Reliability of plane strain compression test: and a note on friction during forming

Citation for published version (APA):

Document status and date:
Published: 01/01/1994

Publisher Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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RELIABILITY OF PLANE STRAIN COMPRESSION TEST
and a note on friction during forming

Eric TRICAUD
Ecole Nationale d'Ingénieurs de Tarbes
2 June 1994
WPA 120013

REPORT

Mentor in TUE:  dr. ir. J.A.H. Ramaekers

Project leader in ENIT:  Pr. Boutoleau

Trainee:  E. Tricaud  option: Materials Engineering

university year 1993-1994
THANKS

When you see the Technical University of Eindhoven for the first time, you can feel a lack of humanity mostly because of its size. Indeed about seven thousand students are working in this school. But on the contrary, as soon as I met the team in which I had to work in the forming technology department, I felt a very good atmosphere. So, I want to thank every people who made my integration in the team easier.

And there are some people I want to thank particularly. M. Ramaekers, my project leader, who followed my work despite of the lot of business he has to deal with. M. De Groot and M. Smeets who helped me to set up experiments, M. Van Ierland who very kindly cut many workpieces for me.

It would be unforgivable from me if I forget every students who were very helpful during this training period.

And of course, I thank M. Kals, responsible of the forming technology department, because he supports this kind of exchange program and so gives the possibility of an experience aboard to students.
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INTRODUCTION

For me, it was important to make my final project aboard first to live with different customs, may be to work differently and also to improve my spoken english. Then a work was proposed to me in the laboratory of forming technology in Eindhoven (Netherlands).

During the last decades, advances in materials science largely conduced to the enormous increase in industrially available materials.

The performance of a new material often is evaluated from its in service properties like hardness, yield strength, fatigue behaviour, etcetera.

But from a manufacturing point of view, it is necessary to define materials workability. And, concentrating on forming technology, this means that we have to evaluate the suitability of a material to forming applications from some characteristic quantities.

Many tests exist to define these datas but in the laboratory of forming technology of Eindhoven university, a new one was developed to reproduce most forming processes. This apparatus can be used to measure also friction during metals forming.

During this project, first I have to test this apparatus on reliability for measuring flow curves of several materials. I'm also expected to study the friction during forming processes. I have to compare different models to describe it.
I. DESCRIPTION OF THE NEW DEVELOPED TEST.

I1. The process chosen.

As many forming processes are compression ones, an upsetting test was used. For more simplicity in the derivation of flow stress and in the realisation. Furthermore, the flow behaviour is similar to many forming processes like upsetting, rolling, die forging and others.

II2. About friction.

Friction increases the necessary energy during forming processes, it also reduces tools life and can decrease the product quality. So, that's why friction is measured in the new developed test.

Many models have been developed to describe friction during forming. But the main ones will be considered: Von Mises and Coulomb, and also a new model developed by two professors of the University: Ramaekers-Kals.

The three models are:

- Coulomb: \[ \tau_{fr} = \mu p \]  

\( \tau_{fr} \) : friction shear stress.  
\( \mu \) : friction coefficient.  
\( p \) : normal pressure.
This is the most widely used model.

_ Von Mises : \( \tau_{fr} = mK \) \hspace{1cm} I2.1.2

\( m \) : friction coefficient.  
\( K \) : shear yield stress of workpiece.  
In this model the friction shear stress is a constant.

_ Ramaekers-Kals : \( \tau_{fr} = qpuA/A_0 \) \hspace{1cm} I2.1.3

\( q \) : friction coefficient.  
\( p \) : normal pressure.  
\( u \) : relative displacement between die and workpiece.  
\( A/A_0 \) : surface strain.

This model is based on physical observations of friction phenomena, the relative displacement between tools and piece is considered.

Friction will be more discussed later with commented results.

Each of these models can be used to derive the flow stress and of course better the model is to foresee the friction value, better is the calculated flow stress.

These derivations are clearly illustrated by flow charts in appendix 1 for all three friction models.

Workpiece dimensions were chosen so that the friction on the sides can be neglected when compared to upper and lower areas.


I3.1. Criteria and hypothesis.

Let consider the equilibrium of a small element of the workpiece in X direction.
\[ W[(\sigma x + d\sigma x)H - \sigma x.H - 2\tau dx] = 0 \]

So \( d\sigma x/dx = 2\tau/H \quad I3.1.1 \)

using Von Mises yield criterion under plane strain conditions:

\[ \sigma x - \sigma z = (2/\sqrt{3})\sigma f \quad I3.1.2 \]

we get by differenciation:

\[ d\sigma z = d(\sigma x - (2/\sqrt{3})\sigma f) \]

and so

\[ d\sigma z = d\sigma x = 2\tau dx/H \quad I3.1.3 \]

first consider Coulomb friction model.

\[ \text{I3.2. Coulomb friction model.} \]

From I3.1.3, we get

\[ d\sigma z = -2\mu \sigma z dx/H \]

so

\[ d\sigma z/\sigma z = -2\mu dx/H \]

deriving this differential equation, we get

\[ \ln \sigma z = -2\mu x/H + \text{Cte} \]

and finally

\[ \sigma z = C_1.\exp[-2\mu x/H] \quad I3.2.1 \]

