Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

Light Metals 2014

ALUMINUM ALLOYS: DEVELOPMENT, CHARACTERIZATION AND APPLICATIONS

Poster Session

Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

FRICTION COEFFICIENTS ON COMPRESSION TESTING OF AA6060 AND 42CrMo4 WITH DIFFERENT LUBRICATION CONDITIONS

Sabbah Ataya[1] and Tobias Emde[2]
[1]Suez University, Faculty of Petroleum and Mining Engineering, 43721 Suez, Egypt
[2]Salzgitter Mannesmann Grobblech GmbH, Rohrbiegewerk, Wiesenstrasse 36, 45473 Mülheim, Germany.

Keywords: Friction Coefficient, Lubrication, Compression Test, Flow Curves, AA6060, 42CrMo4

Abstract

Friction at the interface of compression die/work piece plays an important role in the overall behaviour of metal forming processes. This work is dealing with the determination of the friction coefficient on compression loading of the aluminum alloy AA6060 and the steel 42CrMo4 as under different lubrication conditions.
The coefficient of friction was determined using cylindrical specimens with different diameter d_o/ height h_o ratio (d_o/h_o = 0.5, 0.67, 1.43 and 2.0). The initial specimens diameter was 4mm. Different lubrication conditions were applied: (a) dry, (b) lubrication with Molykote, (c) one Teflon layer and (d) two Teflon layers with oil film between them. The test materials were the aluminum alloy AA6060 and the steel 42CrMo4. Friction coefficients as a function of the strain were determined by the description of the curves of the deformation resistance against the d_o/h_o values at different deformation degrees and different lubrication conditions. A comparative flow curves were determined after the elimination of the friction effect of the different d_o/h_o values.

1. Introduction

The increased application of the finite element simulation in the design and production increases the demand for material laws which describe the deformation behaviour under different loading conditions. The disadvantage of the compression test on determining the flow stresses against the tensile test is the friction between the compression die and the specimen. Material laws are determined mainly from the description of the flow curves that are mostly got either from the tensile or compression Tests. Determination of the flow curves from the tensile has the advantage of avoiding the friction problems. But the occurrence of the necking of the tensile specimens limits the deformation degree that could be attained before the fracture of the specimen. In the compression test, a higher degree of deformation can be reached before the fracture of the specimens than that from the tensile test.
Several experimental and theoretical procedures have been introduced to evaluate the friction coefficient [1-10]. These experimental procedures can be classified into four tests: (a) complete elastic deformation [3], (b) localized deformation [4], (c) partial plastic deformation, and (d) complete plastic deformation [5,6]. Columb's friction coefficient μ could be determined by using Siebel-Type cylindrical test specimens (with different diameter do/ height ho ratio), Rastegaev specimen [7], ring compression test specimens [5,8] and the plan strain specimen [9].
On the upsetting of aluminum between two steel dies, it was found [10] that the friction coefficient was determined in the elastic and plastic range (as shown in Figure1 [10]) in the dry condition. The friction coefficient was monitored very well in the elastic region. Some decrease in the friction coefficient was detected after high strain. This effect was related to the behavior of the mating surfaces under different stress levels. At low applied stress, the real area of contact compared to the apparent area was small and cold deformation of the asperities of mating materials was the main cause of friction in the elastic region. With increasing the normal stress, the real area of contact will increase toward the apparent area [11]. The change in the friction coefficient with increasing the amount of deformation will be studied in the present work.
Determination of the friction coefficient is useful in many applications that apply plastic deformation under compression loading, such as forging and rolling deformation and their simulation.

