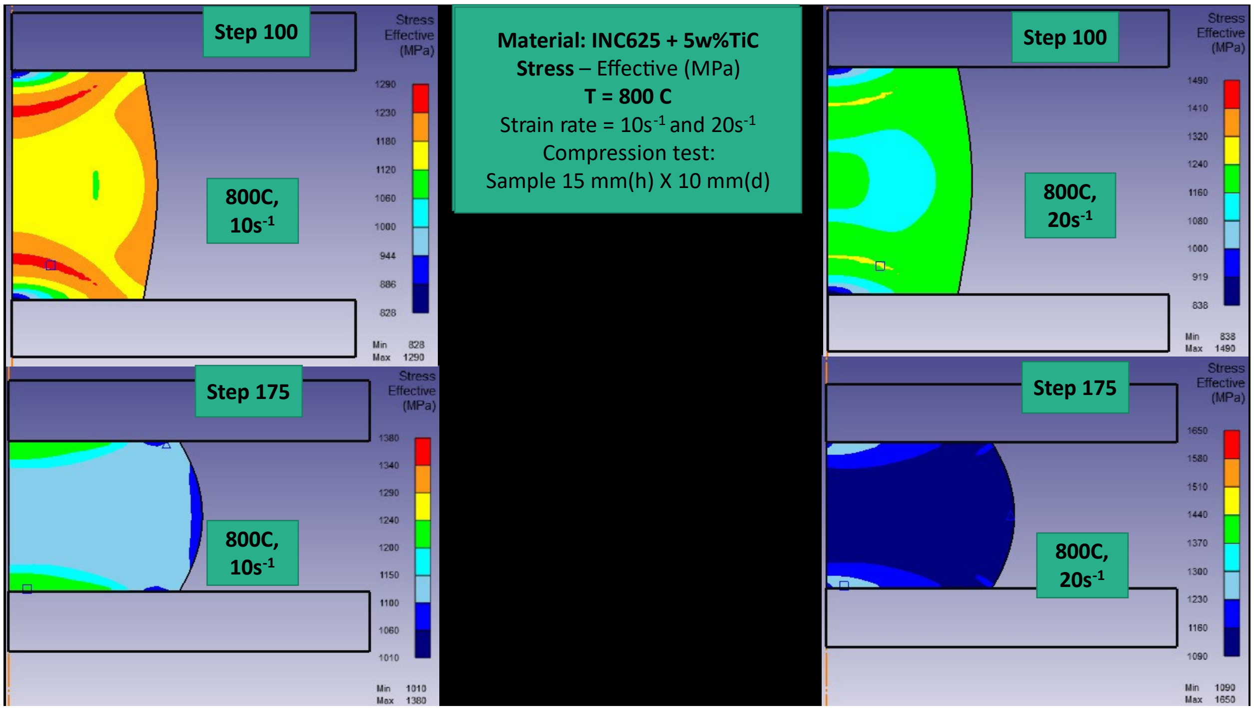

Step 100
Strain rate
Effective
((mm/mm)/sec)
3.64
3.19
2.74
2.29
1.84
1.39
0.940
0.490
0.0398
Min 0.0398
Max 3.64
850C,
1s-1
Material: INC625 + 5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 850 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Strain rate
Effective
((mm/mm)/sec)
17.6
15.4
13.3
11.1
8.91
6.74
4.56
2.39
0.220
Min 0.220
Max 17.6
850C,
5s-1
Step 175
Strain rate
Effective
((mm/mm)/sec)
4.50
3.97
3.44
2.91
2.38
1.85
1.32
0.789
0.260
Min 0.260
Max 4.50
850C,
1s-1
Step 175
Strain rate
Effective
((mm/mm)/sec)
22.3
19.7
17.1
14.4
11.8
9.18
6.55
3.92
1.29
Min 1.29
Max 22.3
850C,
5s-1

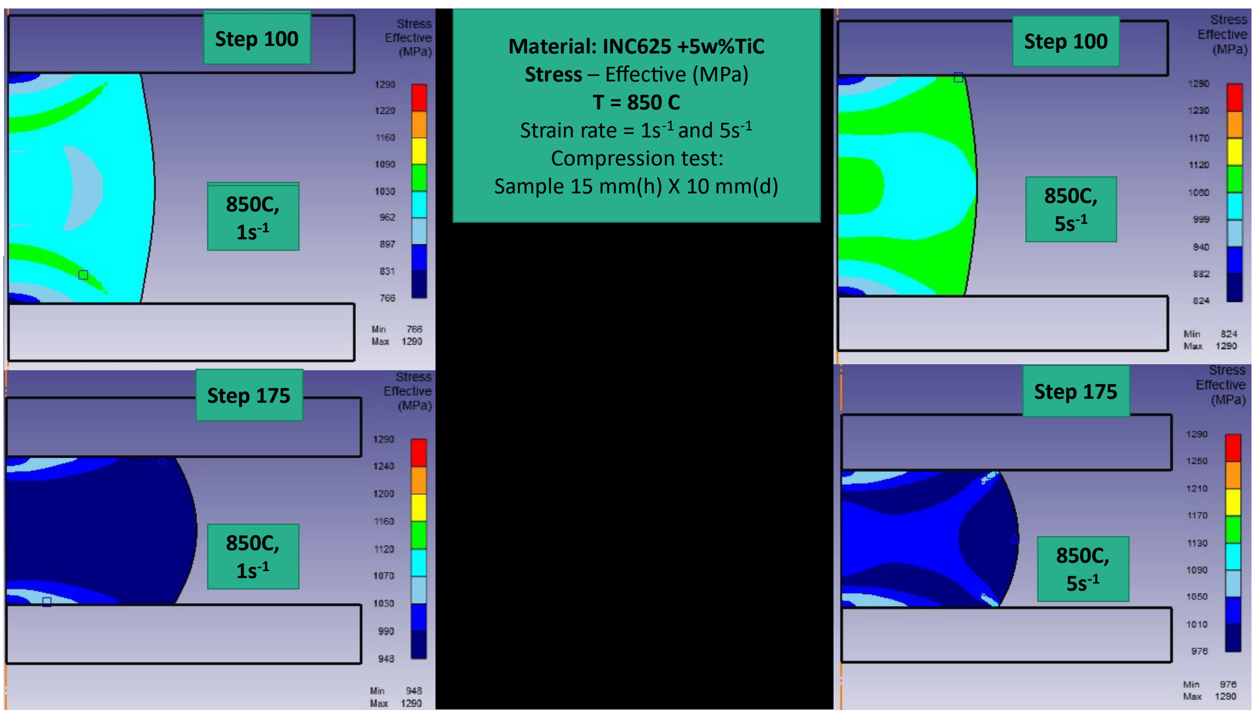

Step 100
Strain rate Effective ((mm/mm)/sec)
850C, $10s^{-1}$
Min 0.492 Max 33.8
Material: INC625 + 5w%TiC
Strain Rate – Effective ((mm/mm)/s)
T = 850 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, $20s^{-1}$
Min 1.17 Max 63.4
Step 175
850C, $10s^{-1}$
Min 2.56 Max 44.7
Step 175
850C, $20s^{-1}$
Min 4.96 Max 87.9

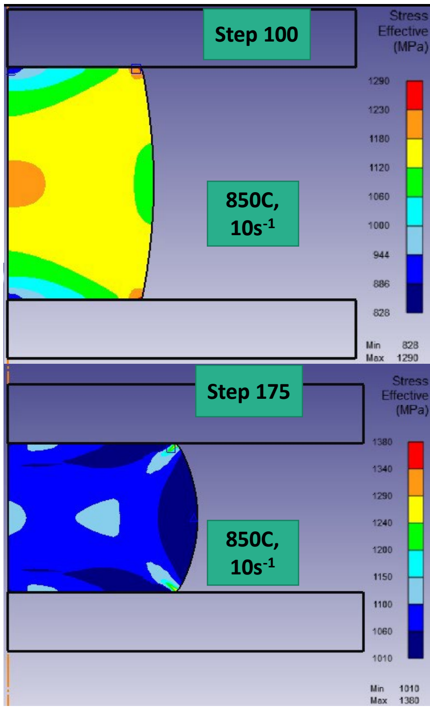

Step 100
Stress Effective (MPa)
750C, $1s^{-1}$
Min 766 Max 1290
Material: INC625 + 5w%TiC
Stress – Effective (MPa)
T = 750 C
Strain rate = $1s^{-1}$ and $5s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, $5s^{-1}$
Min 824 Max 1290
Step 175
750C, $1s^{-1}$
Min 948 Max 1290
Step 175
750C, $5s^{-1}$
Min 976 Max 1290


Material: INC625 + 5w%TiC
Stress – Effective (MPa)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Step 100
750C, 20s-1
Step 175
750C, 10s-1
Step 175
750C, 20s-1
Stress Effective (MPa)

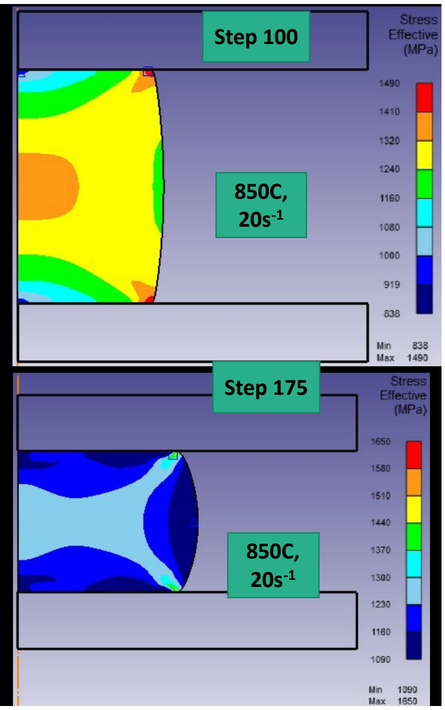

Material: INC625 + 5w%TiC
Stress – Effective (MPa)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Step 100
800C, 5s-1
Step 175
800C, 1s-1
Step 175
800C, 5s-1
Stress Effective (MPa)


Step 100
Stress Effective (MPa)
800C, 10s^{-1}
Material: INC625 + 5w%TiC
Stress – Effective (MPa)
T = 800 C
Strain rate = 10s^{-1} and 20s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 20s^{-1}
Step 175
800C, 10s^{-1}
Step 175
800C, 20s^{-1}


Step 100
Stress Effective (MPa)
850C, 1s^{-1}
Material: INC625 +5w%TiC
Stress – Effective (MPa)
T = 850 C
Strain rate = 1s^{-1} and 5s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 5s^{-1}
Step 175
850C, 1s^{-1}
Step 175
850C, 5s^{-1}



Material: INC625 + 5w%TiC
Stress – Effective (MPa)
T = 850 C
Strain rate = $10s^{-1}$ and $20s^{-1}$
Compression test:
Sample 15 mm(h) X 10 mm(d)



Material: INC625 + 5w%TiC
Steps of the simulations 100 of 200 and 175 of 200

Strain Rate – Effective ((mm/mm)/s)

T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	3.19	0.94	15.4	4.56	29.7	8.83	55.6	16.7
Step 175	1.32	0.78	6.56	3.92	13.1	7.82	25.7	15.3
T= 800 C								
Step 100	3.19	0.9	15.4	4.56	29.7	8.83	55.6	16.7
Step 175	1.32	0.78	6.56	3.92	13.1	7.82	25.7	15.3
T= 850 C								
Step 100	2.74	0.94	13.3	4.56	21.3	8.83	42	19.7
Step 175	1.32	0.78	6.55	3.92	13.1	7.82	25.7	15.3

Strain – Effective (mm/mm)

T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	0.75	0.46	0.75	0.46	0.72	0.45	0.7	0.44
Step 175	1.83	0.79	1.79	0.77	1.76	0.76	1.7	0.74
T= 800 C								
Step 100	0.75	0.46	0.73	0.46	0.73	0.45	0.79	0.44
Step 175	1.83	0.79	1.79	0.77	1.76	0.76	1.7	0.74
T= 850 C								
Step 100	0.75	0.46	0.73	0.46	0.63	0.45	0.6	0.44
Step 175	1.83	0.79	1.59	0.77	1.56	0.76	1.32	0.74

Stress – Effective (MPa)

T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	1160	1290	1230	1290	1230	1290	1320	1320
Step 175	1160	1160	1170	1170	1200	1200	1230	1230
T= 800 C								
Step 100	1160	1220	1170	1230	1180	1230	1240	1240
Step 175	1120	1120	1130	1130	1150	1100	1230	1230
T= 850 C								
Step 100	1030	1030	1120	1060	1230	1120	1410	1240
Step 175	1030	1030	1050	1010	1150	1060	1300	1160

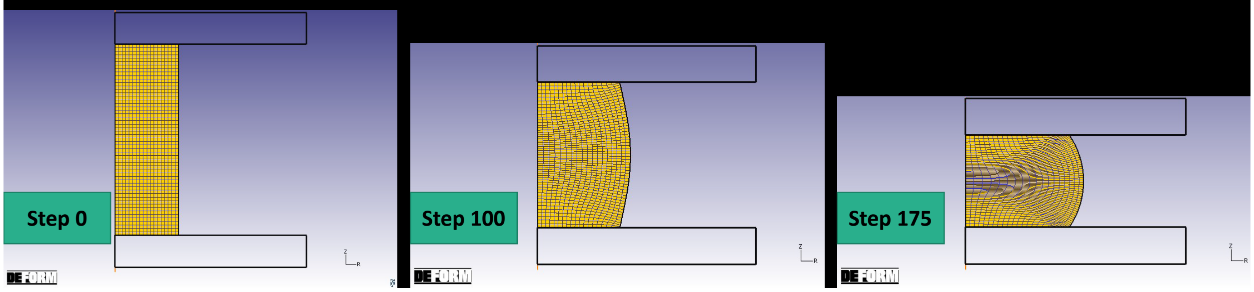
Slides 78 to 95

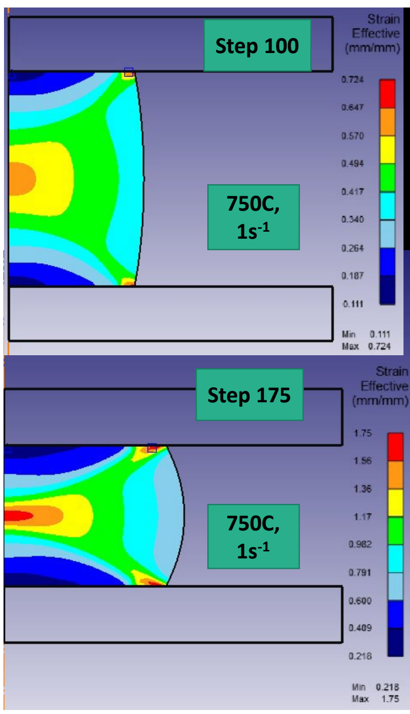
Material: Pure INC625;

Parameters to be evaluated: Strain-Effective (mm/mm), Strain Rate-Effective ((mm/mm)/s), and Stress-Effective (MPa);

For the following slides, the temperatures used were 750 C , 800 C and 850 C, and the strain rates used were $1s^{-1}$, $5s^{-1}$, $10s^{-1}$ and $20s^{-1}$. The flow stress curves came from Gleeble compression test).

