Analysis of rheological properties of metals during hot compression

1. Introduction

In the industrial context, the rheological characterization of metallic materials is fundamental to calibrating finite element simulations (FEM) of manufacturing processes.
To this aim, standard tests such as tensile, compression, and torsion ones on metallic specimens are exploited to find the constitutive equations that govern plastic deformation.
The compression test is widely used to simulate bulk manufacturing processes, since:

- The test is conducted under a monoaxial stress state which leads to easily calculating the stress-strain curves;

- It can be used to obtain high-strain deformations that can be related to real industrial deformation processes (tensile tests are limited by necking and fracture);

- It can be obtained in a stress state which impairs the formation of holes/cavities/cracks in the material like happens under a tensile state of stress.

2. Hot compression test

This type of test consists of the controlled compression of a standard cylindrical specimen between two punches driven by a press machine. The output of this test is the stroke of the punches versus the force applied (see Fig. 1 – on the left). From these data, it is possible to calculate the true strain (Eq. 1) as well as the true strain (Eq. 3).
Fig. 1 (on the right) shows an example of a true stress/true strain curve computed from raw data.

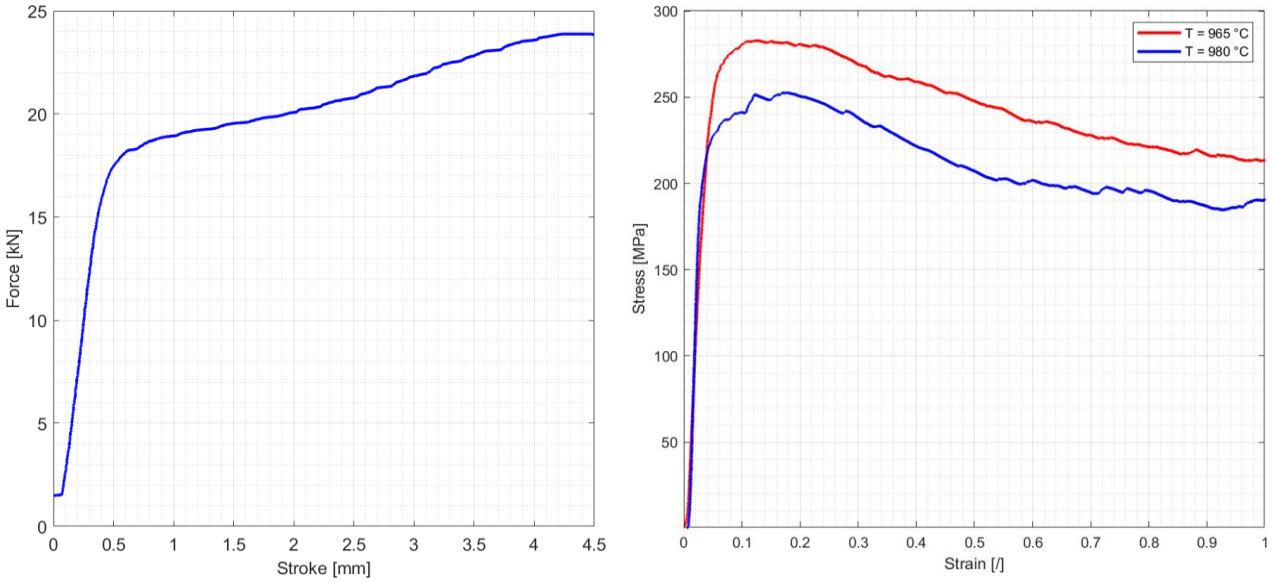


Fig. 1. *(On the left) Force-stroke diagram and stress-strain curve of Inconel 718 at 965°C and 980°C (on the right).*

$$\varepsilon = \ln\left(\frac{h_0 + stroke}{h_0}\right) \quad (1)$$

$$A = A_0 e^{-\varepsilon} \quad (2)$$

$$\sigma = \frac{Force}{A} \quad (3)$$

Within the cold regime, the true stress/true strain curve can be immediately used to calculate the Hollow's coefficients, namely *K* and *n* (Eq. 4):

