DOI: 10.21062/mft.2024.027 http://www.journalmt.com

The Effect of Strain Rate on the Friction Coefficient

Petr Svoboda (0009-0000-4186-5252), Miroslav Jopek (0000-0001-5399-3059)
Brno University of Technology, Faculty of Mechanical Engineering, Institute of Manufacturing Technology, Department Metal Forming and Plastics, Technická 2896/2, 616 69 Brno, Czech Republic. E-mail: 209148@vutbr.cz; jopek@fme.vutbr.cz

The Male and Cockroft ring compression test is one of the methods used to determine the coefficient of friction in forming. This method can be used to determine the coefficient of friction without the need to measure the force. This paper describes the results of the Male and Cockroft ring compression test for the Hardox 450 material at different strain rates without lubricant. The experiment was performed on ZD40 hydraulic press and CFA-80 pneumatic die hammer at the Faculty of Mechanical Engineering of Brno University of Technology. The test results were recorded in a calibration diagram. The results show that the strain rate has a significant effect on the coefficient of friction, specifically such that as the strain rate increases, the coefficient of friction decreases.

Keywords: Strain rate, Friction, Calibration diagrams, Ring compression test, Hardox 450 steel

1 Introduction

Friction on the contact surfaces between the semi-finished product and the forming tool is a very important variable affecting both the semi-finished product and the forming process. Its magnitude largely determines the overall magnitude of deformation resistance, thus forming force and work, it also affects material flow, surface quality, temperature and tool wear [1]. For these reasons, it is necessary to correctly determine the value of the friction coefficient.

In bulk forming processes, such forging, friction coefficient maps (calibration diagrams) based on the ring press test first proposed by Kunogi have been used [2]. The test was subsequently further developed by Male and Cockroft [3]. These charts provide a simple way to determine the coefficient of friction between the blank and the contact surface of the forming tool.

In the initial stages, it was assumed that the calibration diagrams were universal for groups of materials (steel, Al alloys...) and depended only on the ring dimensions. Later it was found that the calibration diagram had to be created for each material separately, i.e. universality for groups of materials was not valid [4]. It was also found that the magnitude of the friction coefficient depends on the temperature of the material [5]. Recently, there has been an interest in evaluating the tribological properties of materials under various strain rates. Higher strain rates are common in the manufacturing of components by forming, since quasi-static strain rates are rarely encountered in forming, e.g. in hydroforming or superplastic forming [6-10].

2 Ring Compression Test

Out of the several methods used to determine the coefficient of friction between the surface of the blank and the forming tool, the ring compression test is recognized as the general standard. This test works on the principle of the change in the inner and outer diameter of the ring when it is compressed. This change is manifested by 'bulging'. If the inner diameter increases during compression, friction is low, Fig. 1. If, on the other hand, the inner diameter decreases during compression, friction is high, Fig. 2.

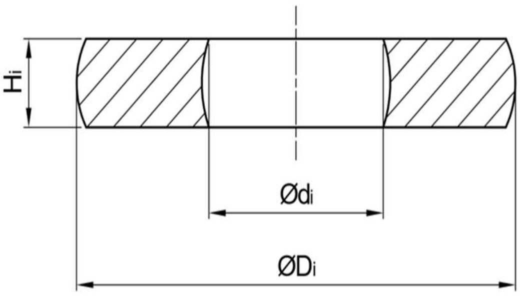

Fig. 1 *Low friction (good lubrication)*

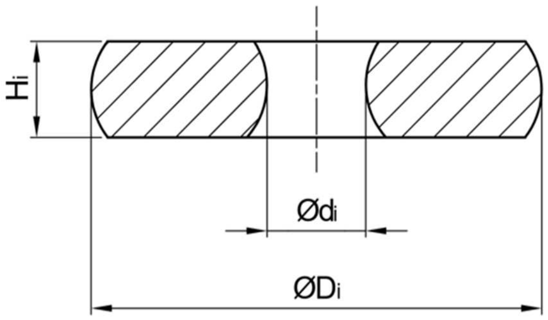

Fig. 2 *High friction (poor lubrication)*

With the knowledge of these dependencies, calibration curves were developed to determine the coefficient of friction. This curve was created by Male & Cockroft for samples with a geometry of 6:3:2, where 6 applies to the outer diameter D, 3 applies to the inner diameter d and 2 applies to the height H, Fig. 3. This ratio was later established as the standard [11].