Considering 200 steps of simulation, the steps evaluated were step 100 and step 175, which are appropriate to check for the properties in specific point of the deformation.





Material: Pure INC625

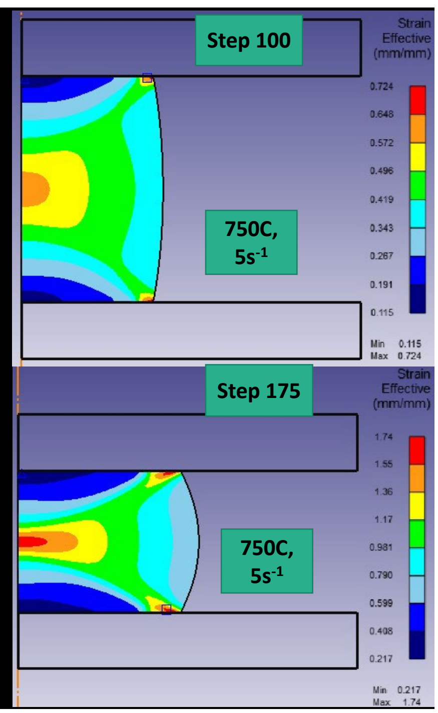
Strain – Effective (mm/mm)

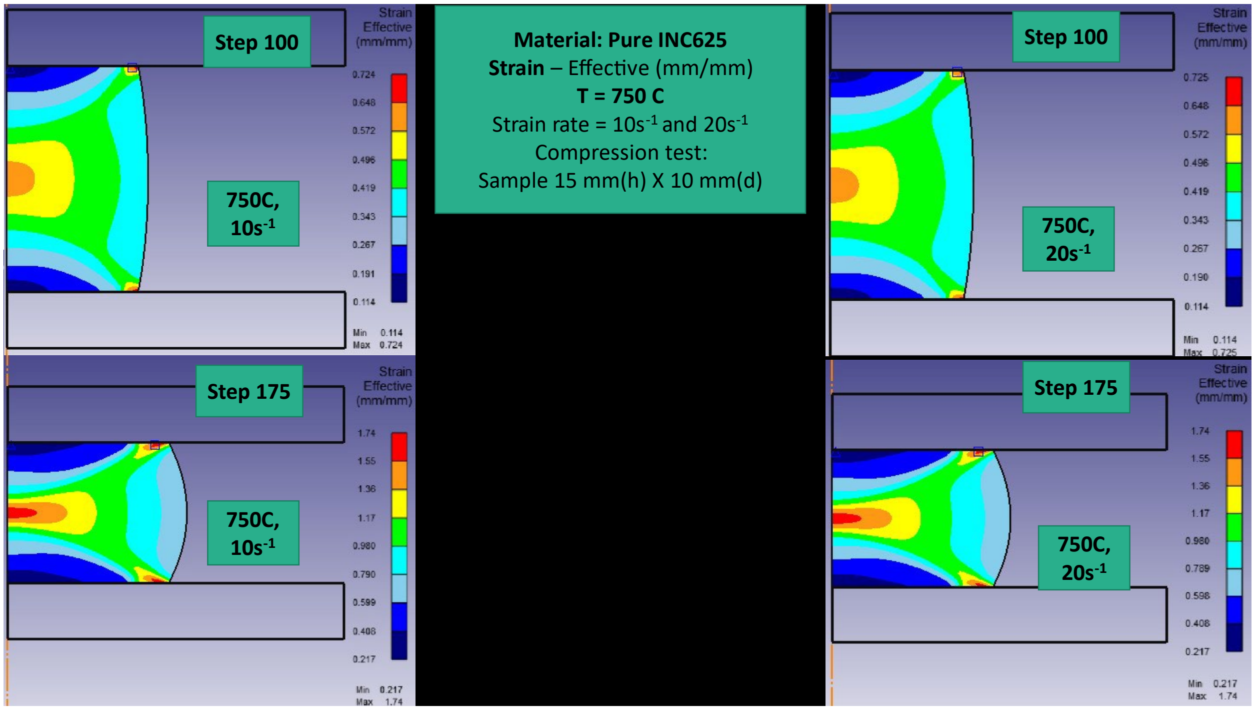
T = 750 C

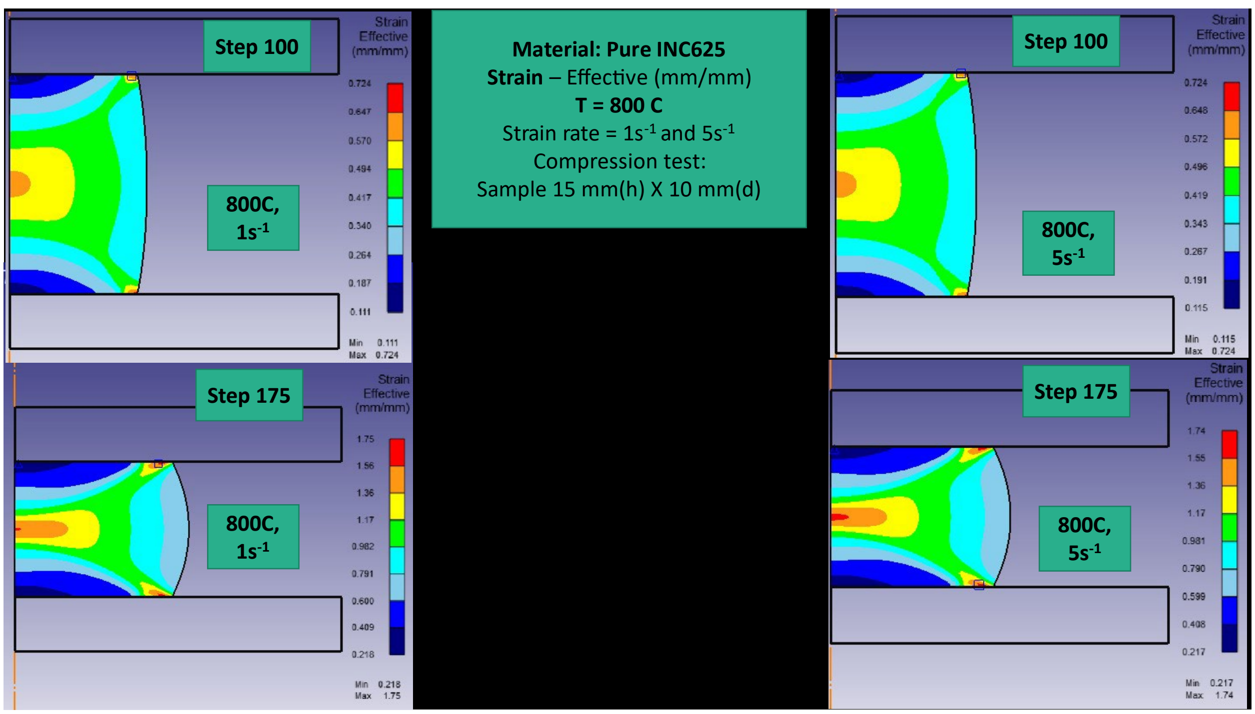
Strain rate = $1s^{-1}$ and $5s^{-1}$

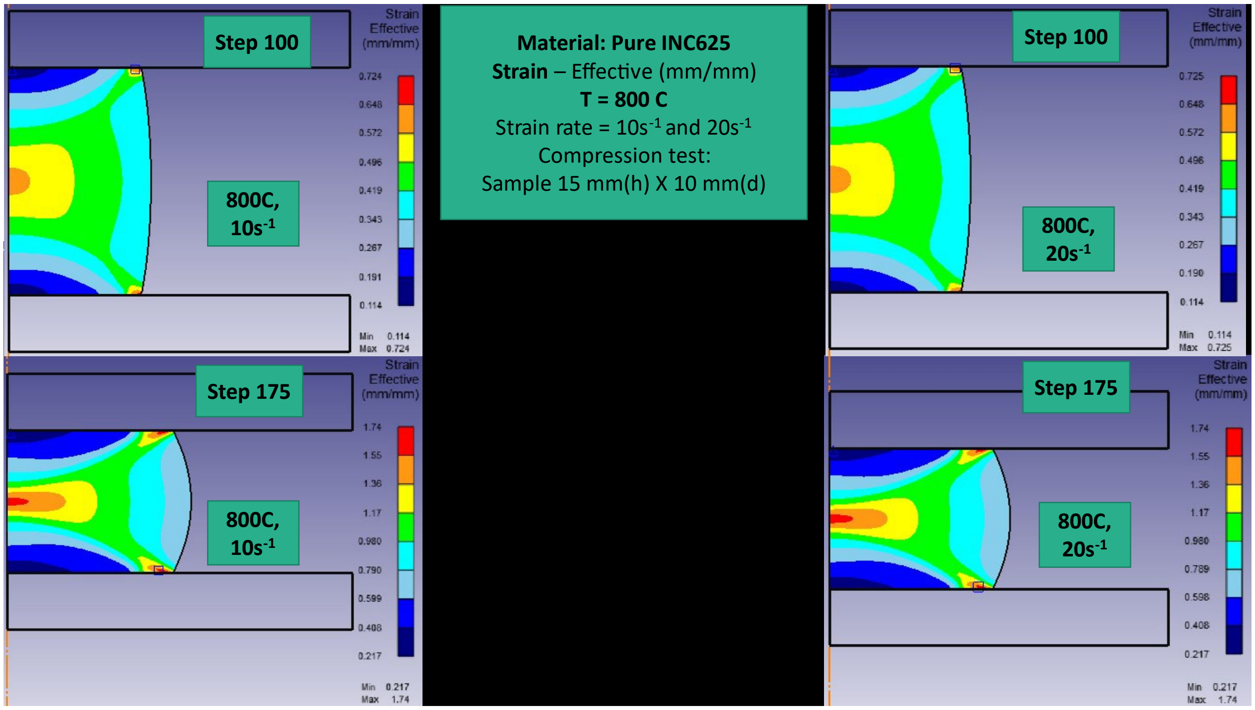
Compression test:

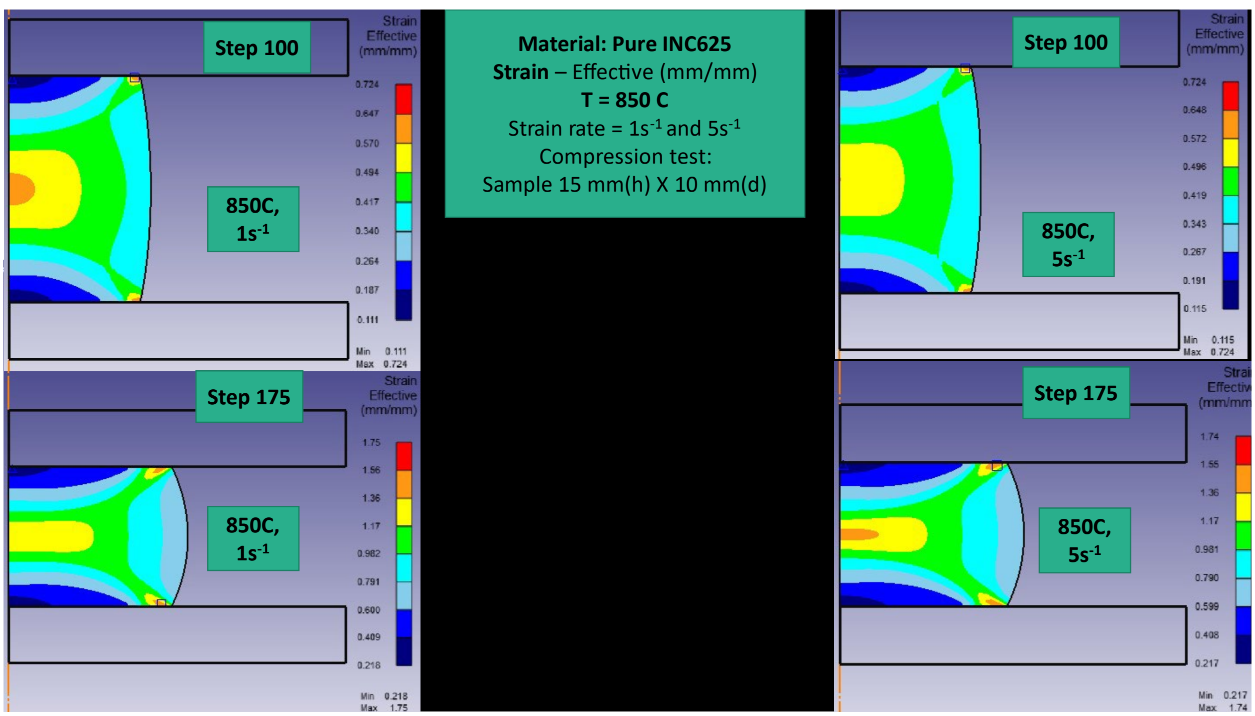
Sample 15 mm(h) X 10 mm(d)