$$\sigma = K\varepsilon^n \quad (4)$$

Within the hot regime, the temperature and strain rate (Eq. 5) must be considered.
It is worth noting that, since the strain rate is an influence variable it is not possible to carry out tests at a constant die speed (*v*) or the strain rate will be varied during tests. For this reason, compression tests are performed at variable punch speeds to keep the material strain rate.
To characterize a metallic material from the rheological point of view, several tests were performed at different strain rates and temperatures to obtain *C* and *m* parameters.
More accurate laws are also available in literature as reported in Eqs. 6,7,8.

$$\dot{\varepsilon} = \frac{v}{h} \quad (5)$$

$$\sigma = C\dot{\varepsilon}^m \quad (6)$$

$$\sigma = e^{m_1 T}\varepsilon^{m_2}\dot{\varepsilon}^{m_3} e^{\frac{m_4}{\varepsilon}} \quad (7)$$

$$\sigma = Ae^{m_1 T}\varepsilon^{m_2}\dot{\varepsilon}^{m_3} e^{\frac{m_4}{\varepsilon}}(1+\varepsilon)^{m_5 T} e^{m_7 T}\dot{\varepsilon}^{m_8 T} T^{m_9} \quad (8)$$

3. Friction influence

The aforementioned Eqs are valid, only if the compression test is performed under a monoaxial state of stress. This assumption can be considered true as long as the specimen remains cylindrical.
The friction between the specimen and the die is the main reason why the monoaxial state of stress is lost, since:

-it generates a shear stress at the interface between the sample and the die;
- it induces barreling phenomenon causing a variation of the specimen area along its axis;

To prevent friction, the adoption of lubricants is strongly suggested.

Even with the adoption of lubricants, barreling can occur. In this scenario, data are considered reliable only if the maximum relative deviation between the maximum diameter and the minimum one is lower than 10%. For higher values, barreling become predominant and the test is considered no more valid.

4. Experimental procedure

The Gleeble 3800® thermal-mechanical simulator is a horizontal press with a maximum load of 200 kN (20 t) which can operate over a wide range of temperatures (from room temperature to 3000°C) by imposing strain rates from 0.001 to 100 s^{-1}. The direct resistance heating system of the Gleeble 3800-GTC can heat specimens at rates of more than 10,000°C/sec or can hold steady-state equilibrium temperatures within ±1°C.

Fig. 2 shows an example of compression tests performed on the Gleeble 3800. The sample, heated by the Joule effect, is compressed between two punches until the desired final height. Thermocouples welded on the sample provide signals for accurate feedback control of specimen temperature.

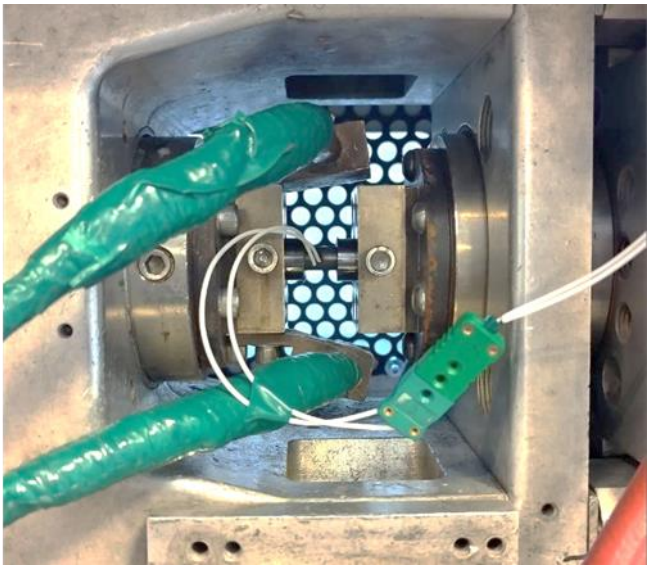


Fig. 2. *Compression test setup.*

5. Lab experience

The laboratory experience consists of the execution of two compression test on Inconel 718 samples at fix thermo-mechanical conditions.
For the tests, the cooling conditions will be varied as follows:

- 1) “Graphite”: a thin sheet of graphite will be put among punches and the specimen
- 2) “Dry”: tests will be performed without the use of any lubricant

At the end of the test, the friction effect will be evaluated by calculating the maximum relative deviation between the maximum diameter and the minimum one.
As previously specified, tests will be considered reliable only if the absolute difference in diameter will be contained within the 10%.

Table 1. *Laboratory tests results.*

	D_{max} (mm)	D_{max} (mm)	$\frac{D_{MAX}-D_{MIN}}{D_{MAX}}*100$	Acceptability
Graphite				
"Dry"				

6. Rheological constants identification

In the following pages, will be given four flow curves obtained at two different temperatures and strain rates. For each temperature, it is asked to graphically obtain the reological constant of the material, on the basis of the following model:

$$\sigma = C\dot{\varepsilon}^m$$

Flow curves for different stain rates at the temperature of 980°C and 1000°C are given in Fig. 3 and 4, respectively.
For a fixed strain of 0.06, it is asked to draw the straight line on the log-log chart given in Fig. 6 and Fig. 7 corresponding to the following Eq:

$$\log(\sigma) = \log(C) + m\log(\dot{\varepsilon})$$

Subsequently calculate C and m values to properly complete Table 2.

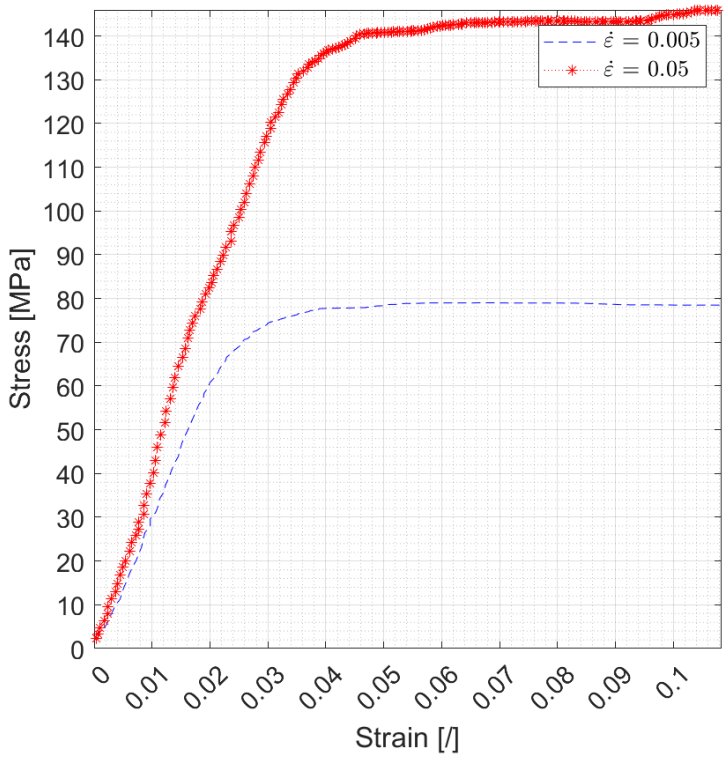


Fig. 3. *Inconel 718 flow curves for T=980°C.*

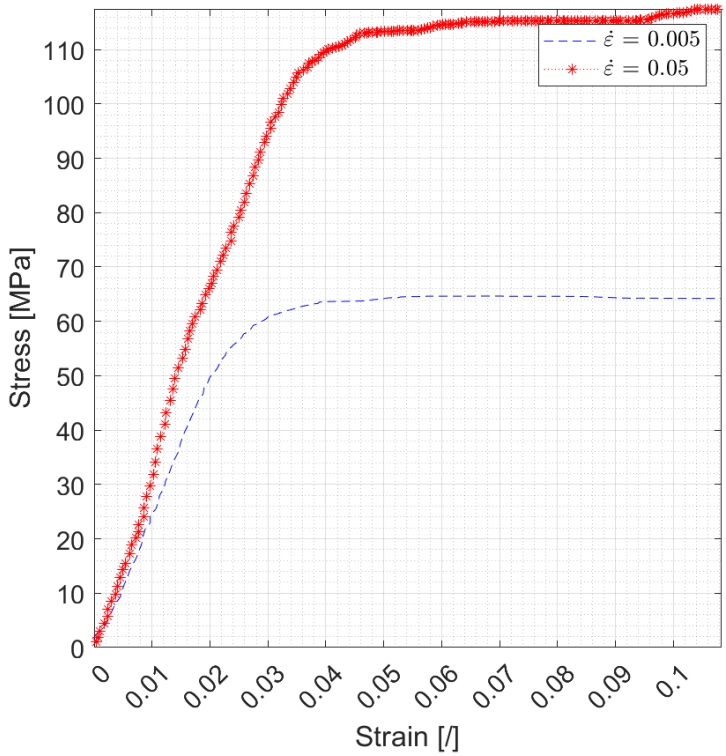


Fig. 4. *Inconel 718 flow curves for T=1000°C.*

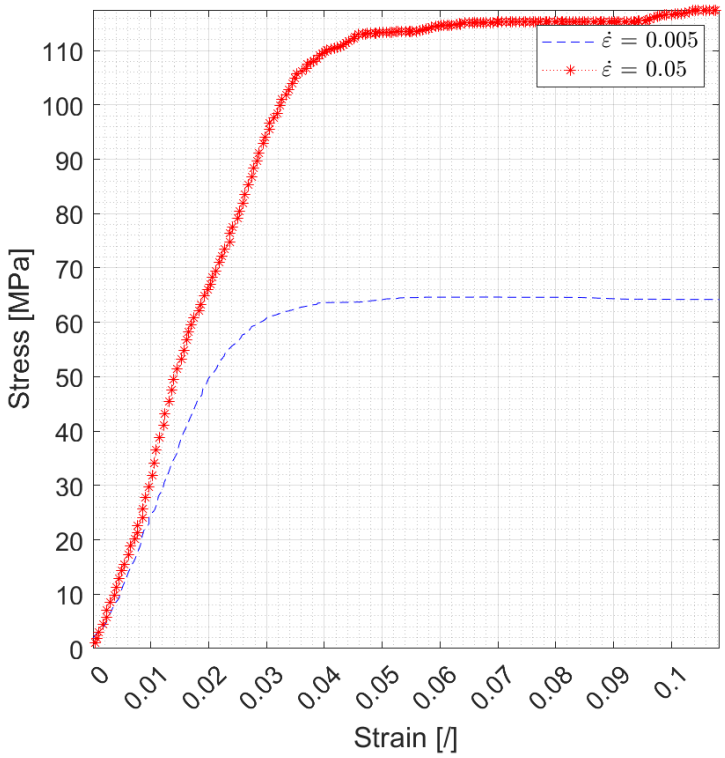
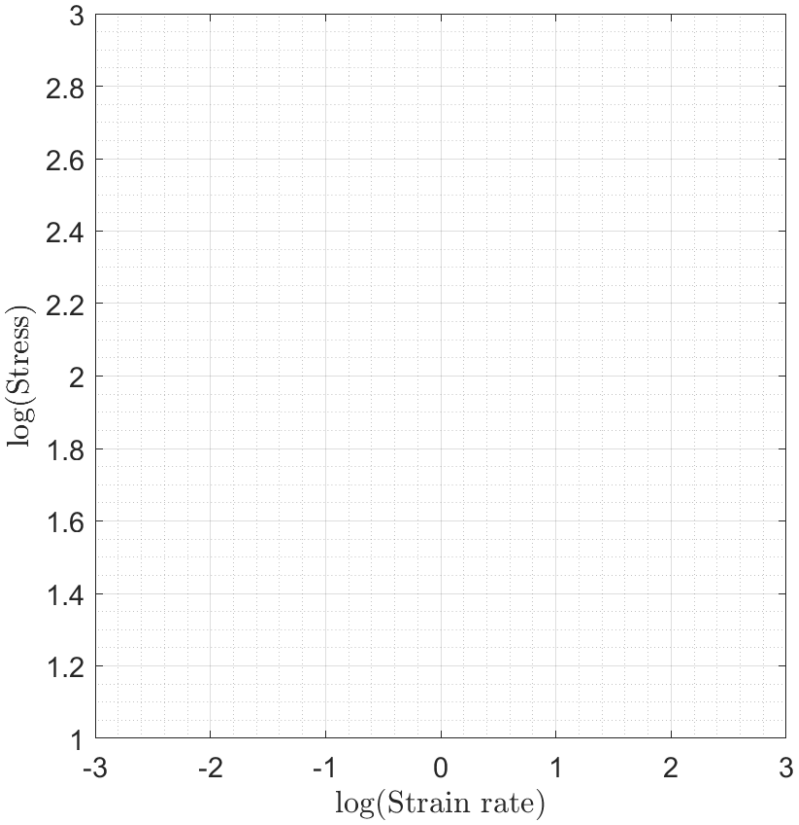