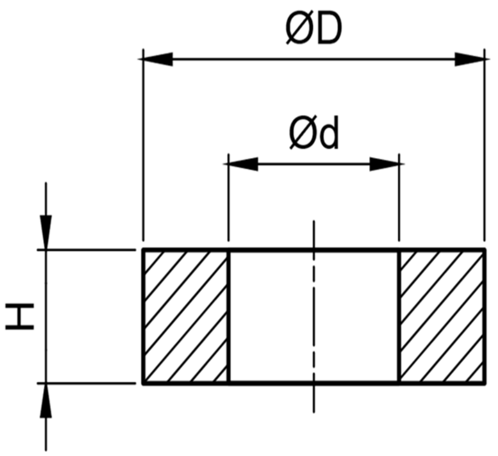

Fig. 3 *Sample before loading*

The following equations are used to evaluate the change in ring height and inner diameter:

$$\varepsilon_d = \frac{d - d_i}{d} \cdot 100\ [\%] \quad (1)$$

$$\varepsilon_H = \frac{H - H_i}{H} \cdot 100\ [\%] \quad (2)$$

Where:

ε_d…Deformation of the inner diameter of the ring [%],

d…Initial inner diameter of the ring [mm],

d_i…Final inner diameter of the ring [mm],

ε_H…Deformation of height of the ring [%],

H…Initial height of the ring [mm],

H_i…Final height if the ring [mm].

The easy applicability of the calibration diagrams consists in determining the dependence of the change in the inner diameter of the ring on the change in its height. These curves are then plotted on a graph for each friction coefficient f or friction factor m. The great advantage is that it is not necessary to measure the forces during the test and that the deformations are sufficiently large and therefore measurable with conventional gauges. The test can also be used to evaluate the suitability of various lubricants in forming processes.

The high-strength Hardox 450 steel (for chemical composition see Tab. 1) was chosen as the material of the samples. Rings with nominal dimensions of 15:7.5:5 were used for testing. The resulting dimensions differed slightly due to machining, the values are shown in Tab. 2. The ring dimensions were measured using a Dial Snap Meter with a tolerance of ±0.001 mm.

Tab. 1 *Chemical composition of Hardox 450 steel*

Element	C	Si	Mn	P	S	Cr	Ni	Mo	B
wt. %	0.18	0.27	0.96	0.007	0.003	0.11	0.08	0.027	0.001

Tab. 2 *Sample dimensions*

Sample	1	2	3	4	5	6
D [mm]	14.904	15.032	14.980	14.977	14.946	14.963
	14.945	14.963	14.977	14.967	14.958	14.969
	14.952	15.055	14.983	14.980	14.966	14.973
Mean Value [mm]	14.934	15.017	14.980	14.975	14.957	14.968
d [mm]	7.611	7.552	7.513	7.551	7.516	7.568
	7.551	7.561	7.541	7.549	7.528	7.574
	7.550	7.580	7.532	7.531	7.511	7.570
Mean Value [mm]	7.571	7.564	7.529	7.544	7.518	7.571
H [mm]	4.956	4.948	4.951	4.946	4.966	4.954
	4.954	4.956	4.953	4.941	4.965	4.955
	4.954	4.958	4.956	4.942	4.959	4.950
Mean Value [mm]	4.955	4.954	4.953	4.943	4.963	4.953

The ring compression test was carried out using a ZD40 hydraulic press and a CFA-80 pneumatic die hammer and no lubricant was used. Samples 1, 2 and 3 were rammed on the CFA-80 pneumatic die hammer; samples 4, 5 and 6 were rammed on the ZD40 hydraulic press. The test conditions such as temperature, tool movement speed and strain rate are given in Tab. 3.