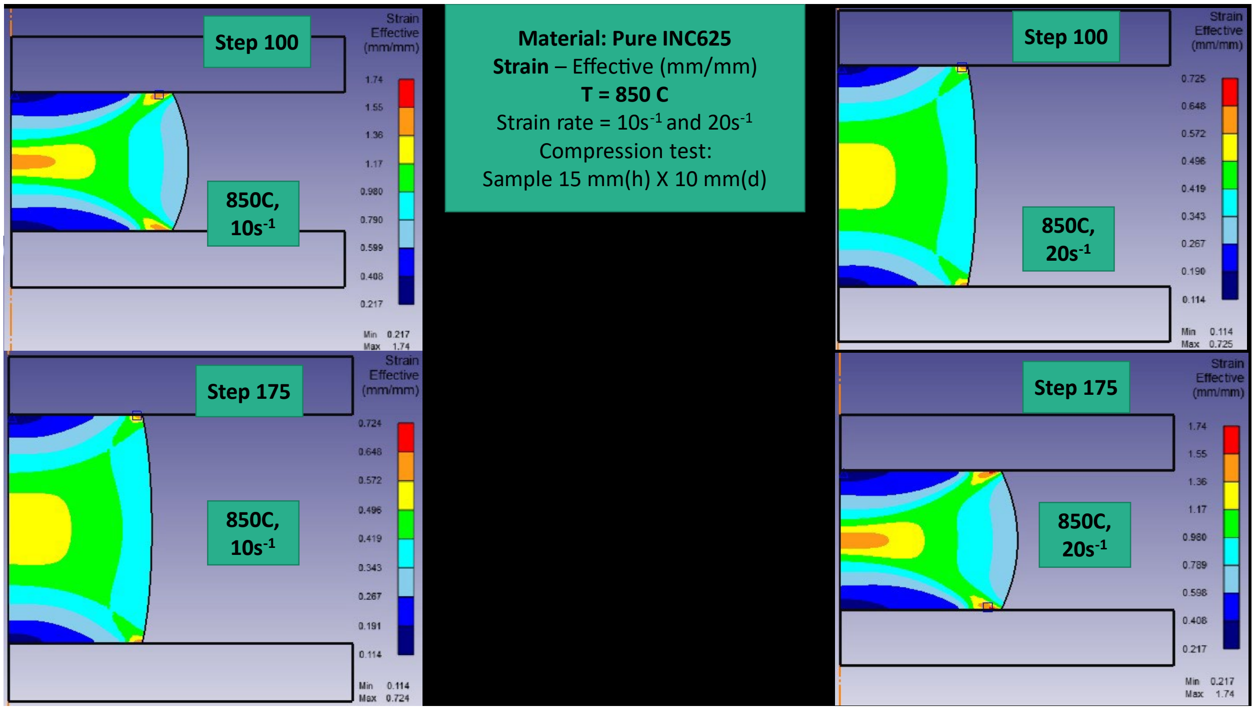


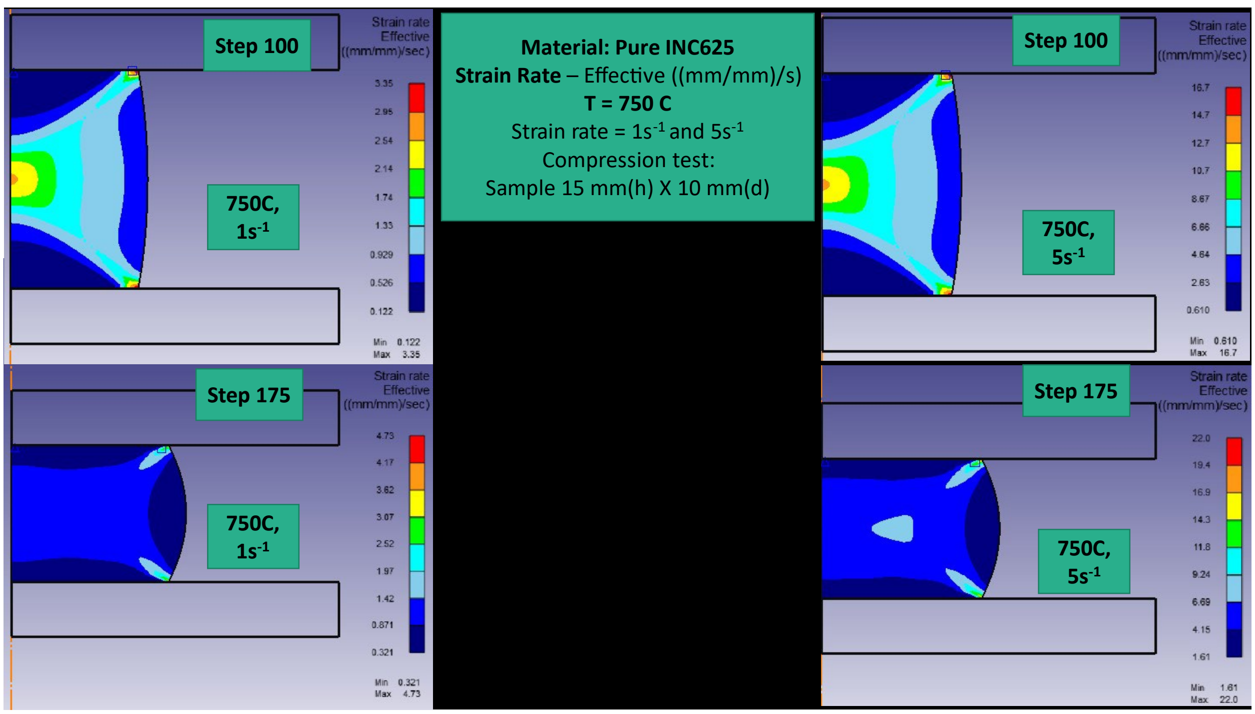

Material: Pure INC625
Strain – Effective (mm/mm)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s-1
Step 175
750C, 10s-1
Step 100
750C, 20s-1
Step 175
750C, 20s-1
Strain Effective (mm/mm)

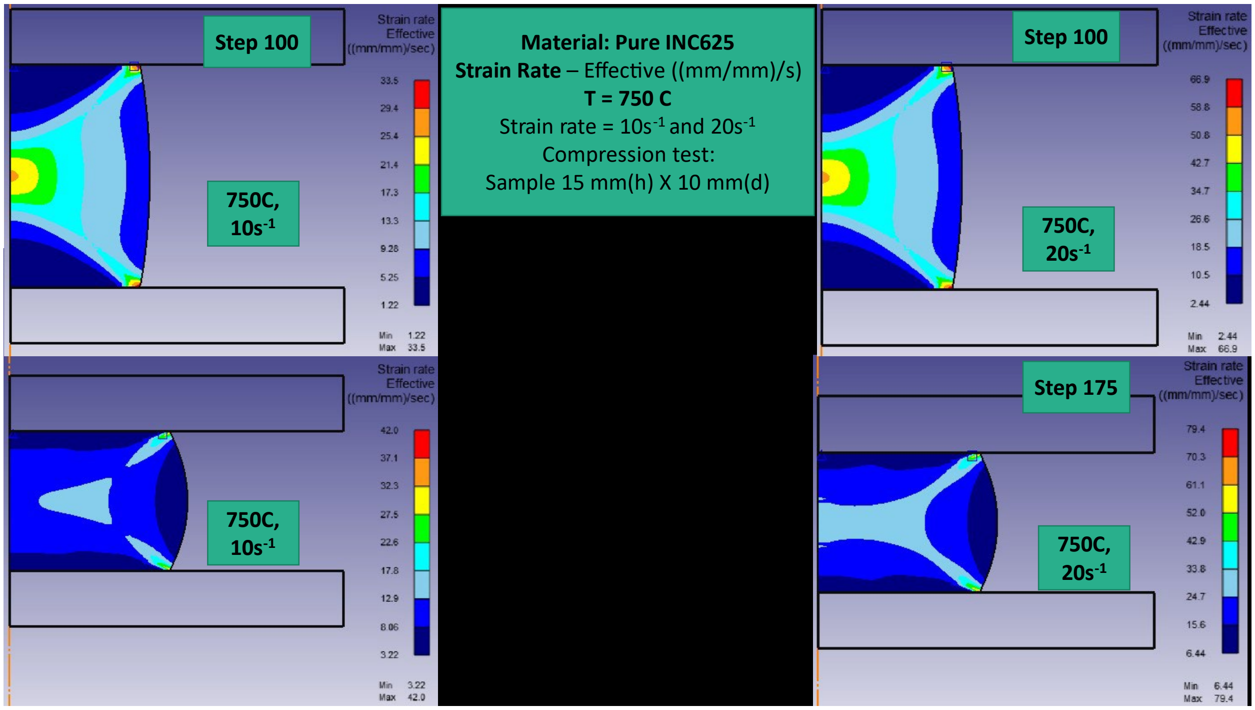

Material: Pure INC625
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s-1
Step 175
800C, 1s-1
Step 100
800C, 5s-1
Step 175
800C, 5s-1
Strain Effective (mm/mm)

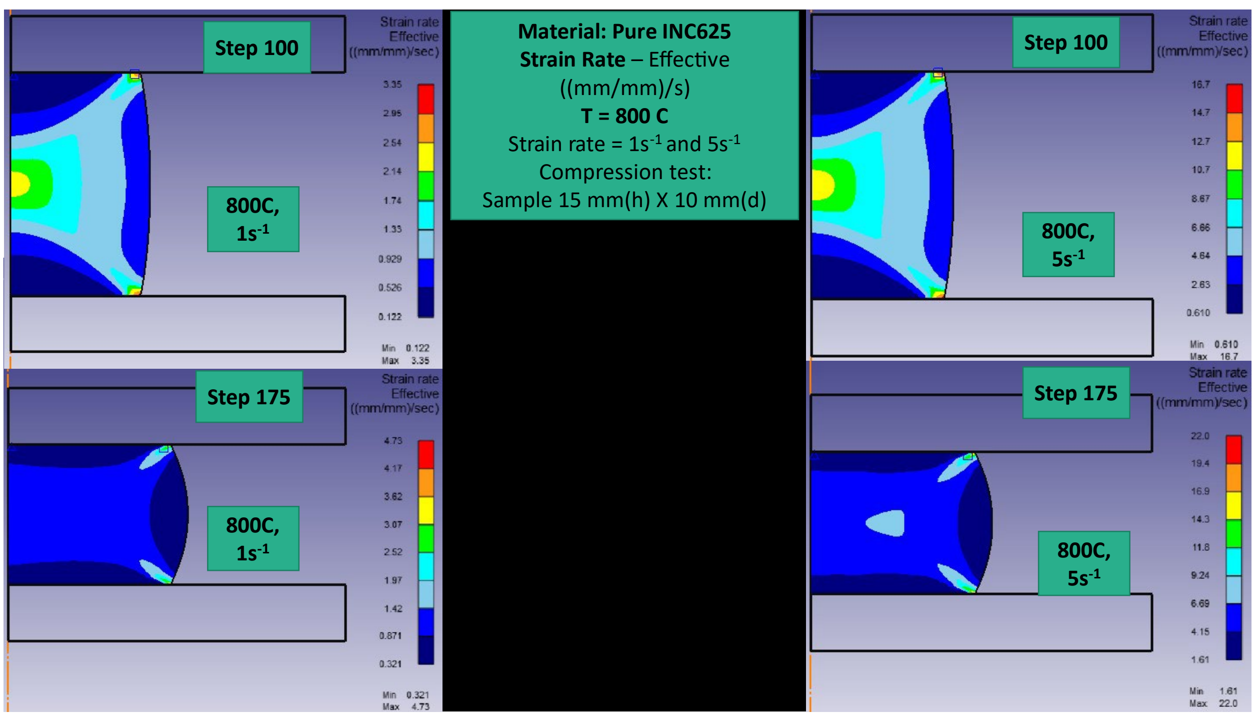

Material: Pure INC625
Strain – Effective (mm/mm)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Step 175
800C, 10s-1
Step 100
800C, 20s-1
Step 175
800C, 20s-1
Strain Effective (mm/mm)

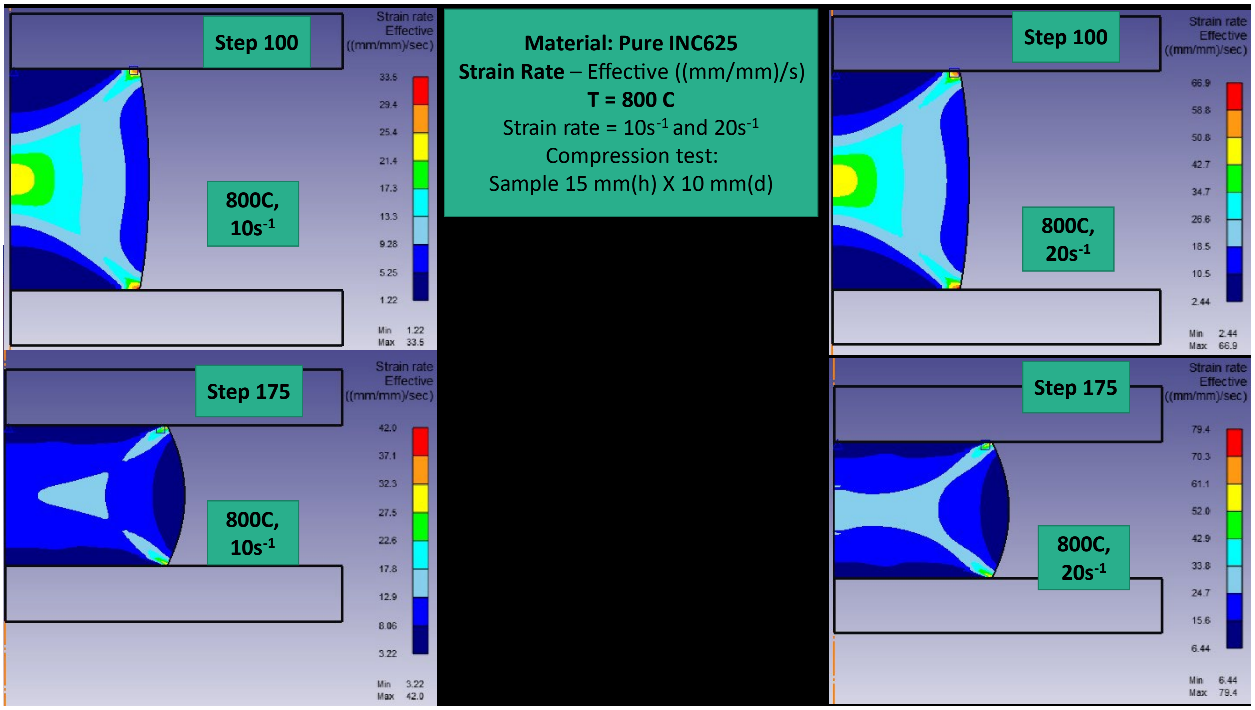

Material: Pure INC625
Strain – Effective (mm/mm)
T = 850 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 1s-1
Step 175
850C, 1s-1
Step 100
850C, 5s-1
Step 175
850C, 5s-1
Strain Effective (mm/mm)