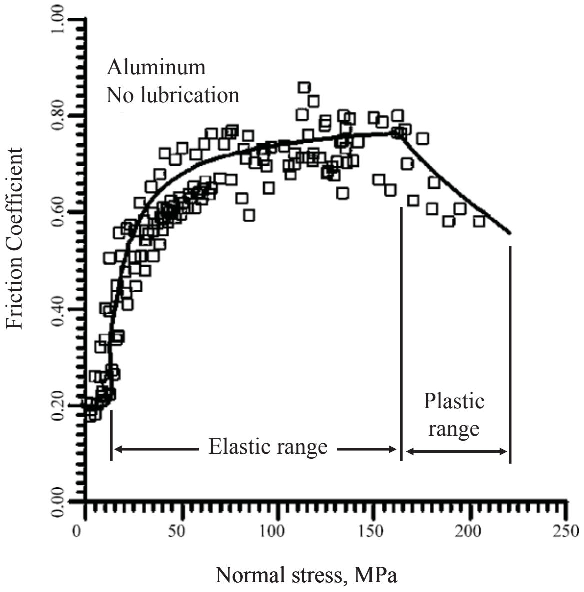

Figure1. Friction coefficient vs. normal stress in elastic and plastic regions [10].

This work is dealing with the determination of the friction coefficients by using Siebel-Type compression specimens using different lubrication for a soft material (aluminum alloy AA6060) and a hard material (steel 42CrMo4) on steel dies. This calculation process includes description of the curves of the deformation resistance against the d_o/h_o values by extrapolation to friction free condition at different deformation degrees and different lubrication conditions.

2. Test Material and Experimental Procedure

The aluminum alloy AA6060 and the steel alloy 42CrMo4 in the as-received condition were used as test materials in the form of rods of diameter of 8 mm and 15 mm, respectively. Specimens were machined by turning into in the same diameter (d_o = 4mm) and in different heights to have different d_o/h_o values (0.5, 0.67, 1.43 and 2).

Compression tests were carried out using the universal testing machine type MTS-810 under a strain rate of 0.004 s^{-1} at room temperature. Hard compression dies (maraging steel, HRc 54) were used. These dies are harder than the tested steel 42CrMo4, which has a hardness value of HRC 45. The contact faces of the test specimens and steel dies surface were ground using an emery paper (SiC) with grit size of 800 to attain the same initial roughness. From the properties of the SiC papers grit 800, a surface roughness of ~ 25 μm could be reached after grinding. Different lubrication conditions were applied at the compression die/specimen interfaces; namely (a) dry (without lubricant), (b) lubrication with molykote, (c) one teflon layer and (d) two teflon layers with a mineral oil film between them. Teflon here is the commercial transparent plastic sheet with a layer thickness of ~ 0.02 mm. The results at all conditions were calculated from two compression tests.

3. Results and Discussion

3.1. Effect of lubrication and d_0/h_0 on the deformation resistance

Aluminum alloy AA6060 is used as an example of the soft materials due to its very wide applications in different industrial and contractual fields. As a hard material, steel 42CrMo4 is used to study its frictional behavior against steel die. Steel alloy 42CrMo4 is corrosion resistant and it is applied in the production of cold drawn pipes and cold forged products of the automobile industry.

Figure 2a. shows the effect of different lubrication conditions on the deformation resistance of the aluminum alloy AA6060, for example. The test specimen without lubrication has shown the highest deformation resistance. With the application of molykote, the stresses needed for deformation clearly decreased especially at a higher degree of deformation compared with the compression curves with no lubrication. Double teflon layers, with oil film between them, made the specimen deform under the lowest stress compared with other lubrication conditions, even at a high degree of plastic deformation. Figure 2b. shows an example of true compressive stress-strain curves for alloy AA6060 using specimens with different d_0/h_o rations (0.5, 0.67, 1.43 and 2) while the specimen's diameter was kept constant d_o =4 mm with no lubrication. The specimens, with d_0/h_o value that equals 2, have shown the highest deformation resistance. This increase in the deformation resistance in the short wide specimens was due to the increased shear stress on the specimen/die mating surface, where the shear stress developed from zero at the end of the specimen/die mating surface to the maximum value at the center of the specimen forming the so-called friction hill [12]. The height of the friction hill, which describes the level of the deformation resistance, was due to the friction effect. With decreasing the d_0/h_o value, the friction effect decreased to reach its minimum at d_0/h_o value of 0.5 within the investigated d_0/h_o range.