Tab. 3 *Test conditions*

Machine	ZD40	CFA-80
Temperature [°C]	18	18
Tool movement speed [m·s^{-1}]	$3.333 \cdot 10^{-5}$	2.023
Strain rate [s^{-1}]	$7.741 \cdot 10^{-3}$	23.561
The tool movement speed was measured with a high-speed camera.		

After packing the rings, the outer and inner diameters bulged as shown in Fig. 2. The samples were rammed to a nominal height of 3.65 mm. The dimensions of the samples after the test are shown in Tab. 4. The ring dimensions were measured using a Dial Snap Meter with a tolerance of ±0.001 mm.

Tab. 4 *Sample dimensions*

Sample	1	2	3	4	5	6
D [mm]	16.781	16.779	16.776	16.966	16.835	16.821
	16.762	16.771	16.781	16.973	16.842	16.816
	16.765	16.780	16.773	16.968	16.839	16.823
Mean Value [mm]	16.769	16.777	16.777	16.969	16.839	16.820
d [mm]	7.423	7.411	7.425	7.192	7.183	7.193
	7.419	7.421	7.422	7.187	7.176	7.189
	7.427	7.415	7.428	7.193	7.181	7.186
Mean Value [mm]	7.423	7.416	7.425	7.191	7.180	7.189
H [mm]	3.647	3.636	3.639	3.646	3.661	3.655
	3.651	3.645	3.641	3.649	3.655	3.649
	3.641	3.634	3.635	3.652	3.662	3.651
Mean Value [mm]	3.646	3.638	3.638	3.649	3.659	3.652

3 Discussion of results

From the measured dimensions, the values of the inner diameter deformation and values of the height deformation were calculated according to equation (1) and (2), sample calculation was performed for sample 1, other results are shown in Tab. 5.

$$\varepsilon_d = \frac{d - d_i}{d} \cdot 100 = \frac{7.571 - 7.423}{7.571} \cdot 100 = 1.955\ \% \tag{3}$$

$$\varepsilon_H = \frac{H - H_i}{H} \cdot 100 = \frac{4.955 - 3.646}{4.955} \cdot 100 = 26.417\ \% \tag{4}$$

Tab. 5 *Deformation values*

Sample	1	2	3	4	5	6
ε_d [%]	1.955	1.957	1.381	4.679	4.496	5.046
ε_H [%]	26.418	26.564	26.550	26.178	26.274	26.267
The values were then entered into a calibration diagram for Hardox 450 steel at 291.15 K (18 °C), Fig. 4.						