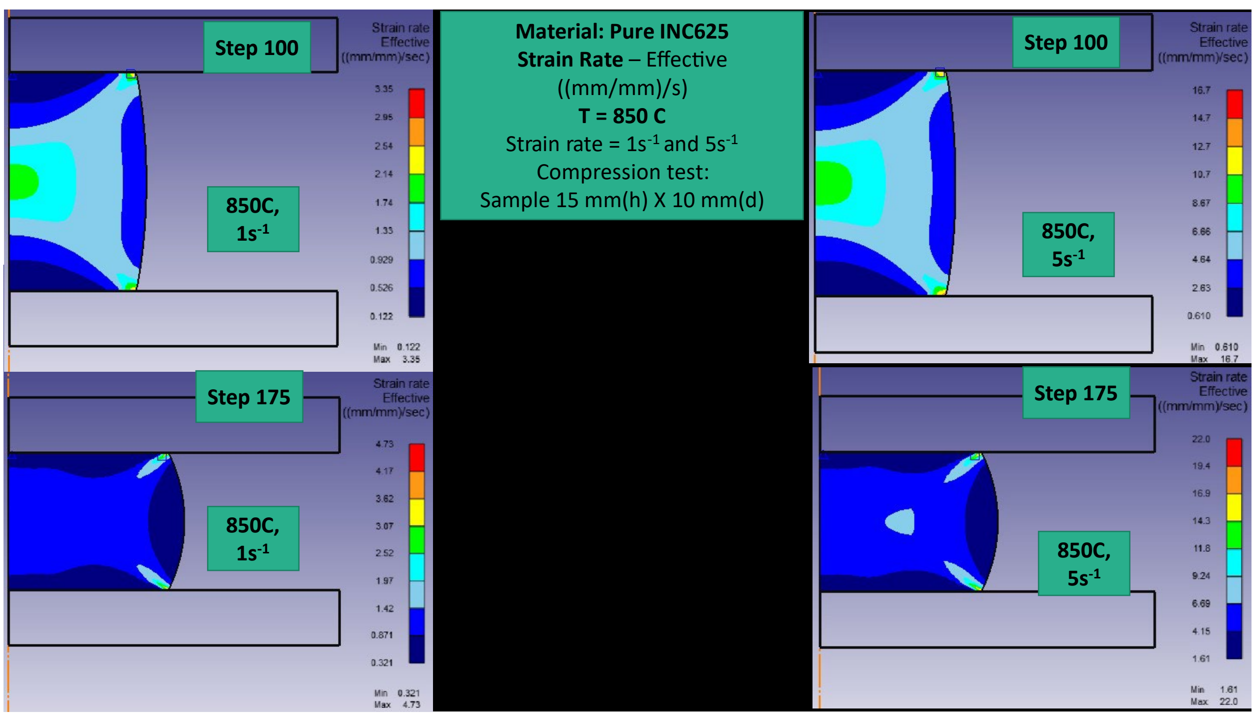

Material: Pure INC625
Strain – Effective (mm/mm)
T = 850 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 10s-1
Step 175
850C, 10s-1
Step 100
850C, 20s-1
Step 175
850C, 20s-1
Strain Effective (mm/mm)

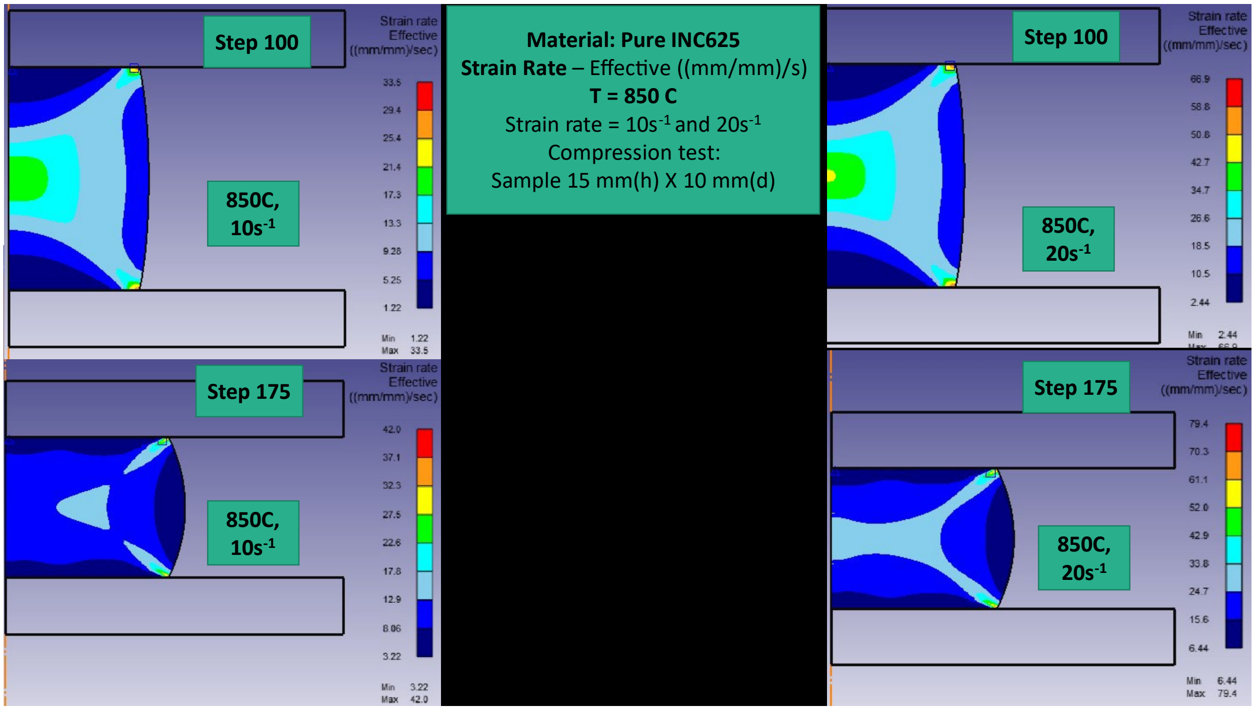

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 1s-1
Step 175
750C, 1s-1
Step 100
750C, 5s-1
Step 175
750C, 5s-1
Strain rate Effective ((mm/mm)/sec)

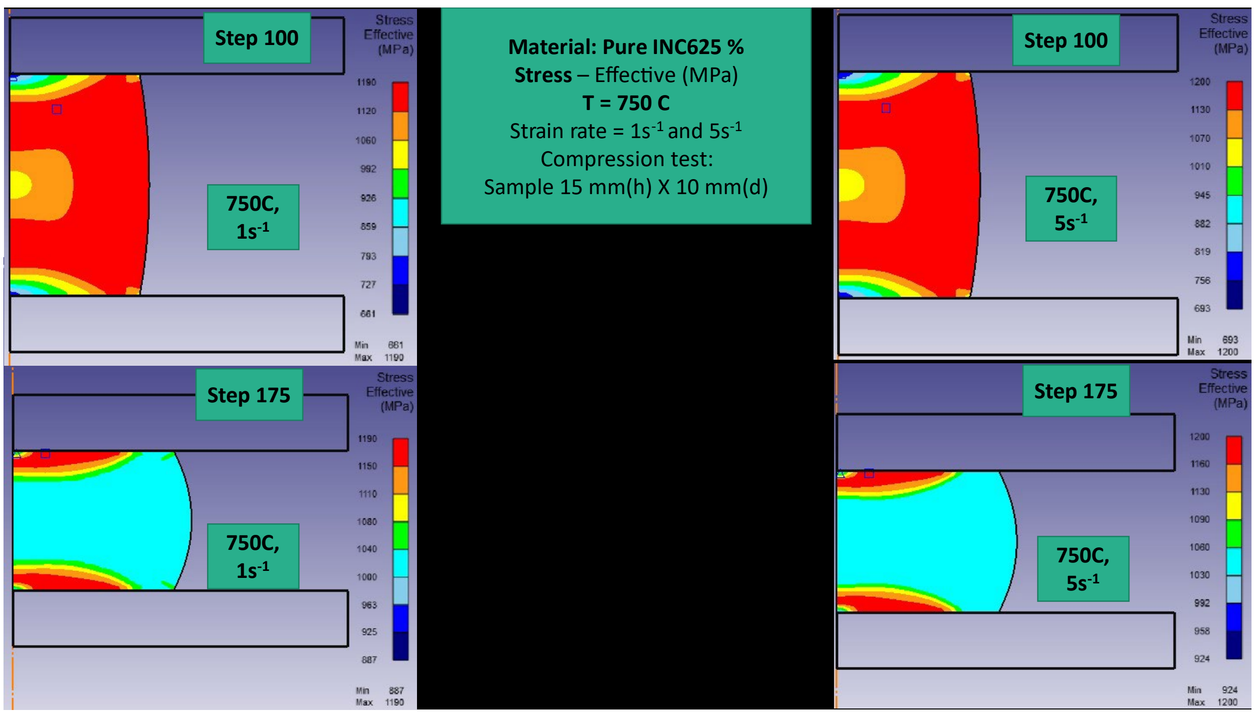

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 750 C
Strain rate = 10s^{-1} and 20s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 10s^{-1}
Strain rate Effective ((mm/mm)/sec)
33.5 29.4 25.4 21.4 17.3 13.3 9.28 5.25 1.22
Min 1.22 Max 33.5
Step 100
750C, 20s^{-1}
Strain rate Effective ((mm/mm)/sec)
66.9 58.8 50.8 42.7 34.7 26.6 18.5 10.5 2.44
Min 2.44 Max 66.9
750C, 10s^{-1}
Strain rate Effective ((mm/mm)/sec)
42.0 37.1 32.3 27.5 22.6 17.8 12.9 8.06 3.22
Min 3.22 Max 42.0
Step 175
750C, 20s^{-1}
Strain rate Effective ((mm/mm)/sec)
79.4 70.3 61.1 52.0 42.9 33.8 24.7 15.6 6.44
Min 6.44 Max 79.4

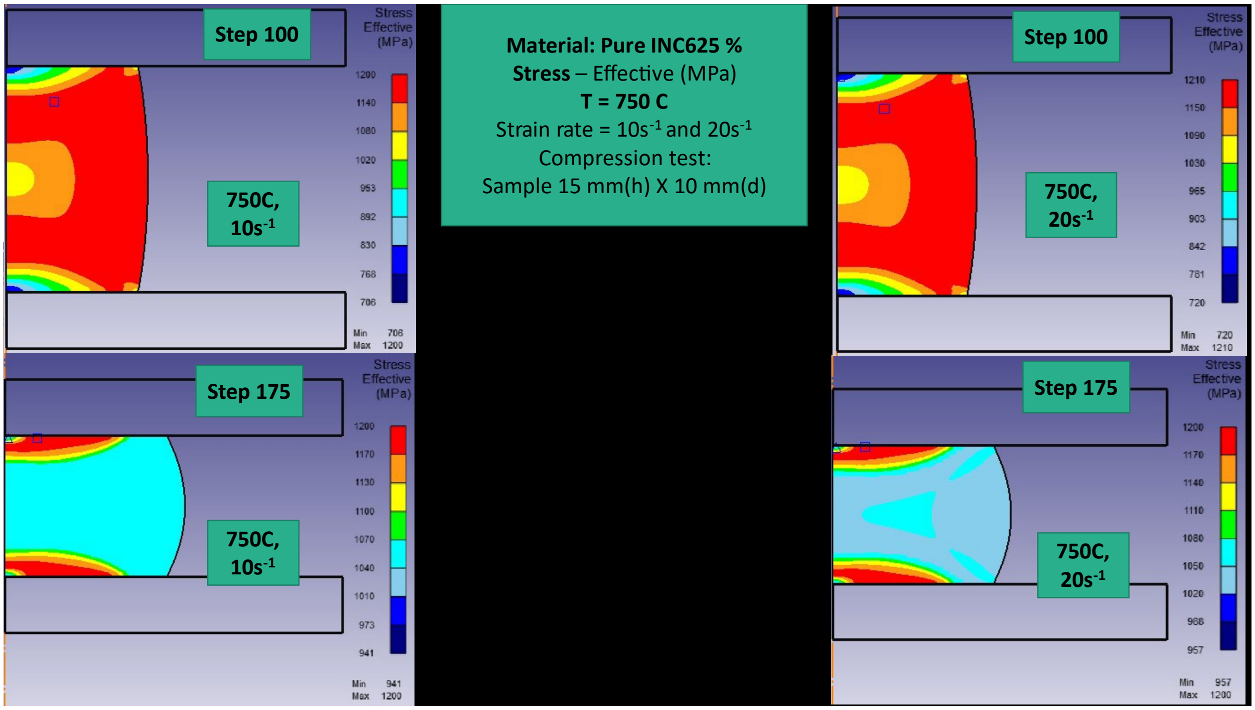

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 1s^{-1} and 5s^{-1}
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 1s^{-1}
Strain rate Effective ((mm/mm)/sec)
3.35 2.95 2.54 2.14 1.74 1.33 0.929 0.526 0.122
Min 0.122 Max 3.35
Step 100
800C, 5s^{-1}
Strain rate Effective ((mm/mm)/sec)
16.7 14.7 12.7 10.7 8.67 6.66 4.64 2.63 0.610
Min 0.610 Max 16.7
Step 175
800C, 1s^{-1}
Strain rate Effective ((mm/mm)/sec)
4.73 4.17 3.62 3.07 2.52 1.97 1.42 0.871 0.321
Min 0.321 Max 4.73
Step 175
800C, 5s^{-1}
Strain rate Effective ((mm/mm)/sec)
22.0 19.4 16.9 14.3 11.8 9.24 6.69 4.15 1.61
Min 1.61 Max 22.0

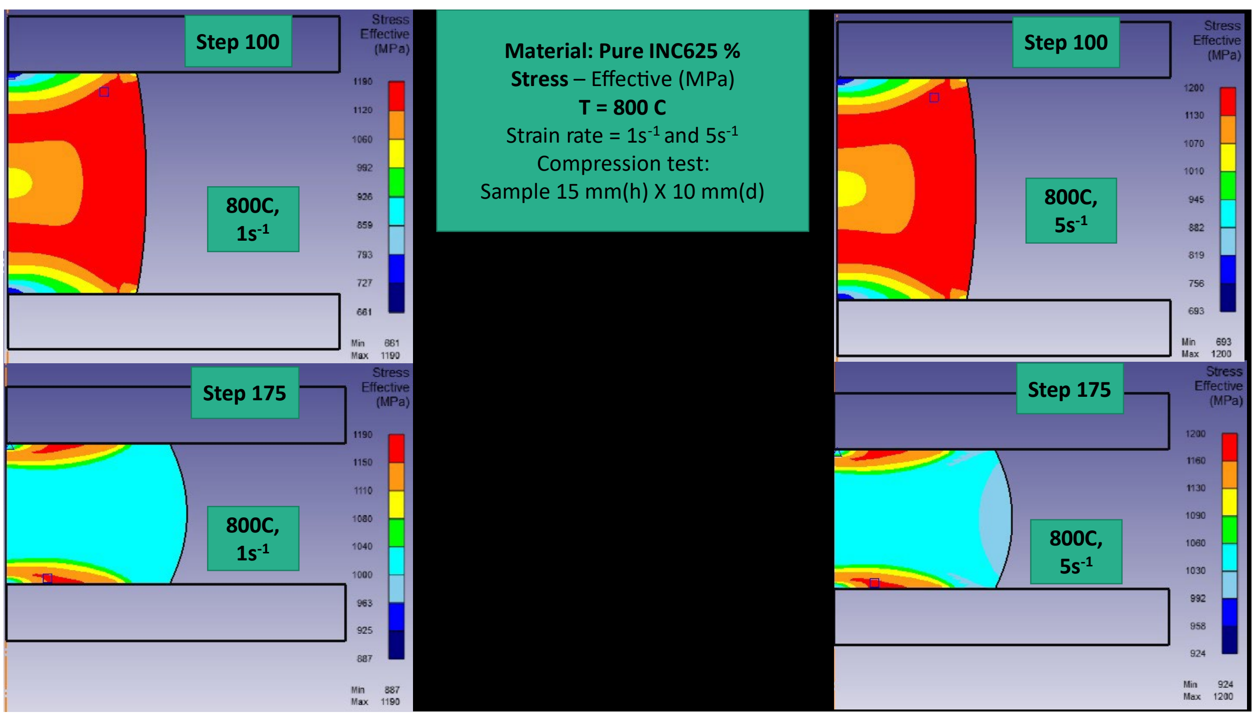

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Step 175
800C, 10s-1
Step 100
800C, 20s-1
Step 175
800C, 20s-1
Strain rate Effective ((mm/mm)/sec)