Compression curves were measured for both aluminum alloy AA6060 and steel 42CrMo4 using lubrication by molykote, one teflon layer and double teflon layers. Figure 3 includes examples of the true compressive stress-strain curves with no lubrication (dry) and with lubrication using one teflon layer of different d_0/h_o values for steel 42CrMo4.

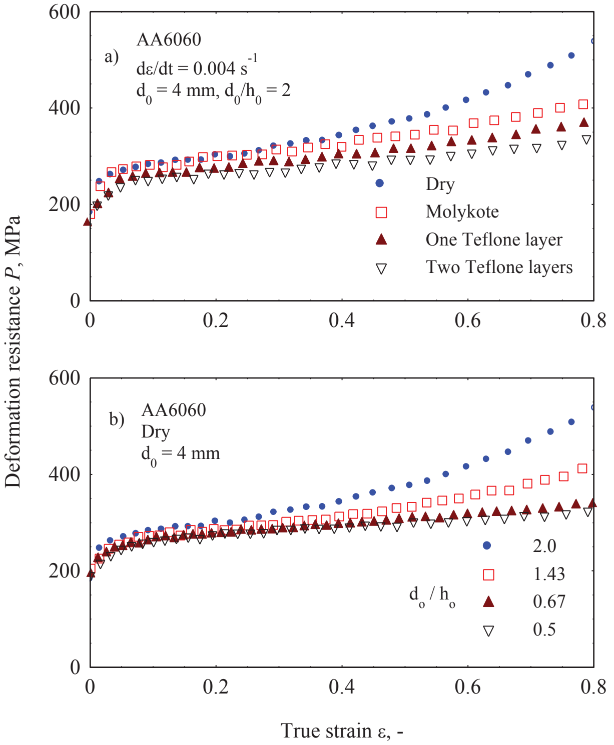

Figure 2. Deformation resistance of the aluminium alloy AA6060 at room temperature at a) different lubrication conditions and b) different d_o/h_o values.

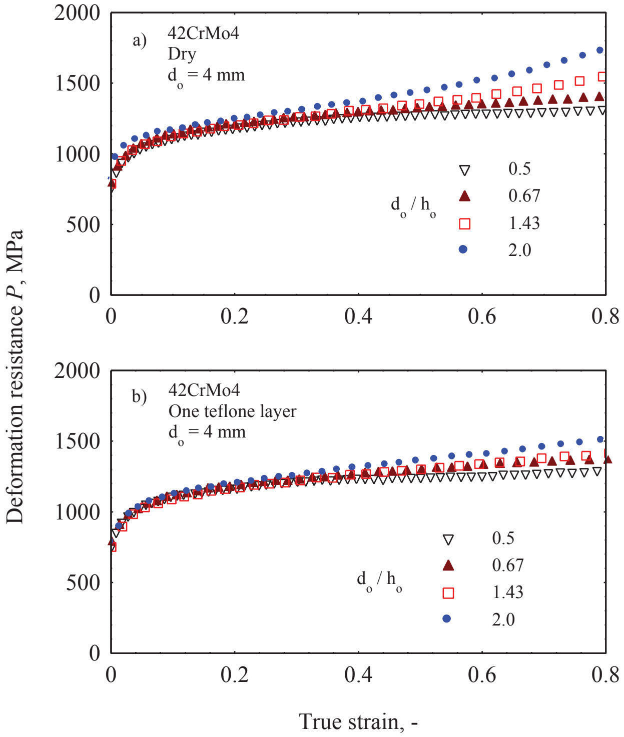

Figure 3. a) Deformation resistance of the steel 42CrMo4 without lubrication and b) with lubrication using one teflon layer at different specimen's diameter to height rations (d_o = 4 mm).

The level of the deformation resistance on applying lubrication by one teflon layer was obviously lower than that obtained in the dry condition. The deformation resistance decreased with decreasing the d_o/h_o value to reach the lowest deformation resistance at $d_o/h_o = 0.5$. These curves represent the base for calculating the friction coefficient at the different lubrication conditions.

