

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF STRAIN RATE- AND TEMPERATURE-DEPENDENT FLOW BEHAVIOUR OF 1.7139 AND 1.1303 STEEL ALLOYS

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Abstract

The majority of highly stressed steel components are manufactured through hot forming due to the increase in strength and toughness resulting from the fine-grained microstructure. Thereby, the alloying element manganese is added to further increase the material strength and hardness. Also, sulfur is added in order to ensure an improved machinability in the post-machining steps. However, despite their individual benefits, manganese and sulfur tend to form non-metallic inclusions consisting of manganese sulfide (MnS) at high temperatures present during hot forming. These inclusions act as mechanical weak points in the steel matrix and can lead to an early failure of components. In order to accurately model the hot forming process by taking this into account and to predict the final properties of the component, a detailed numerical description of the behaviour of the steel matrix as well as the MnS-inclusions is required. Therefore, the focus of this paper lies in the characterisation of the flow behaviour of two commonly used steel alloys containing varying contents of manganese and sulfur, 1.7139 (16MnCrS5) and 1.1303 (38MnVS6). Cylinder compression tests are conducted at different strain rates as well as temperatures typical for hot forming to determine the resulting flow curves, which are then used to parameterise a flow curve model according to the approach of Hensel-Spittel. For this, a mesh study is conducted first, and the resulting force-displacement curves are compared to the experimental data. The models are validated using numerical simulations based on the finite element method (FEM) to recreate the force-displacement curve of the cylinder compression tests.

Keywords: Manganese steel, cylinder compression test, flow curves, finite element method

1. INTRODUCTION

Due to the strict requirements concerning CO₂-emissions, lightweight design becomes increasingly the focus in order to reduce moving loads, therefore saving energy and material cost [1]. Additionally, a long operating life of the final component is beneficial in this regard. For this, high strength materials are needed, paired with adequate toughness. Steels with significant amounts of manganese added as an alloying element offer these properties, reaching tensile strengths of more than 1,000 MPa in case of 1.7139 and up to 900 MPa for 1.1303 depending on the heat treatment and the resulting microstructure [2,3]. Furthermore, key components for power transmission in drives are often hot formed, further improving their mechanical properties due to the formed fine-grained microstructure and the load adjusted grain orientations [4].

As a final step in production, the hot formed parts are machined to manufacture the final shape including hard finished functional surfaces. To support this, sulfur is added in steel alloys to ensure short chip breaking provoked by emerging sulfide compounds [5]. In steels containing manganese and sulfur as an alloying element, manganese sulfide (MnS) forms at high temperatures present during hot forming as non-metallic inclusions [6]. These inclusions, while beneficial for chip breaking, weaken the steel matrix and can lead to

early failure of the component, since they act as internal notches. This effect is particularly critical for alternating loads and results in a significantly reduced fatigue life [7].

The shape of the MnS-inclusions at formation is spherical at first, but is altered during the forming process, leading to a more flattened and ellipsoidal appearance [8]. This amplifies the internal notch effect. To take this into account for the numerical prediction of the hot forming process and the resulting final properties of parts made of steels with manganese and sulfur, the behaviour of MnS-inclusions has to be considered in numerical simulations. For this, precise material data is required, including the flow behaviour of the inclusions as well as the steel matrix. Therefore, the focus of this paper is the characterisation of the strain-rate and temperature-dependent flow behaviour of the two steel alloys 1.7139 and 1.1303 in order to analyse the influence of varying amounts of manganese and sulfur. The derived data is further validated through numerical simulation of a cylinder compression test with different test parameters.

2. MATERIALS AND METHODS

For the experimental flow curve determination, cylindrical specimens with the dimensions of $\varnothing 5 \text{ mm} \times 10 \text{ mm}$ were cut by wire-cut erosion. The cylinder compression tests were performed with a forming dilatometer DIL 805A/D+T from TA Instruments at four different temperatures with up to three different strain rates with an additional parameter combination for validation. Each parameter set was tested five times. **Table 1** lists the investigated parameters within this study.