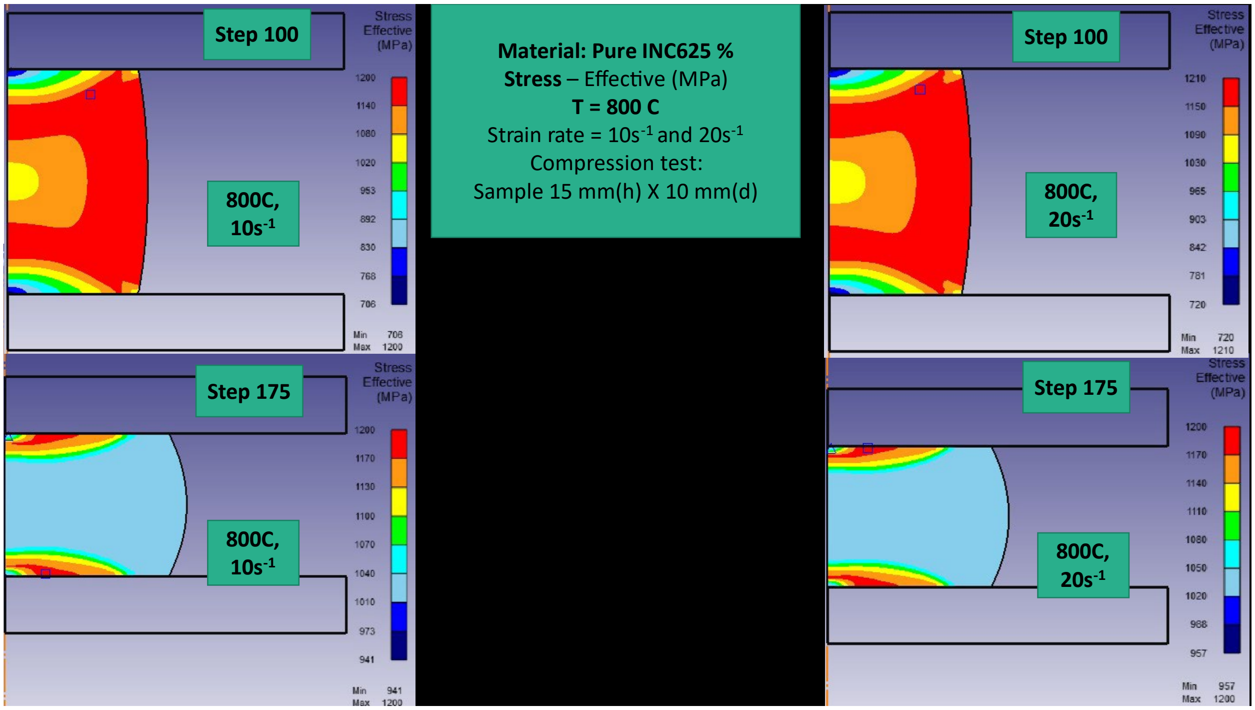

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 850 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 1s-1
Step 175
850C, 1s-1
Step 100
850C, 5s-1
Step 175
850C, 5s-1
Strain rate Effective ((mm/mm)/sec)

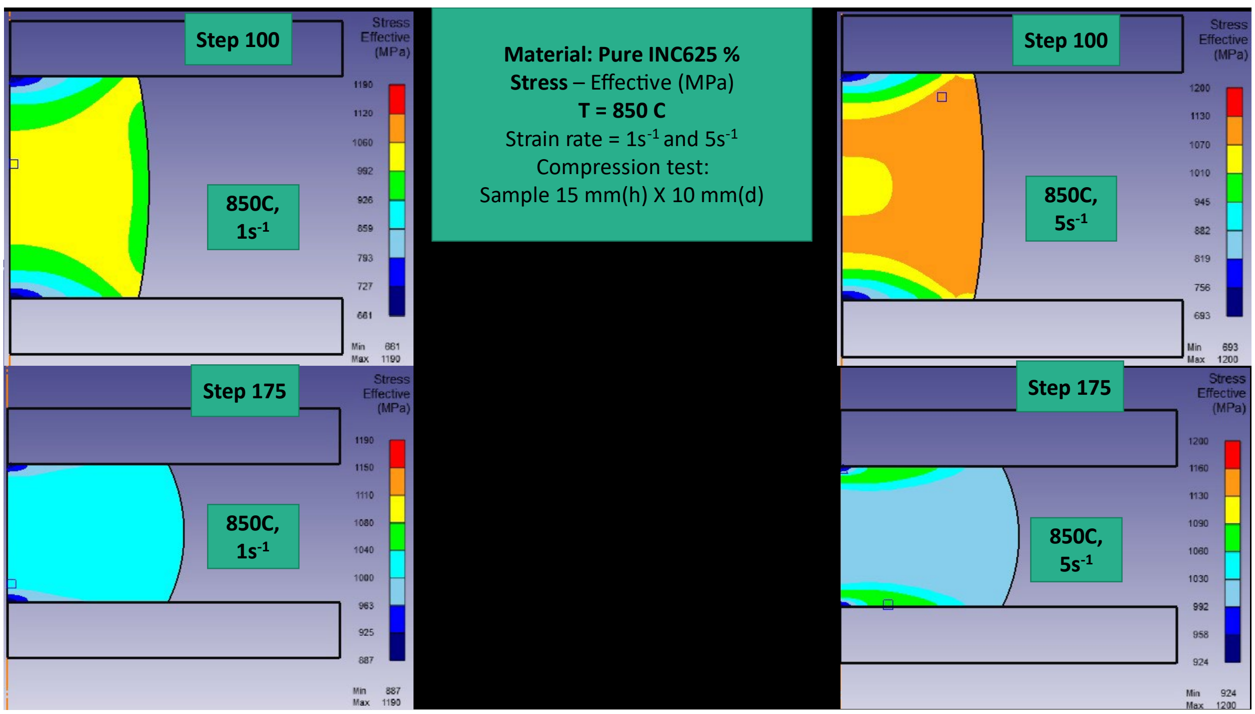

Material: Pure INC625
Strain Rate – Effective ((mm/mm)/s)
T = 850 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 10s-1
Step 175
850C, 10s-1
Step 100
850C, 20s-1
Step 175
850C, 20s-1
Strain rate Effective ((mm/mm)/sec)

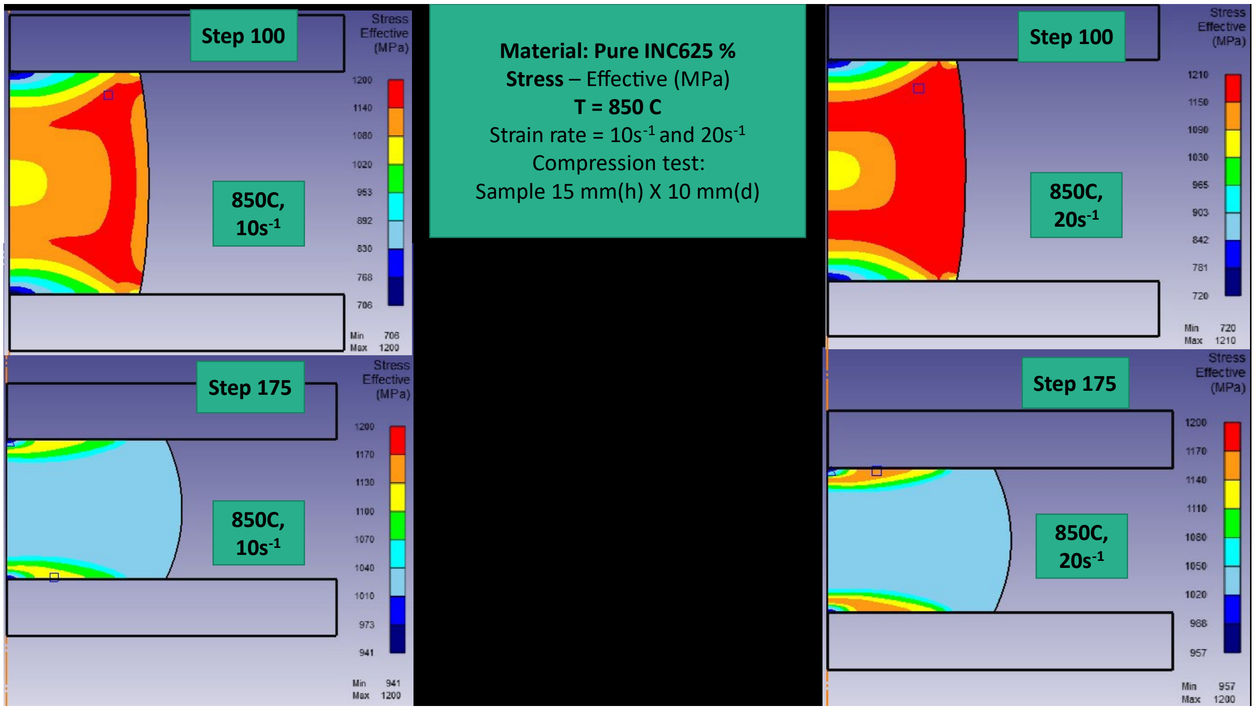

Material: Pure INC625 %
Stress – Effective (MPa)
T = 750 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
750C, 1s-1
Step 175
750C, 1s-1
Step 100
750C, 5s-1
Step 175
750C, 5s-1
Stress Effective (MPa)


Step 100
Stress Effective (MPa)
750C, 10s-1
Material: Pure INC625 %
Stress – Effective (MPa)
T = 750 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Stress Effective (MPa)
750C, 20s-1
Step 175
Stress Effective (MPa)
750C, 10s-1
Step 175
Stress Effective (MPa)
750C, 20s-1


Step 100
Stress Effective (MPa)
800C, 1s-1
Material: Pure INC625 %
Stress – Effective (MPa)
T = 800 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
Stress Effective (MPa)
800C, 5s-1
Step 175
Stress Effective (MPa)
800C, 1s-1
Step 175
Stress Effective (MPa)
800C, 5s-1


Material: Pure INC625 %
Stress – Effective (MPa)
T = 800 C
Strain rate = 10s-1 and 20s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
800C, 10s-1
Step 175
800C, 10s-1
Step 100
800C, 20s-1
Step 175
800C, 20s-1
Stress Effective (MPa)


Material: Pure INC625 %
Stress – Effective (MPa)
T = 850 C
Strain rate = 1s-1 and 5s-1
Compression test:
Sample 15 mm(h) X 10 mm(d)
Step 100
850C, 1s-1
Step 175
850C, 1s-1
Step 100
850C, 5s-1
Step 175
850C, 5s-1
Stress Effective (MPa)



Material: Pure INC625
Steps of the simulations 100 of 200 and 175 of 200

Strain Rate – Effective ((mm/mm)/s)

T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	2.95	0.92	14.7	4.64	29.4	9.28	58.8	18.5
Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6
T= 800 C								
Step 100	2.54	0.92	12.7	4.64	21.4	9.28	50.8	18.5
Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6
T= 850 C								
Step 100	2.14	0.92	10.7	4.64	21.4	9.28	50.8	18.5
Step 175	1.42	0.87	6.69	4.15	12.9	8.06	33.8	15.6

Strain – Effective (mm/mm)

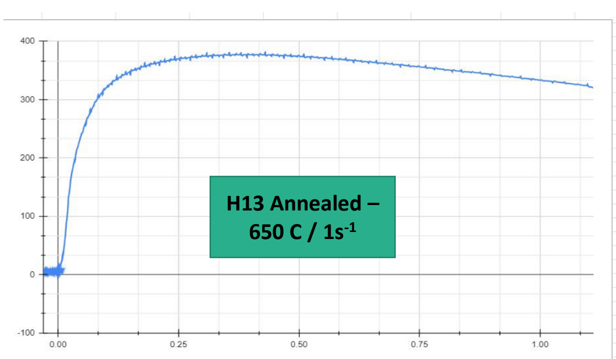
T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	0.64	0.41	0.64	0.41	0.64	0.41	0.64	0.41
Step 175	1.75	0.79	1.74	0.79	1.74	0.79	1.74	0.79
T= 800 C								
Step 100	0.64	0.41	0.64	0.41	0.64	0.41	0.64	0.41
Step 175	1.75	0.79	1.74	0.79	1.74	0.79	1.74	0.79
T= 850 C								
Step 100	0.64	0.41	0.57	0.41	0.57	0.41	0.57	0.41
Step 175	1.36	0.79	1.55	0.79	1.55	0.79	1.55	0.79

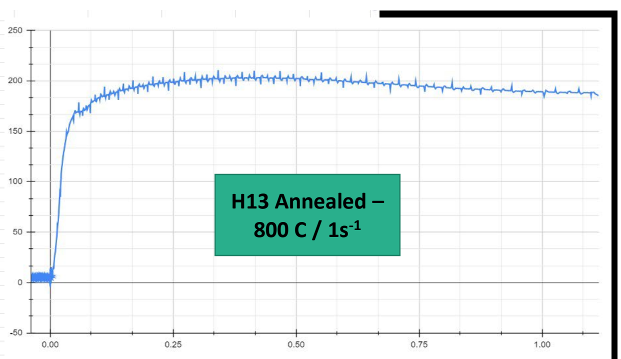
Stress – Effective (MPa)