3.2. Determination of friction coefficients

The total deformation resistance σ is the result of the summation of the flow stress σ_y and the friction resistance stress σ_f ($\sigma = \sigma_y + \sigma_f$). The deformation resistance as a function of the flow stress σ_y, the friction coefficient μ, and the diameter/height ratio (d/h) is usually described by the approximate mathematical expression after Siebel as in equation (1):

$$\sigma \approx \sigma_y \left(1 + \frac{\mu}{3}\frac{d}{h}\right) \tag{1}$$

under the condition that the $\mu d/h \leq 0.35$, where, μ is the friction coefficient, d and h are the instantaneous diameter and height of the test specimen. This condition is suitable for the specimens geometry applied in the present work.

A similar formula is derived and verified in the work after Kim [13] in the form of the friction stress σ_f as a function of the flow stress σ_y as :-

$$\sigma_f = \sigma_y \left(\frac{\mu}{3}\frac{d}{h}\right) \tag{2}$$

The instantaneous specimen diameter d and height h in Equation (2) could be expressed by the initial specimen dimensions (d_o and h_o) as a function of the true strain (ε) as follows:

$$h = h_o \, exp(-\varepsilon) \;\; and \;\; d = do \, exp(\varepsilon/2)$$

$$d/h = d_o/h_o \, exp(3\varepsilon/2) \tag{3}$$

Substituting into equation (1):-

$$\sigma_y = \sigma\left[1 - \left(\frac{\mu}{3}\frac{d_o}{h_o}.\exp\left(\frac{3}{2}\varepsilon\right)\right)\right] \tag{4}$$

Han [14] reported that when the friction at the die/work piece interface is expressed according to Coulob's friction rule, the mathematical model of describing the total resistance P of cylinder upsetting can be given by the Equation (5) after Thomsen [15]:

$$P = 2\sigma \left(\frac{h}{\mu d}\right)^2 \left(exp\left(\frac{\mu d}{h}\right) - 1 - \frac{\mu d}{h}\right) \tag{5}$$

Substituting Equation (3) into Equation (5):

$$P = 2\sigma \left(\frac{h_o}{\mu d_o} e^{(-3\varepsilon/2)}\right)^2 \left(exp\left(\frac{\mu d_o}{h_o} e^{(3\varepsilon/2)}\right) - 1 - \frac{\mu d_o}{h_o} e^{(3\varepsilon/2)}\right) \tag{6}$$

where σ is equal to the total stress P on extrapolation to friction free condition (at d_o/h_o=0).

The deformation resistance at certain true stains of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 was extracted from the compression curves of samples with different diameters to height values for both aluminum alloy AA6060 and steel 42CrMo4 at different lubrication conditions (dry, lubrication using molykote, one teflon layer and double teflon layers). Each curve represents the deformation resistance at a certain true strain. The extracted deformation resistance values were plotted against d_o / h_o values as shown in Figure 4 and Figure 5. These plots in Figure 4 and Figure 5 were described by Equation (6) very well, where all parameters and geometrical values are well known for each curve, except for the values of the friction coefficient which were determined by curve fitting.