Table 1 Investigated parameters for the cylinder compression tests (* marks validation parameters)

Material	Test temperature in $^{\circ}\text{C}$	Test strain rate in s^{-1}
1.7139 (16MnCrS5)	900 1,000 1,030* 1,100 1,200	1 8* 10 20
1.1303 (38MnVS6)	900 1,000 1,030* 1,100 1,200	1 8* 10

Figure 1.a) illustrates the schematic setup of the cylinder compression tests. As shown, the test specimens were clamped between the punches made of silicon nitride (Si_3N_4) and subsequently inductively heated through a coil. During testing, the temperature was measured continuously with a thermocouple type K, which was welded on the cylindrical surface of the specimen.

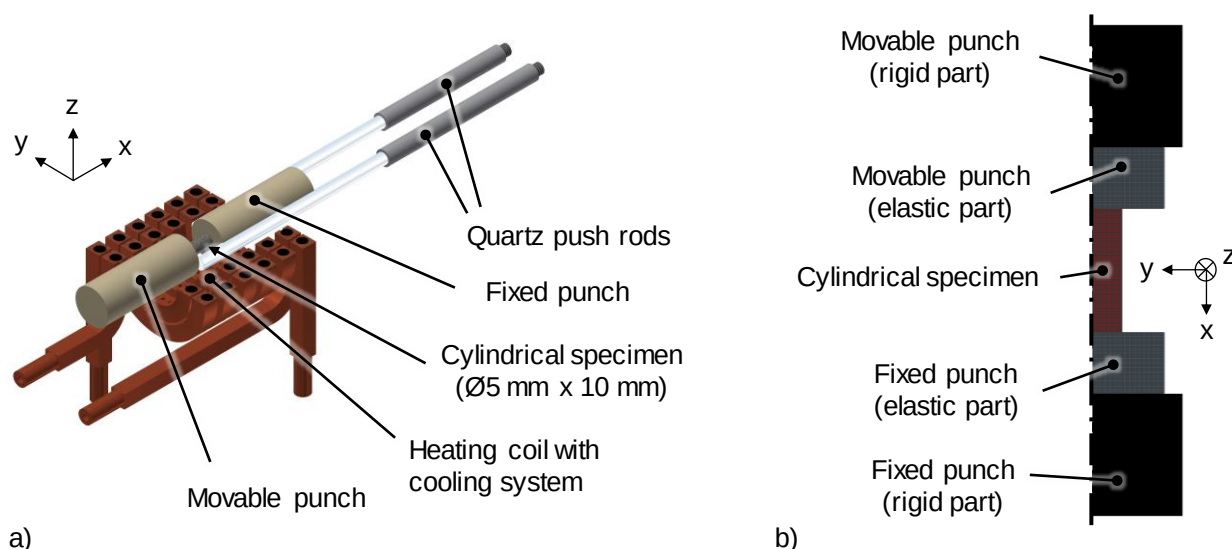


Figure 1.a) Cylinder compression test setup and **b)** derived FE-model for simulation

The heating route consists of continuous heating from room temperature with a heating rate of 10 K/s, followed by a holding and soaking segment of 120 s at the target temperature. In order to minimise scaling, the tests were carried out in a vacuum. Afterwards, the specimens were compressed up to a true strain of around 0.7 with the parameters shown in **Table 1**, followed by final cooling to room temperature. Two quartz push rods were used to measure the reduction of the length Δl of the cylinder with a resolution of 0.01 μm . Together with the synchronised force measurement, the resulting true stress σ and true plastic strain ε can be calculated as follows by **Equation (1)** and **(2)**:

$$\sigma = \frac{F}{A_i} = \frac{F \cdot l_i}{A_0 \cdot l_0} = \frac{F}{A_0} \left(1 + \frac{\Delta l}{l_0} \right) \quad (1)$$

$$\varepsilon = \ln \left(\frac{l}{l_0} \right) = \ln \left(1 + \frac{\Delta l}{l_0} \right) \quad (2)$$

where:

F – the compression force (N)

A_0 – the initial cross-sectional area (mm^2)

l_0 – the initial length (mm)

Δl – the elongation or reduction of length (mm)

A_i – the instantaneous cross-sectional area (mm^2)

l_i – the instantaneous length (mm)

The experimental data was then resampled in order to generate the same number of evenly spaced data points independent of the strain rate during measurement. For this, the stress value was determined through linear interpolation of the two data points closest to the current strain value. The flow behaviour was implemented in the simulation through a suitable hardening law, which offers higher accuracy at interpolation and more plausible values when extrapolating. Different phenomenological models exist, taking strain, strain rate and temperature into account. For this investigation, the Hensel-Spittel model was utilised, described in **Equation (3)**, which is often employed in hot forming simulations and which was successfully used for a different manganese steel [9-11].