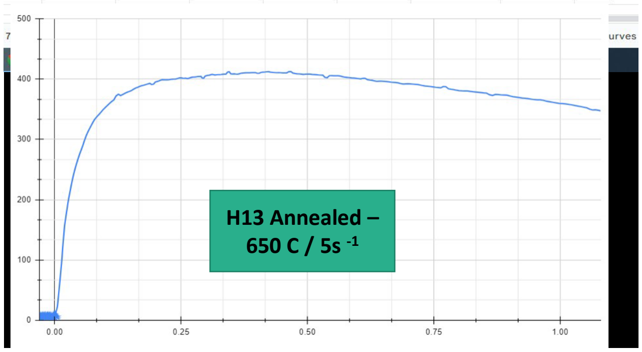
T= 750 C	$1 S^{-1}$ Center	$1 S^{-1}$ Border	$5 S^{-1}$ Center	$5 S^{-1}$ Border	$10 S^{-1}$ Center	$10 S^{-1}$ Border	$20 S^{-1}$ Center	$20 S^{-1}$ Border
Step 100	1060	1190	1070	1200	1080	1200	1090	1210
Step 175	1040	1040	1060	1060	1070	1070	1050	1050
T= 800 C								
Step 100	1060	1190	1070	1200	1080	1200	1090	1210
Step 175	1040	1040	1080	1030	1040	1040	1050	1050
T= 850 C								
Step 100	1060	992	1070	1130	1080	1140	1090	1210
Step 175	1040	1040	1030	1030	1040	1040	1050	1050

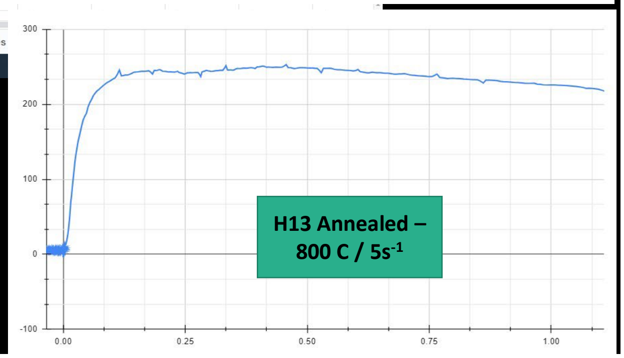
Comparisons and evaluations through Strain Rates, Strain and Stress
Materials: H13 annealed, H13 Hardened, INC625 + 5w%TiC, Pure INC625 and H13 HARDENED + (INC625 + 5w%TiC)

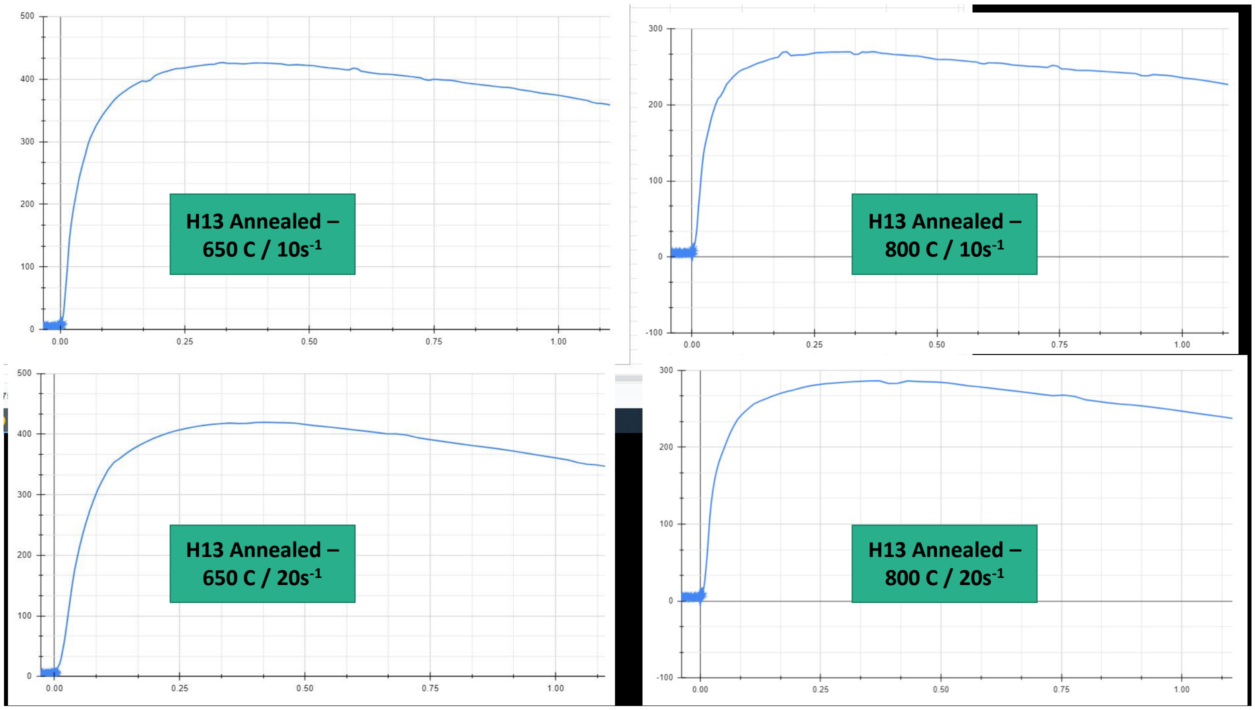
The following slides present the results of Gleeble 3500 compression tests and appropriate parameters.