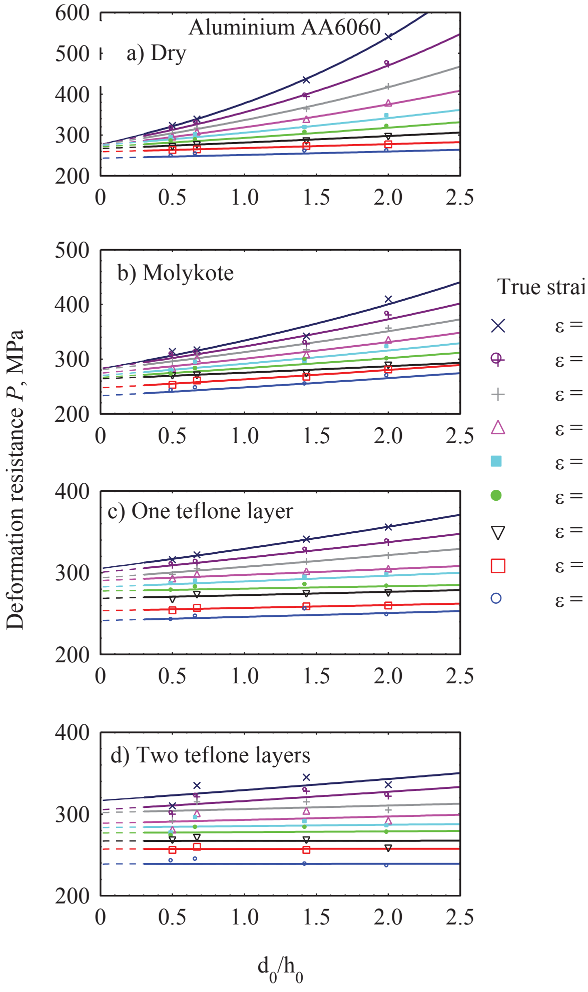

Figure 4. Determination of the friction coefficient on compression testing of AA6060 with applying different lubrication conditions at different strains by extrapolation to friction-free condition.

It was found that an average value for the friction coefficient at different degrees of deformation under certain lubrication conditions was not accurate enough to describe the curves. The variation of the friction coefficient with the deformation degree could be explained by the change of the surface conditions, the change of the amount of the lubricant at the interface and the altering of specimens form. So the friction coefficients were determined as a function of the degree of deformation.

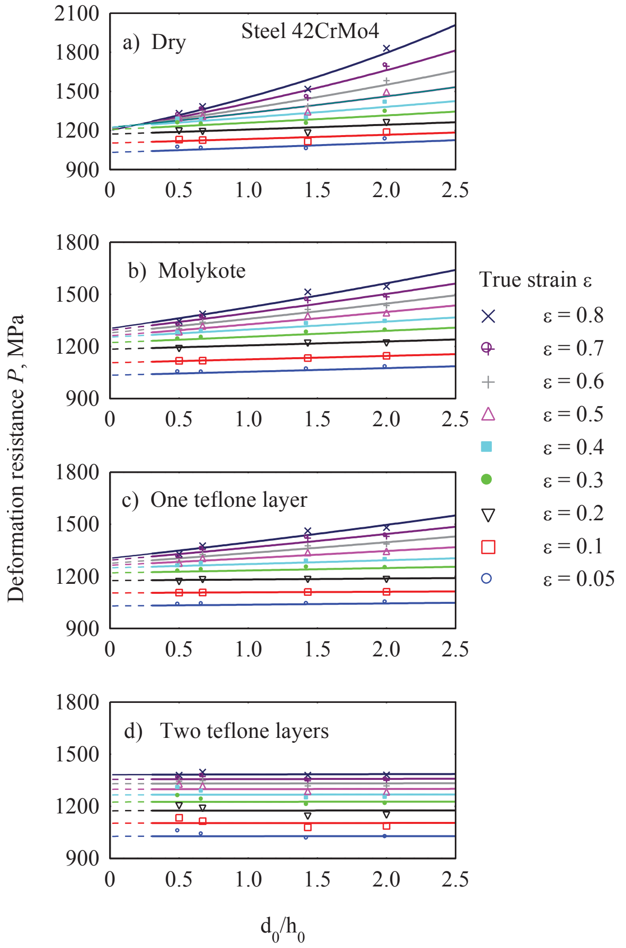

Figure 5. Determination of the friction coefficient on compression testing of 42CrMo4 at different strains with applying different lubrication conditions by extrapolation to friction-free condition.

Figure 6 shows the plot of the friction coefficient as a function of the true strain. The development of the friction coefficient with the degree of deformation delivers nearly similar tendency. There are two different regions that can be distinguished over the extended plastic region. The friction coefficient tends to decrease with increasing the degree of deformation up to a true strain around 0.2, then changes to increase with the true strain. Depending on the lubrication conditions, this increase in the coefficient of friction could either continue or begin to decrease after true strain values higher than 0.7. Little decrease was shown after this degree of deformation higher with moderate lubrication conditions (molykote and one teflon layer) as shown in Figure 6.b and c.