$$\sigma_f = A \cdot e^{m_1 T} \cdot \varepsilon^{m_2} \cdot \dot{\varepsilon}^{m_3} \cdot e^{\frac{m_4}{\varepsilon}} \cdot (1 + \varepsilon)^{m_5 T} \cdot e^{m_6 \varepsilon} \cdot \dot{\varepsilon}^{m_7 T} \cdot T^{m_8} \quad (3)$$

where:

σ_f – the modelled flow stress (MPa)

$\dot{\varepsilon}$ – the strain rate (s^{-1})

T – the temperature (K)

A, m_1 to m_8 – the fitting coefficients (various units, see **Table 2**)

For the flow curve fitting, the median experimental curve across the five repetitions for each parameter set was chosen. Initial parameters for the Hensel-Spittel model were taken from the Simufact material library. The coefficients are fitted to the experimental data by minimising the root mean squared error (RMSE) between the experimental flow stress and the flow stress predicted by the Hensel-Spittel model. For this, the generalised reduced gradient nonlinear solver implemented in Excel was used, where the parameter A was limited to an upper value of 180.

As a next step, the fitted flow curves were implemented in Simufact Forming 2025.2 for verification and final validation through numerical simulation of the experimental cylinder compression tests. The test with a

temperature of 1,030 °C and a strain rate of 8 s⁻¹, a combination which has not been used for fitting, was analysed for validation. For the simulations, a 2D rotationally symmetric model is set up, as shown in **Figure 1.b)**, where each punch is represented by a combination of two bodies. The body in contact to the cylindrical specimen is modelled as deformable in order to recreate the elastic deformation of the punch, with a quad mesh with an element size of 0.1 mm and a Young's modulus of 320 GPa [12]. The other is rigid and either fixed or movable in order to initiate the deformation movement. For contact modelling, a combined Coulomb-Tresca friction model was implemented with a friction coefficient of 0.3 and a friction shear factor of 0.4 [13,14]. The movement of the punch is set to achieve a uniform strain rate through specified speeds in x-direction at given times, and at the start of the forming simulation a thermally expanded cylinder with a homogenous temperature profile is implemented. The resulting numerical force-displacement curve is then compared to the experiment. Regarding the specimen, it is also meshed with quadrilateral elements. In order to find the optimal mesh size, where the results converge and a good trade-off between accuracy and computation time is achieved, a mesh study is conducted first. **Figure 2.a)** shows a non-steady force-displacement curve with a significant jump in force at the end when a large element size of 0.5 mm is used. This is due to an inadequate representation of the bulging during compression especially at high true strains, where only after several increments the deformed cylinder surface elements close to the edge of the specimen come fully into contact with the punch, leading to a sharp increase in force. By reducing the size, a smoother curve is achieved.

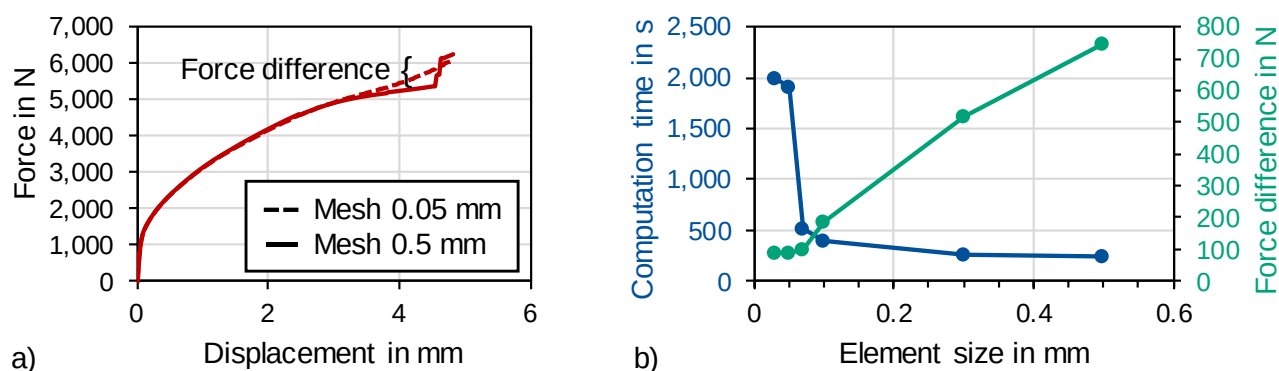


Figure 2.a) Force-displacement curve at 1,000 °C and a strain rate of 10 s⁻¹ for 1.7139 and
b) mesh study with the same parameter combination