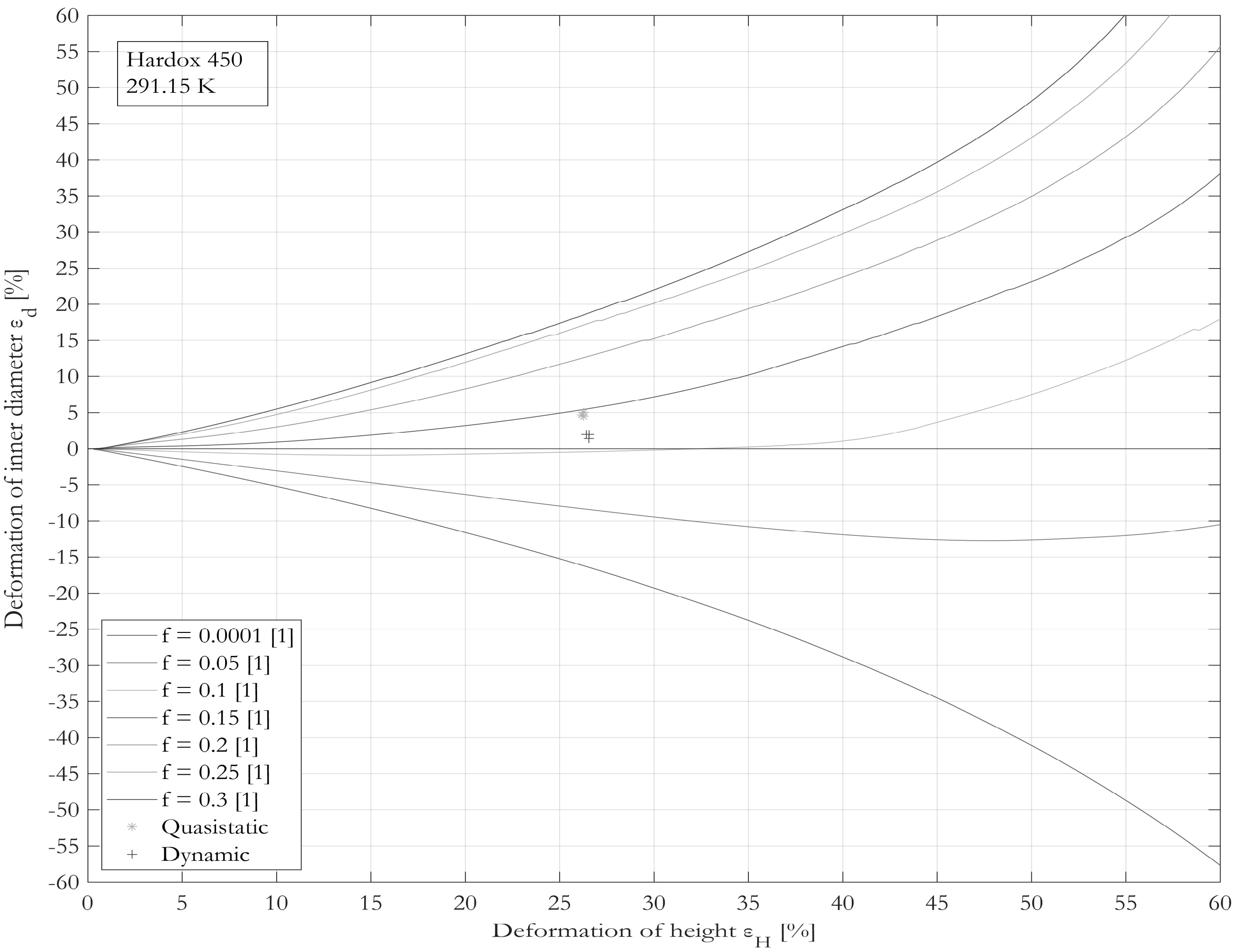

Fig. 4 *Hardox 450 – calibration diagram*

From the resulting graph, it can be seen that although the value of the ramping height is the same, the inner diameter of the sample after ramming is different. As a result, the final value of the friction coefficient is also different. Specifically, the values are 0.145 for quasi-static loading and 0.125 for dynamic loading, see Fig. 5.

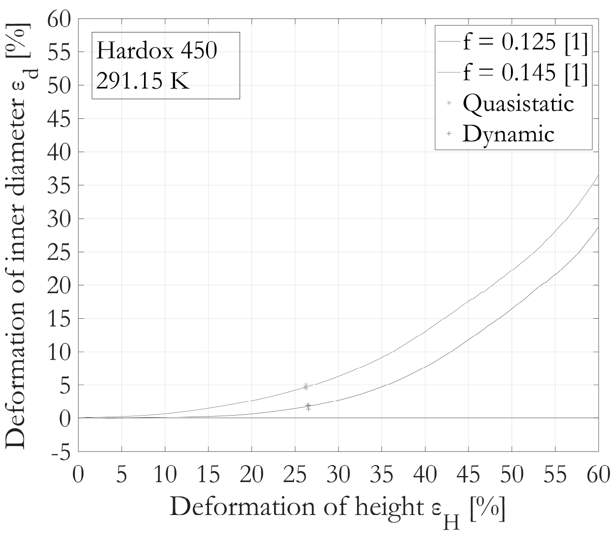

Fig. 5 *Hardox 450 – calibration diagram*

4 Conclusion

The Male and Cockroft ring compression test is often used in forming to determine the coefficient of friction because of its simplicity. The results show that the test gives a good description of the frictional behaviour of the packing of Hardox 450. The results also show the dependence of the friction coefficient value on the strain rate. Specifically, the magnitude of the friction coefficient decreases by 16% as the strain rate increases. This fact is an important contribution to the design of bulk forming tools, as it allows the determination of the total forming force required for a given part. The total force will be lower than if the value of the friction coefficient determined under quasi-static conditions is included. This makes it possible to produce a smaller tool and also buy a smaller and cheaper machine.