The friction coefficient values of the aluminium alloy AA6060 were found to be higher than that of the steel 42CrMo4 at the different lubrication conditions. This could be related to the increased tendency of the adhesive nature of the aluminum against the steel die producing cold welding of the aluminum asperities [10]. Very low and constant friction coefficient ($\mu = 0.001$) for steel 42CrMo4 was determined over all the deformation degrees (Figure 6.d). These μ-ε relations were well described as a third degree polynomial function. Similar results were obtained [13] by upsetting of cylindrical specimens of annealed aluminum alloy AA6082 using Molykote and Teflon lubricant.

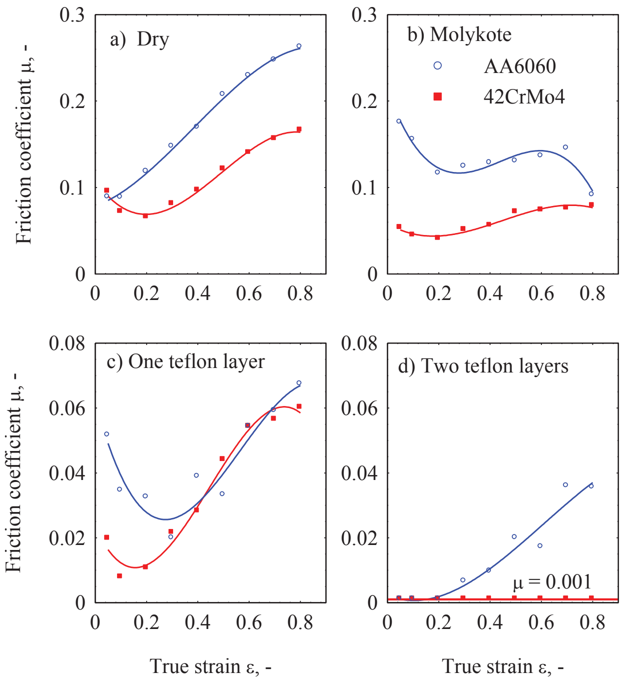

Figure 6. Friction coefficient as a function of the true strain on compression testing of AA6060 at different lubrication conditions.

Using Equation (4) and with the knowledge of the friction coefficient $\mu\ (\varepsilon)$ for each lubrication condition, d_o/h_o value and friction-free yield stress (σ) at $d_o/h_o = 0$, the friction effect can be eliminated from the flow curve. Subtraction of the stress component representing the resistance due to friction has produced nearly similar flow curves for the different lubrication conditions, regardless the different d_o/h_o value. Figure 7 shows the friction-free flow curves of tested alloys 42CrMo4 and AA6060 from the compression tests without lubricant, for example.

4. Conclusions

Using Siebel-Type cylindrical compression test specimens at different lubrication conditions; no lubrication, molykote one teflon layer and two teflon layers, the friction coefficients were determined on compression testing of the aluminium alloy AA6060 and the steel 42CrMo4 as a function of the degree of deformation at room temperature. The following conclusions can be drawn:-

1- Curves of compression resistance against d_o/h_o values with different lubricants at different strains are very well described by extrapolation to friction-free condition.

2- The friction coefficient decreases down to a certain value, with the exception of the case of lubrication with two teflon layers, at degree of deformation lower than 0.2,
3- Proportional increase of the friction coefficient is noticed at true strains higher than 0.2.
4- At moderate lubrication conditions (molykote and one teflon layer), there is a little decrease of the friction coefficient at a degree of deformation higher than 0.7.
5- The friction coefficient on upsetting of steel 42CoMo4 on steel dies is μ=0.001 and independent on the degree of deformation using lubrication with two teflon layers.
6- Elimination of the stress component representing the friction resistance produces equal flow curves at different lubrication conditions, regardless the d_o/h_o values.