As **Figure 2.b)** illustrates, the observed sudden increase in force decreases steadily when smaller elements are used, until a plateau is reached. At the same time, the computation time does not increase significantly up to a size of 0.07 mm, and quadruples afterwards. Therefore, a mesh size of 0.07 mm was chosen for the specimen. Overall, no remeshing was used.

3. RESULTS AND DISCUSSION

At first, for the modelling of the strain-rate and temperature dependent flow curve, the flow stress and the true strain were calculated according to **Equation (1)** and **(2)**. After resampling, the resulting flow curves were modelled using the Hensel-Spittel approach. **Figure 3** illustrates the flow curves of the model at a strain rate of 10 s⁻¹ compared to the experimental flow curves.

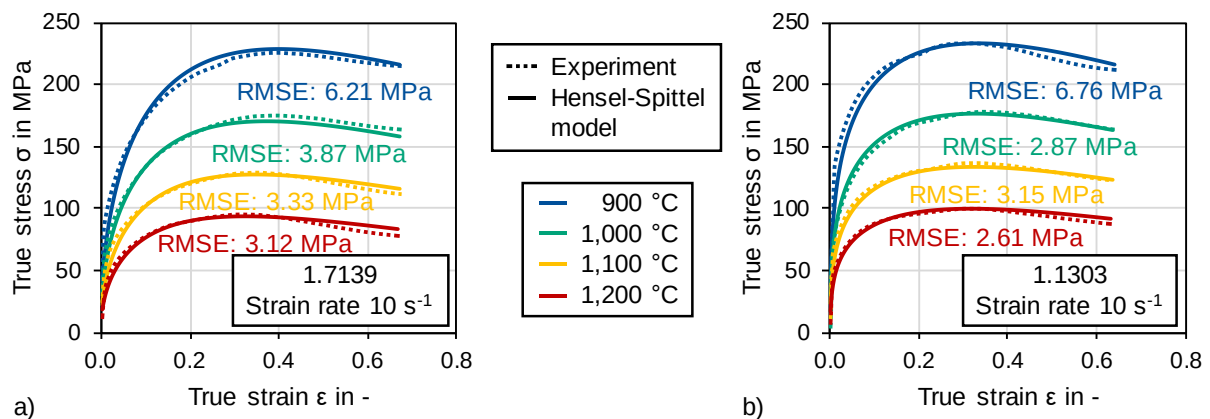


Figure 3 Experimental and fitted flow curves for the investigated temperatures at strain rate 10 s^{-1} regarding **a)** 1.7139 and **b)** 1.1303

Both materials show initial strain hardening followed by softening for all temperatures, which is also represented by the modelled flow curves. Also, as expected, an increase in temperature leads to lower flow stresses. In total, the experimental flow curves are accurately modelled through the Hensel-Spittel approach for both materials, with an overall RMSE of 4.61 MPa for 1.7139 and 4.35 MPa in case of 1.1303 across all tested parameters. Only minor differences are seen, with slightly greater deviations at the lowest temperature for both materials, which is also reflected in the higher RMSE-value of around 7 MPa. **Table 2** shows the final parameters for both fitted flow curves.

Table 2 Model coefficients of the Hensel-Spittel hardening law

Material	A in $\frac{\text{MPa} \cdot \text{s}^2}{\text{K}}$	m_1 in $\frac{1}{\text{K}}$	m_2 in -	m_3 in -	m_4 in -	m_5 in $\frac{1}{\text{K}}$	m_6 in -	m_7 in $\frac{1}{\text{K}}$	m_8 in -
1.7139	153.2145	-0.0040	0.4697	-0.2704	0.0005	-0.0010	-0.3626	0.0003	0.8265
1.1303	167.9049	-0.0040	0.2981	-0.2743	-0.0011	-0.0002	-0.7363	0.0003	0.7826

For the validation of the determined models, an additional cylinder compression test was conducted at a temperature of $1,030 \text{ °C}$ and a strain rate of 8 s^{-1} for each material. The experimental force-displacement curve is compared to the result of the numerical simulation of the cylinder compression test with the same validation parameter combination. **Figure 4** shows the result of the validation tests. Overall, similar force-displacement curves can be seen between the simulation and the experiment with slight deviations for both materials. Overall, RMSE-values of 0.32 kN for 1.7139 and 0.24 kN for 1.1303 were achieved.