References

[1] JOUN, M.S.; MOON, H.G.; CHOI, I.S.; LEE, M.C. a JUN, B.Y. Effects of friction laws on metal forming processes. *Tribology International.* 2009, Volume 42, Issue 2, Pages 311-319. ISSN 0301-679X.

[2] KUNOGI, MAHITO. A New Method of Cold Extrusion. *Transactions of the Japan Society of Mechanical Engineers.* 1957, Volume 23, Issue 134, Pages 742-749. Available from: https://doi.org/10.1299/kikai1938.23.742.

[3] MALE, A. and COCKROFT, M., 1965/01/01. A Method for the Determination of Coefficient of Friction of Metals under Condition of Bulk Plastic Deformation. *Journal of Institute of Metals.* Volume 93, Pages 38-46.

[4] CAMACHO, A.M.; TORRALVO, A.I.; BERNAL, C. and SEVILLA, L., 2013. Investigations on Friction Factors in Metal Forming of Industrial Alloys. *Procedia Engineering.* Volume 63, Pages 564-572. Available from: https://doi.org/10.1016/j.proeng.2013.08.240 .

[5] WANG, WEN AND ZHOU, XIANG, 2023. Temperature-dependent friction coefficient on flat graphite plane. *Surface Science.* Volume 729, Pages 122-233. Available from: https://doi.org/10.1016/j.susc.2022.122233.

[6] JOPEK, MIROSLAV, 2021. Determination of Carbon Steel Dynamic Properties. *Manufacturing Technology*, Volume 21, Issue 4, pages 479-482. Available from: https://doi.org/10.21062/mft.2021.061.

[7] GIULIANO, GILLO; PARODO, GIANLUCA; POLINI, WILMA and SORRENTINO, Luca, 2023. Cold Blow Forming of a Thin Sheet in AA8006 Aluminum Alloy. *Manufacturing Technology*, Volume 23, Issue 3, pages 284-289. Available from: https://doi.org/10.21062/mft.2023.038.

[8] VILIS, JINDRICH; POKORNY, ZDENEK; ZOUHAR, JAN and JOPEK, MIROSLAV, 2022. Ballistic Resistance of Composite Materials Tested by Taylor Anvil Test. *Manufacturing Technology*, Volume 22, Issue 5, pages 610-616. Available from: https://doi.org/10.21062/mft.2022.074.

[9] LIPIŃSKI, TOMASZ. Influence of Impurity Morphology on the Fatigue Strength of High-Purity Structural Steel Melted in an Electric Furnace, 2023. *Manufacturing Technology.* Volume 23, Issue 1, pages 53-59. Available from: https://doi.org/10.21062/mft.2023.001.

[10] SVOBODA, PETR, JOPEK, MIROSLAV, SVOBODA, ONDŘEJ and MARTIN HARANT. DETERMINATION OF DYNAMIC PROPERTIES OF 3D PRINTED G3SI1 STEEL, 2024. *MM Science Journal.* Volume 16, Issue 2, pages 7230-7233. Available from: https://doi.org/10.17973/MMSJ.2024_03_2021183.

[11] CAMACHO, A.M.; TORRALVO, A.I.; BERNAL, C. and SEVILLA, L., 2013. Investigations on Friction Factors in Metal Forming of Industrial Alloys. *Procedia Engineering.* Volume. 63, Pages. 564-572. Available from: https://doi.org/10.1016/j.proeng.2013.08.240 .