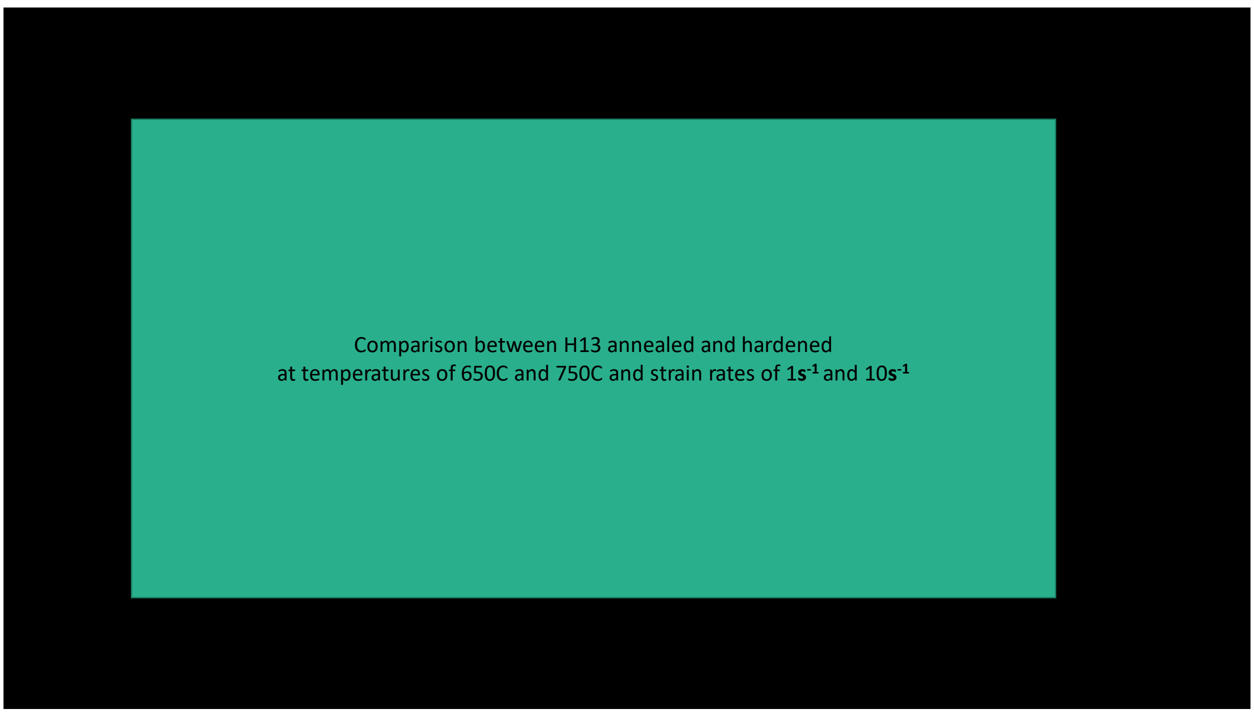


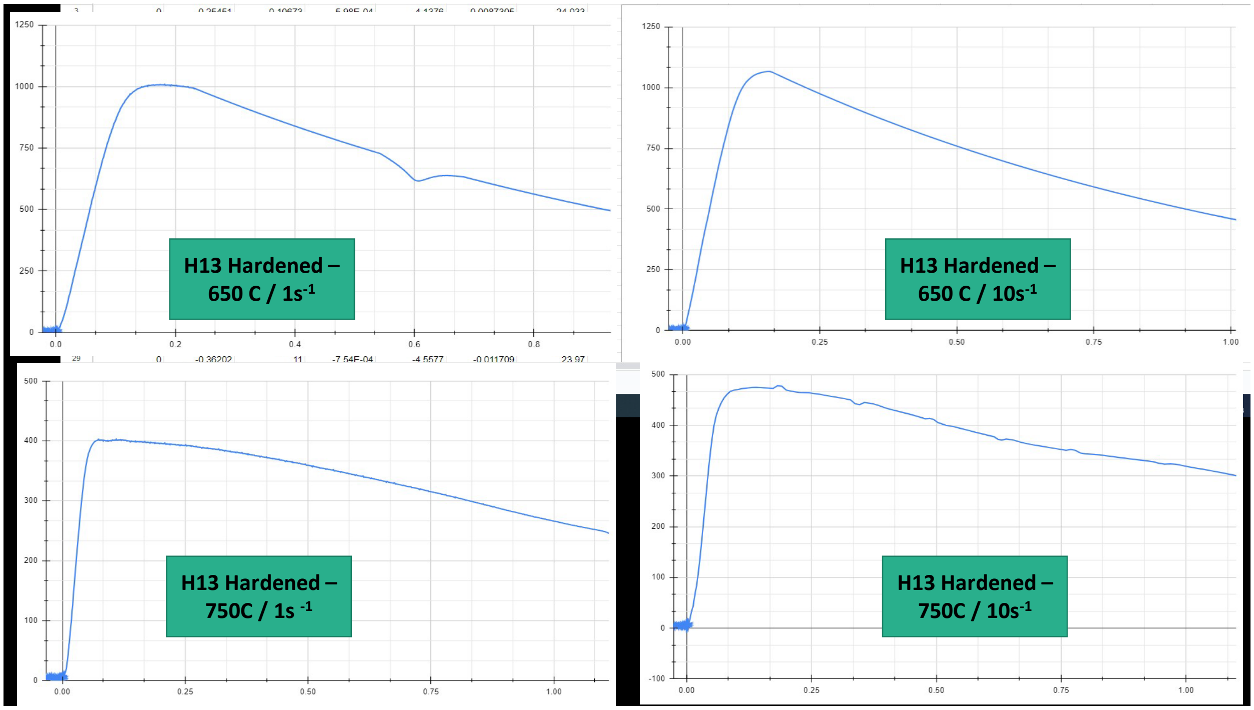


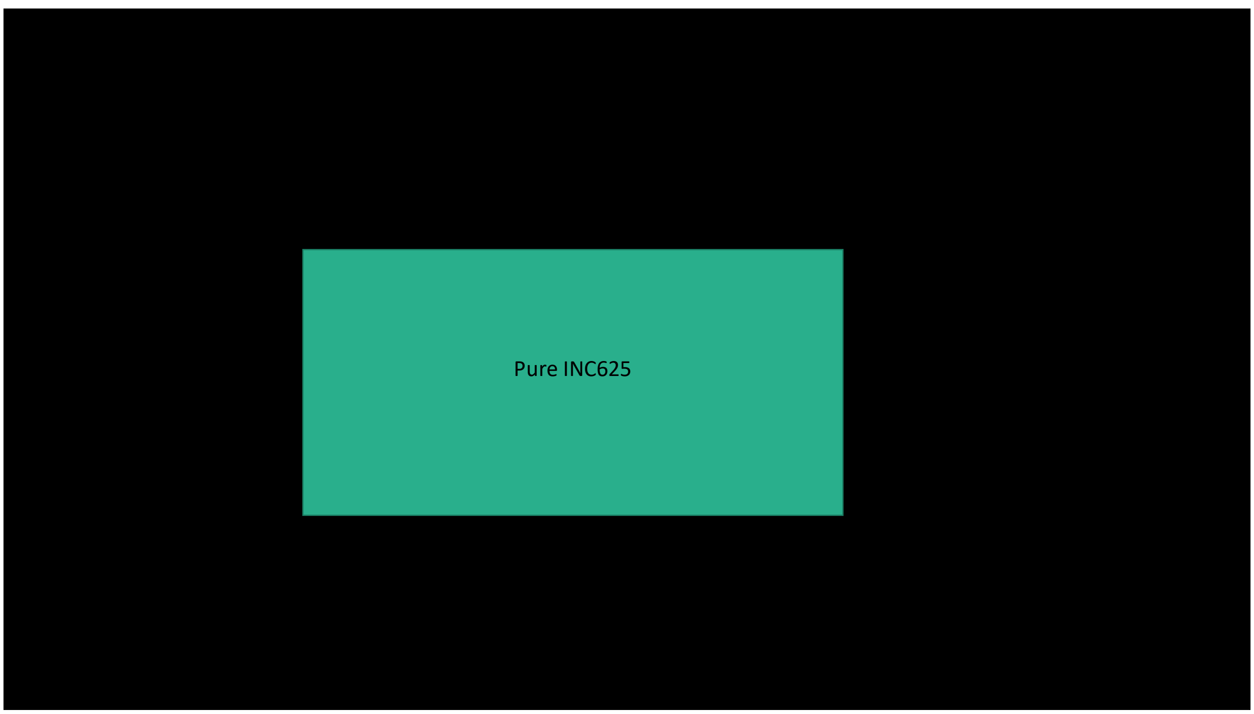


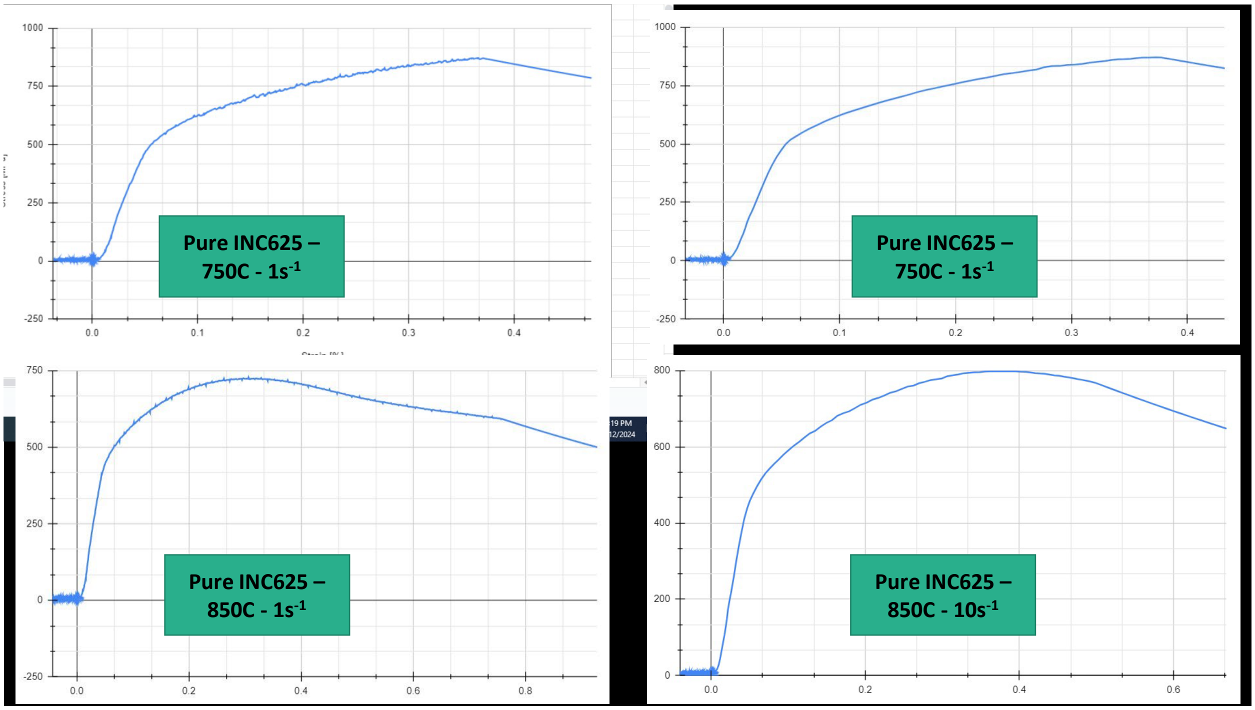


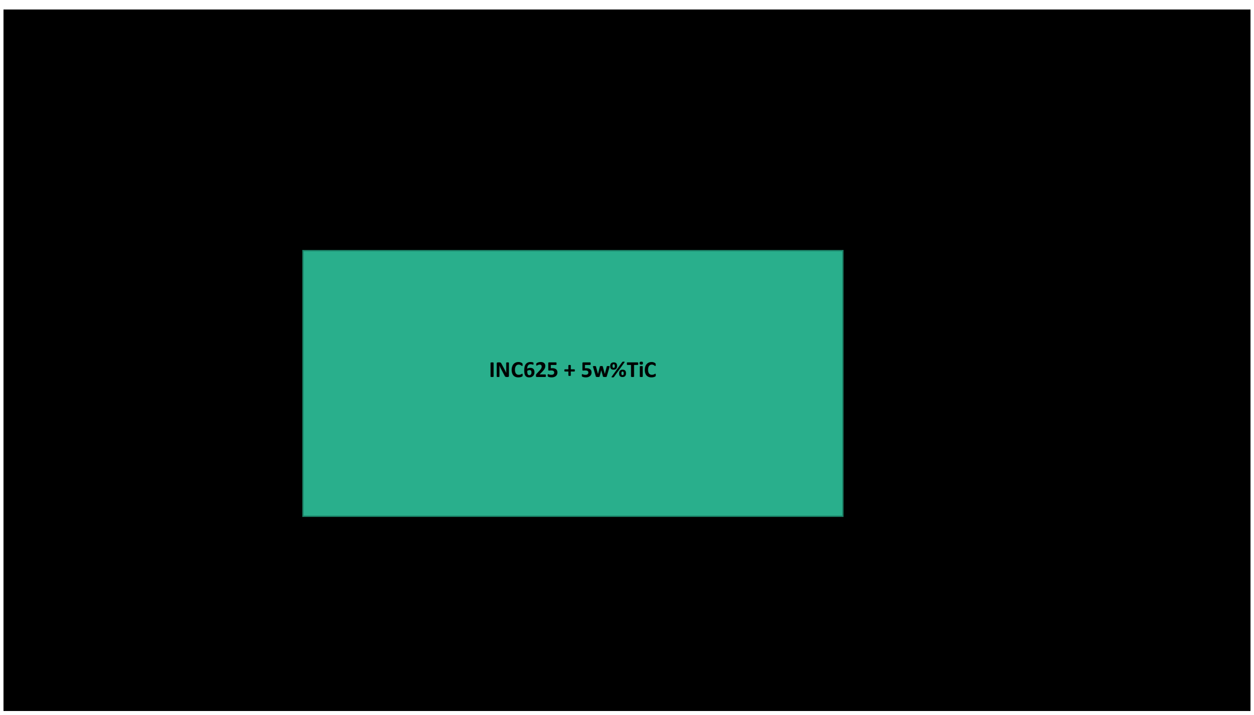

H13 Annealed – 650 C / 10s^{-1}
H13 Annealed – 800 C / 10s^{-1}
H13 Annealed – 650 C / 20s^{-1}
H13 Annealed – 800 C / 20s^{-1}

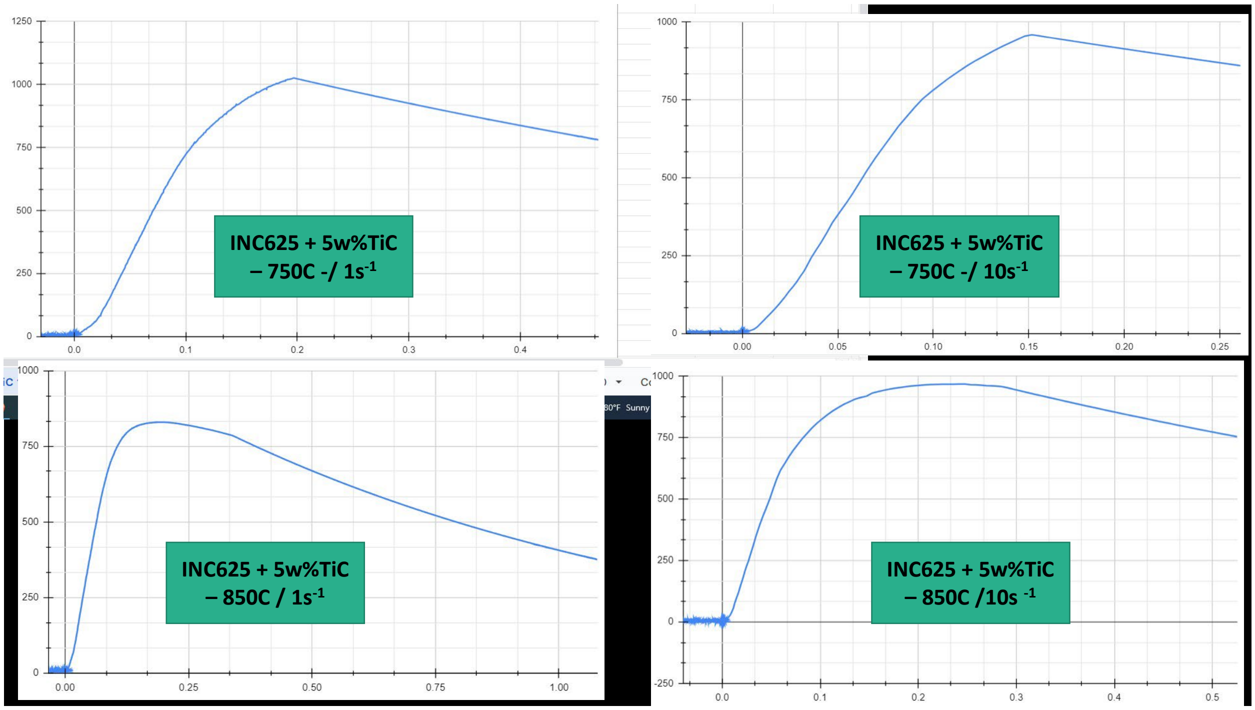

Comparison between H13 annealed and hardened
at temperatures of 650C and 750C and strain rates of 1s^{-1} and 10s^{-1}

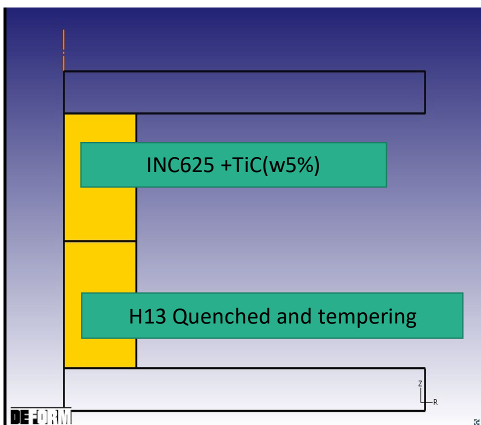

H13 Hardened – 650 C / 1s-1
H13 Hardened – 650 C / 10s-1
H13 Hardened – 750C / 1s -1
H13 Hardened – 750C / 10s-1


Pure INC625


Pure INC625 – 750C - 1s-1
Pure INC625 – 750C - 1s-1
Pure INC625 – 850C - 1s-1
Pure INC625 – 850C - 10s-1
1000
750
500
250
0
-250
0.0
0.1
0.2
0.3
0.4
0.6
0.8
800
600
400
200
19 PM
12/2024