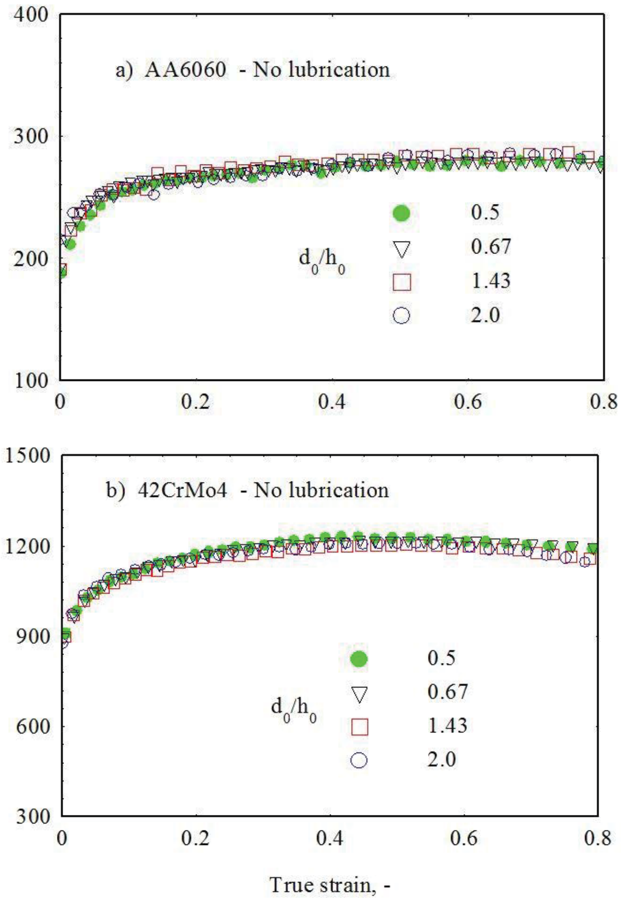

Figure 7. Friction-free flow curves determined from compression tests after the elimination of the friction effect (42Crmo4 and AA6060, without lubrication).

Acknowledgment

The authors would like to express their great thanks to Prof. Dr.-Ing. Habil Essam El-Magd, for carrying out the experimental work at the laboratories of the Department of Materials Science, RWTH Aachen University, Germany, and for the valuable discussion.

References

[1] A.Pougis, et al., Dry friction of steel under high pressure in quasi-static conditions, TribologyInternational, 67 (2013) 27–35

[2] X. Lai, et al., An experimental method for characterizing friction properties of sheet metal under high contact pressure, Wear 289 (2012) 82–94

[3] R.L. Chaplin and P.B. Chilson, The coefficient of kinetic friction for aluminum, Wear, 107 (1986) 213–225.

[4] N.P. Suh and H.C. Sin, The genesis of friction, Wear 69 (1981) 91–114.

[5] A.T. Male and M.G. Cockcroft, A method for the determination of the coefficient of friction of metals under bulk plastic deformation, J. Inst. Met. 93 (1964) 38–46.

[6] G.T. Van Rooyen and W.A. Backofen, A study of interface friction in plastic compression, Int. J. Mech. Sci. 1 (1960) 1–27

[7] M.V. Rastergaev, Neue Methode der Homogene Stauchen, Zavodskaja Laboratoria, 3 (1940) 354-355.

[8] M. Kunogi, A new method of cold extrusion, J. Sci Res Inst (Tokyo), 50 (1956) 215-246

[9] A.B. Watt and H. Ford, An experimental investigation of the yielding of strip between smooth dies, Proc. Inst. Mech. Eng. B1, (1952-1953) 448-453

[10] M. Tajdari and M. Javadi, A new experimental procedure of evaluating the friction coefficient in elastic and plastic regions, Journal of Materials Processing Technology, 177 (2006) 247–250

[11] G.M. Yang, et al., Contact pressure between two rough surfaces of a cylinderical fit, Journal of Materials Processing Technology, 123 (2002) 490-497.

[12] G. E. Dieter, Mechanical Metallurgy, McGraw-Hill, London, 1988, pp 541

[13] Moon Saeng Kim, An Analysis and Evaluation of the Dynamic Flow Function of Metals under Impact Loading, Ph.D. thesis, The University of Alabama, 1985, pp 25-50

[14] Han Han, The validity of mathematical models evaluated by two-specimen method under the unknown coefficient of friction and flow stress, J. Mater Proc. Techn., Vol 122, 2002, p 386-396

[15] E.G. Thomsen, Mechanics of plastic deformation in metal processing, Macmillan. New York, 1965