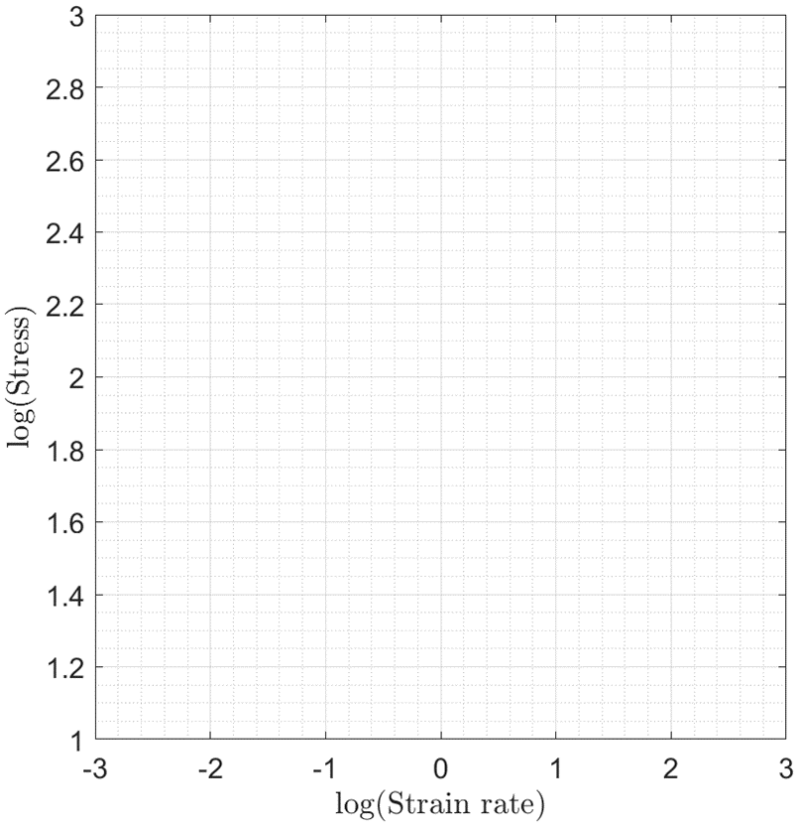
Fig. 5. *Inconel 718 flow curves for T=1000°C.*

Table 2. *Rheology constant identification.*

Temperature (°C)	C (MPa)	m(-)
980		
1000		

What are the conclusions related to C and m values obtained?


log(Stress)
log(Strain rate)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
-3
-2
-1
0
1
2
3


log(Stress)
log(Strain rate)
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
-3
-2
-1
0
1
2
3