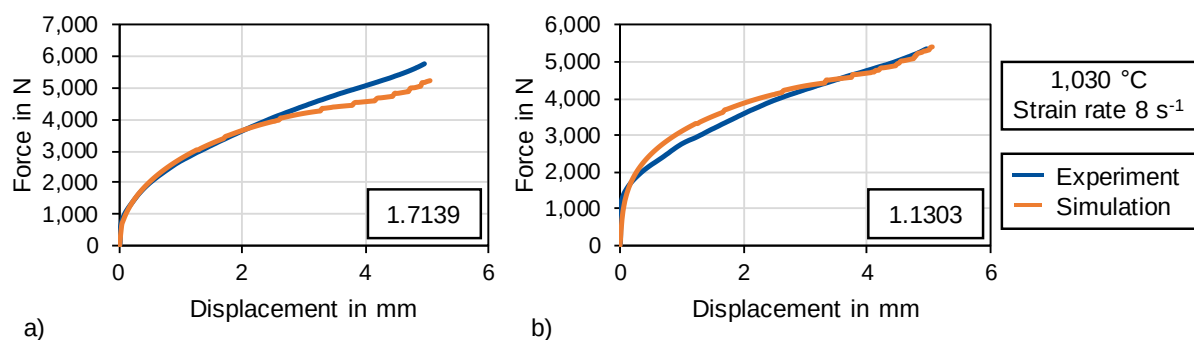


Figure 4 Experimental and numerical force-displacement curves for **a)** 1.7139 and **b)** 1.1303

In case of 1.7139, the numerical force-displacement curve matches the experimental curve more or less up to around 3 mm displacement, where deviations are starting to exceed 5%. Afterwards, the numerically calculated forces are lower than the forces determined in the experiments. When comparing this to the flow curves seen in **Figure 3.a)**, this behaviour can be attributed to the flow curve model. For the parameter combination closest to the validation (1,000 °C and 10 s⁻¹), the fitted flow curve matches the experimental one up to a true strain of around 0.3 corresponding to a displacement of around 3 mm. After that, the modelled flow curve shows slight deviations, and the lower flow stresses from the model lead to lower forces seen in the simulation. Similarly, the simulated forces are higher for 1.1303 up to 3 mm displacement with maximum deviations of around 10%, since the modelled flow curve is slightly higher compared to the experimentally determined curve. Afterwards, the numerical and experimental force curve are in good agreement. All in all, both flow curve models are validated for the two materials.

4. CONCLUSION AND OUTLOOK

For two manganese steels, 1.7139 and 1.1303, the flow behaviour was experimentally characterised through cylinder compression tests at different temperatures and strain rates. The flow stress was then successfully modelled with the Hensel-Spittel flow curve approach, which also takes temperature and strain rate dependency into account. Here, a good agreement with the experimental data was achieved, further supported by low RMSE-values of around 4.5 MPa. Finally, the modelled flow behaviour was validated with an additional experimental test with the parameter combination of 1,030 °C and 8 s⁻¹ through numerical simulation of the experiment for both steels 1.7139 and 1.1303.

As a next step, the flow behaviour of MnS-inclusions will be determined, and the material data of the manganese steel and MnS implemented in microstructure simulations with representative volume elements. This allows for a more accurate and in-depth simulation and analysis of the multiphase forming behaviour.