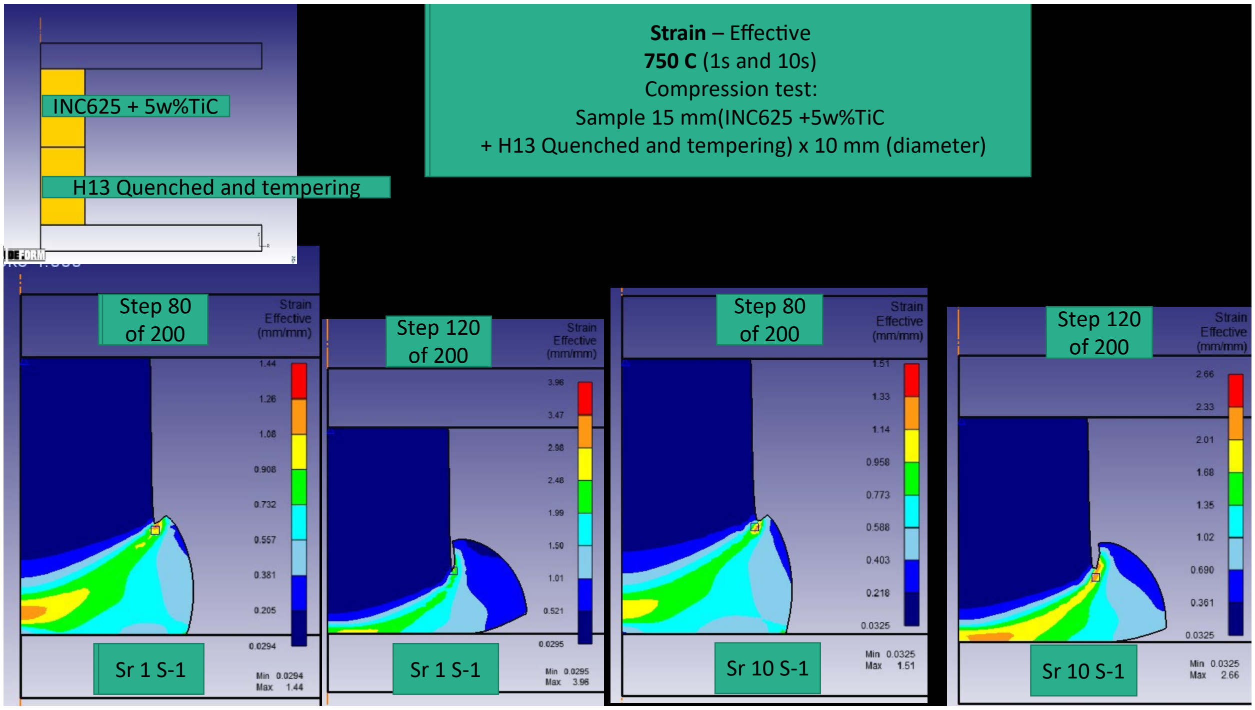

INC625 + 5w%TiC

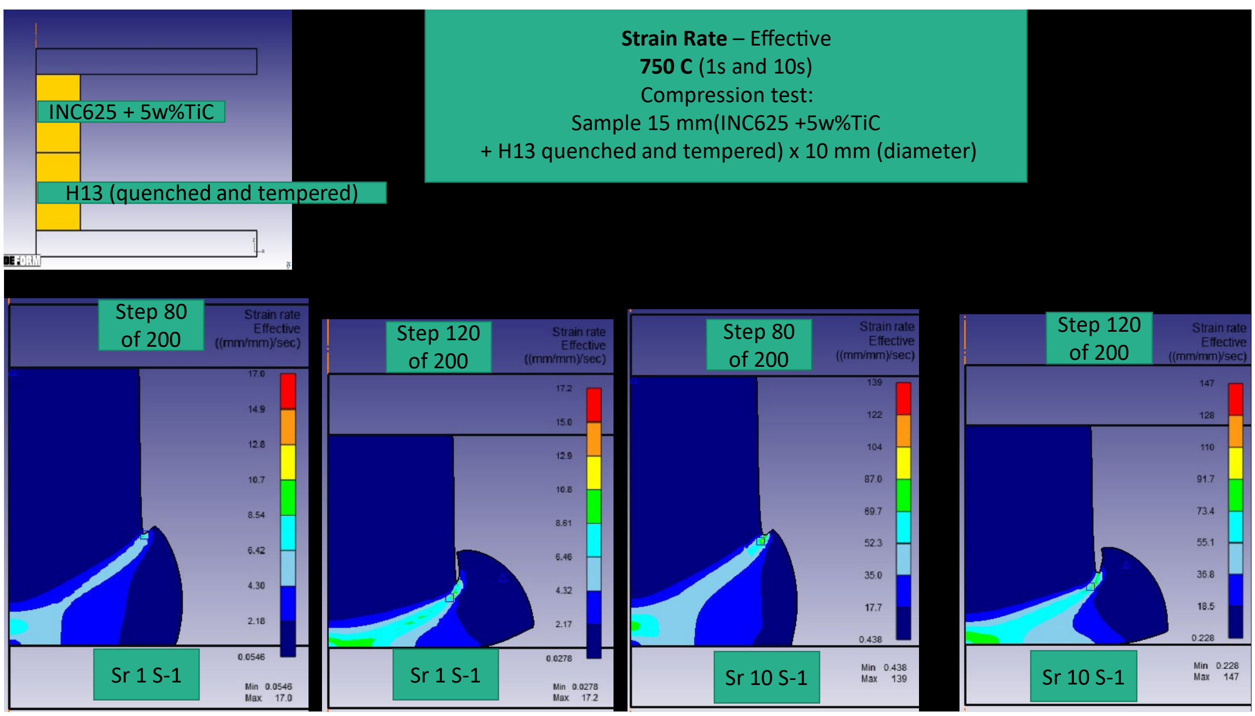


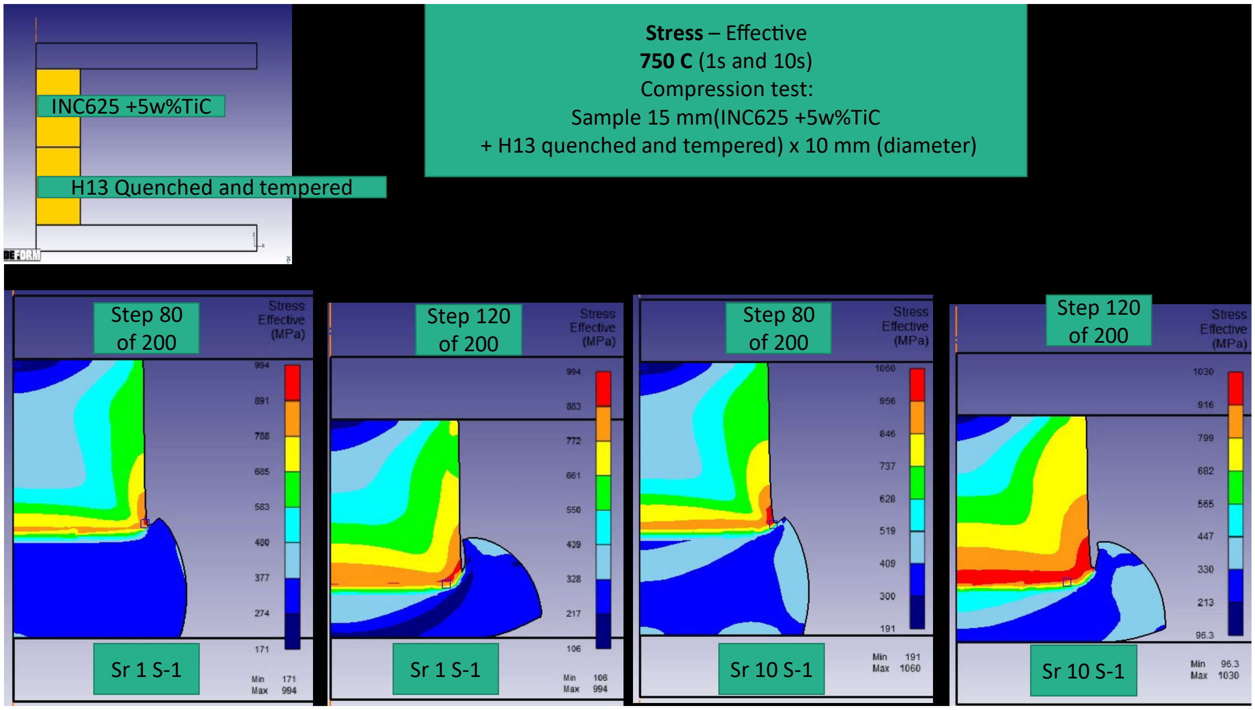


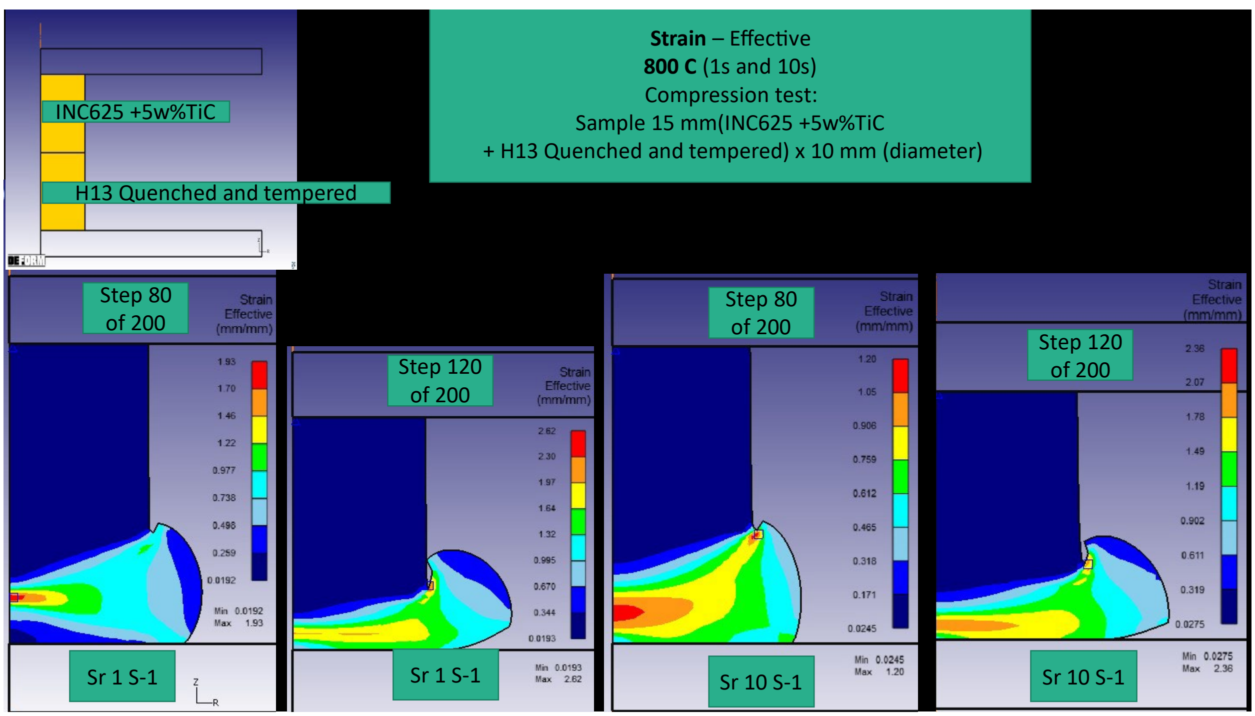
Updates of compression between two materials with the objective to evaluate the behavior, mainly on the boundary.

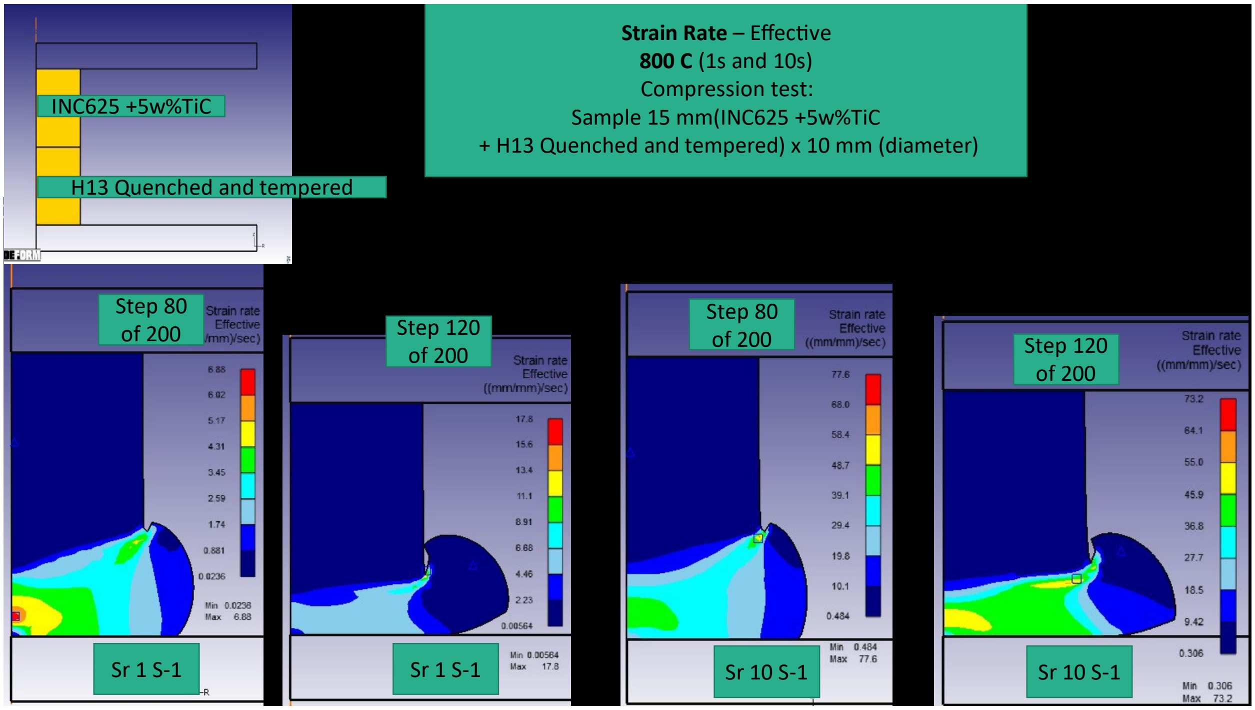
Comparison between the behavior of INC625 and IN625 + 5w%TiC.

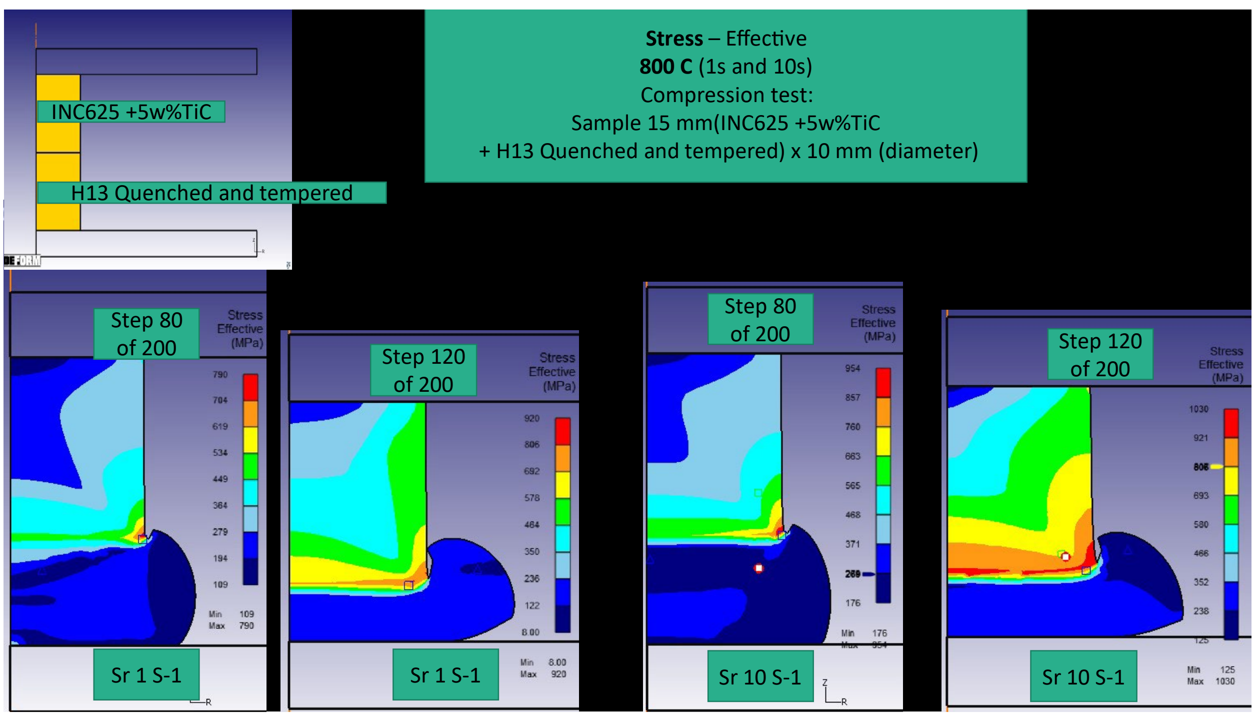

Strain – Effective
750 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 Quenched and tempering) x 10 mm (diameter)
INC625 + 5w%TiC
H13 Quenched and tempering
Step 80 of 200
Step 120 of 200
Step 80 of 200
Step 120 of 200
Strain Effective (mm/mm)
Sr 1 S-1
Sr 1 S-1
Sr 10 S-1
Sr 10 S-1
Min 0.0294 Max 1.44
Min 0.0295 Max 3.96
Min 0.0325 Max 1.51
Min 0.0325 Max 2.66


Strain Rate – Effective
750 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 quenched and tempered) x 10 mm (diameter)
INC625 + 5w%TiC
H13 (quenched and tempered)
Step 80 of 200
Step 120 of 200
Step 80 of 200
Step 120 of 200
Strain rate Effective ((mm/mm)/sec)
Sr 1 S-1
Sr 1 S-1
Sr 10 S-1
Sr 10 S-1
Min 0.0546 Max 17.0
Min 0.0278 Max 17.2
Min 0.438 Max 139
Min 0.228 Max 147


Stress – Effective
750 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 quenched and tempered) x 10 mm (diameter)
INC625 +5w%TiC
H13 Quenched and tempered
Step 80 of 200
Step 120 of 200
Step 80 of 200
Step 120 of 200
Stress Effective (MPa)
Sr 1 S-1
Sr 1 S-1
Sr 10 S-1
Sr 10 S-1


Strain – Effective
800 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 Quenched and tempered) x 10 mm (diameter)
INC625 +5w%TiC
H13 Quenched and tempered
Step 80 of 200
Step 120 of 200
Step 80 of 200
Step 120 of 200
Strain Effective (mm/mm)
Sr 1 S-1
Sr 1 S-1
Sr 10 S-1
Sr 10 S-1


Strain Rate – Effective
800 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 Quenched and tempered) x 10 mm (diameter)
INC625 +5w%TiC
H13 Quenched and tempered
Step 80 of 200
Sr 1 S-1
Step 120 of 200
Sr 1 S-1
Step 80 of 200
Sr 10 S-1
Step 120 of 200
Sr 10 S-1


Stress – Effective
800 C (1s and 10s)
Compression test:
Sample 15 mm(INC625 +5w%TiC
+ H13 Quenched and tempered) x 10 mm (diameter)
INC625 +5w%TiC
H13 Quenched and tempered
Step 80 of 200
Sr 1 S-1
Step 120 of 200
Sr 1 S-1
Step 80 of 200
Sr 10 S-1
Step 120 of 200
Sr 10 S-1

Proposition of tolling to use in hot forging process and modeling in DEFORM 2D/3D with INC625 + 5w%TiC