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REFERENCES

- [1] ROMERO, C. A., CORREA, P., ARIZA ECHEVERRI, E. A., VERGARA, D. Strategies for Reducing Automobile Fuel Consumption. *Applied Sciences*. 2024, vol. 14-2, Art.-No. 910. doi: [10.3390/app14020910](https://doi.org/10.3390/app14020910).
- [2] SABUZ, E. H., SHABIB, I. Microstructure, Hardness, and Tensile Properties of Additively Manufactured Low-Alloy Steel: A Review. *Steel Research Int.* 2025, vol. 96-7, Art.-No. 2400421. doi: [10.1002/srin.202400421](https://doi.org/10.1002/srin.202400421).
- [3] DIN EN 10267. *Von Warmformgebungstemperatur ausscheidungshärtende ferritisch-perlitische Stähle*. Berlin, Germany: DIN Deutsches Institut für Normung e.V., 1998.
- [4] SURIS, J. A., YURGEL, C. C., ALVES DE SOUSA, R. Influence of the Grain-Flow Orientation after Hot Forging Process Evaluated through Rotational Flexing Fatigue Test. *Metals*. 2023, vol. 13-2, Art.-No. 187. doi: [10.3390/met13020187](https://doi.org/10.3390/met13020187).
- [5] SHIIKI, K., YAMADA, N., KANO, T., TSUGUI, K. Development of Shape-Controlled-Sulfide Free Machining Steel for Application in Automobile Parts. In: *2004 SAE World Congress Detroit*. Warrendale: SAE, 2004, Art.-No. 1526.
- [6] YAN, J., CHEN, L., ZHANG, C., MIAO, H., WANG, S., WU, G., GAO, J., WU, H., ZHAO, H. Influence of Sulfur on the Splitting Fracture and Machining Performance of Microalloyed Medium-Carbon Steel 36MnVS4 Connecting Rods. *J. of Materi Eng and Perform.* 2024, vol. 33-22, pp. 12125–12132. doi: [10.1007/s11665-023-08841-1](https://doi.org/10.1007/s11665-023-08841-1).
- [7] MACIEJEWSKI, J. The Effects of Sulfide Inclusions on Mechanical Properties and Failures of Steel Components. *J Fail. Anal. and Preven.* 2015, vol. 15-2, pp. 169–178. doi: [10.1007/s11668-015-9940-9](https://doi.org/10.1007/s11668-015-9940-9).

- [8] TEMMEL, C., KARLSSON, B., INGESTEN, N.-G. Fatigue crack initiation in hardened medium carbon steel due to manganese sulphide inclusion clusters. *Fatigue Fract Eng Mat Struct*. 2008, vol. 31-6, pp. 466–477. doi: [10.1111/j.1460-2695.2008.01243.x](https://doi.org/10.1111/j.1460-2695.2008.01243.x).
- [9] WESTER, H., BEHRENS, B.-A. Numerical Process Analysis of Forming Semi-Finished Hybrid Parts. *Key Engineering Materials*. 2023, vol. 957, pp. 135–142. doi: [10.4028/p-p1hZbB](https://doi.org/10.4028/p-p1hZbB).
- [10] HENSEL, A., SPITTEL, T. *Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren*. Leipzig: VEB Deutscher Verlag für Grundstoffindustrie, 1978.
- [11] SUN, C., QIN Y., LIU, Y., XIAO, G., ZHANG, J., ZHOU, J. Research on the Hot Deformation Process of A100 Steel Based on High-Temperature Rheological Behavior and Microstructure. *Materials*. 2024, vol. 17, Art.-no. 991. doi: [10.3390/ma17050991](https://doi.org/10.3390/ma17050991)
- [12] BRULS, R. J., HINTZEN, H. T., DE WITH, G., METSELAAR, R. The temperature dependence of the Young's modulus of MgSiN₂, AlN and Si₃N₄. *Journal of the European Ceramic Society*. 2001, vol. 21-3, pp. 263–268, doi: [10.1016/S0955-2219\(00\)00210-7](https://doi.org/10.1016/S0955-2219(00)00210-7).
- [13] LIN, Z.-C., LIN, V.-H. Friction coefficient of upsetting with a procedure of combining the inverse model and the Tikhonov method. *International Journal of Mechanical Sciences*. 2006, vol. 48-7, pp. 717–725, doi: [10.1016/j.ijmecsci.2006.01.015](https://doi.org/10.1016/j.ijmecsci.2006.01.015).
- [14] YAO, J., WU, Y., SUN, J., TIAN, J., ZHOU, P., BAO, Z., XIA, Z., GAO, L. Friction and wear characteristics of silicon nitride ceramics under dry friction condition. *Mater. Res. Express*. 2021, vol. 8-3, Art.-No. 35701, doi: [10.1088/2053-1591/abe8ab](https://doi.org/10.1088/2053-1591/abe8ab).