Under boundary conditions

At \( x = L \quad \sigma x = 0 \) so \( \sigma z = -(2/\sqrt{3})\sigma f \)

replacing \( \sigma z \) into I3.2.1 we get

\[ -(2/\sqrt{3})\sigma f = C_1.\exp[-2\mu L/H] \]

then the constant is identified:

\[ C_1 = -(2/\sqrt{3})\sigma f.\exp[2\mu L/H] \]

and I3.2.1 becomes
The deformation force is:

\[ P_d = \int -\sigma z W dx \]

so \( P_d = (2/\sqrt{3}) \sigma f W \int \exp[-2\mu x/H] \)

Then \( P_d = (2/\sqrt{3}) \sigma f W \exp[(2\mu L/H)[(-H/2\mu)\exp(-2\mu X/H)]] \)

and simpliest

\[ P_d = (WH/\sqrt{3}.\mu) \sigma f \exp[(2\mu L/H) - 1] \]

From experimental datas, the vertical force \( F_{ver} \) or \( P_d \), the friction load \( F_{fr} \) or \( F_{hor} \) and the actual height of workpiece \( H \), we have to derive the flow stress:

As \( \mu = F_{fr}/2F_{ver} \)

I3.2.3 gives \( \sigma f = (\sqrt{3} F_{fr}/2 F_{ver}) F_{ver}/W H \exp[(F_{fr} L/F_{ver} H) - 1] \)

Then \[ \sigma f = \sqrt{3} F_{fr}/2W H \exp[(F_{fr}.L/F_{ver}.H) - 1] \]

I3.2.4

I3.3. Von Mises friction model.

Using the same criterions and hypothesis than for Coulomb, we have

\[ \sigma x = 2\tau X/H + \text{Cte} \]

with boundary condition : at \( x = L \), \( \sigma x = 0 \) it comes

\[ \sigma x = 2\tau (X - L)/H \]

and with I3.1.2

\[ \sigma z = -(2/\sqrt{3}) \sigma f + 2\tau (X - L)/H \]

I3.3.1

and the deformation load is \( P_d = \int -\sigma z dx \)

so \( P_d = (2/\sqrt{3}) \sigma f W L - 2\tau W/H \int (X - L)dx \)

Finally \[ P_d = [(2/\sqrt{3}) \sigma f + L.\tau/H] W L \]

I3.3.2

And from experimental datas : as \( \tau = F_{fr}/2 L W \)

\[ \sigma f = (\sqrt{3}/2).[(F_{ver}/W L) - (F_{fr}/2W H)] \]

I3.3.3
I3.4. Ramaekers-Kals friction model.

The relative displacement between die and workpiece is

\[ u = X - X_0 \]

Considering the volume unvariance \( X_0 \cdot W_0 \cdot H_0 = X \cdot W \cdot H \)

and under plane strain conditions \((W_0 = W), \ X_0 \cdot H_0 = X \cdot H \)

so that \( u = X(1 - H/H_0) \) and \( A/A_0 = H_0/H = X/X_0 \)

Then using I2.1.3 and I3.1.3 it comes

\[ \delta \sigma z = -2q \delta z (\Delta H/H^2) X dx \]

so \( \delta \sigma z/\delta z = -2q(\Delta H/H^2) X dx \) integrating, we get

\[ \ln \sigma z = -q(\Delta H/H^2) X^2 + Cte \]

and \( \sigma z = C_2 \exp[-q(\Delta H/H^2) X^2 + C_3] \)

with boundary condition: at \( X = L \) \( \sigma z = -(2/\sqrt{3}) \sigma f \)

so \( C_2 = -(2/\sqrt{3}) \sigma f \) and \( C_3 = q(\Delta H/H^2)L^2 \)

Then

\[ \sigma z = -(2/\sqrt{3}) \sigma f \exp[q(\Delta H/H^2)(L^2 - X^2)] \]

I3.4.1

And the deformation load is:

\[ P_d = (2/\sqrt{3}) \sigma f W \int \exp[q(\Delta H/H^2)(L^2 - X^2)] dx \]

as \( H = H_0 \cdot X_0 / X \), then \( \Delta H/H^2 = (X^2/X_0^2 \cdot H_0^2)(H_0 - H) \)

or \( \Delta H/H^2 = (X/X_0 \cdot H_0)(X/X_0 - 1) \) so

\[ P_d = (2/\sqrt{3}) \sigma f W \int \exp[(qX/X_0H_0)(X/X_0 - 1)(L^2 - X^2)] dx \]

I3.4.2

and the vertical normal pressure is:

\[ p = -\delta z = (2/\sqrt{3}) \sigma f \int \exp[q(\Delta H/H^2)(L^2 - X^2)] \]

and I3.1.3 gives \( \tau = (H/2) \delta \sigma z / \delta x \)

so \( \tau = -(2/\sqrt{3}) \sigma f \exp[q(\Delta H/H^2)(L^2 - X^2)] \cdot q(\Delta H/H^2)(-2X).H/2 \)

and

\[ \tau = (2/\sqrt{3}) \sigma f q(\Delta H/H) X \cdot \exp[q(\Delta H/H^2)(L^2 - X^2)] \]

I3.4.3
Integrating \( \tau \) over the contact area, we get the total friction force:

\[
F_{fr} = 2W \int \tau \, dx
\]

\[
F_{fr} = (4\sqrt{3})\sigma f W (\Delta H/H) \int X \exp[q(\Delta H/H^2)(L^2 - X^2)] \, dx
\]

\[
F_{fr} = (4\sqrt{3})\sigma f W (\Delta H/H) \exp[q(\Delta H/H^2)L^2] \left[ (-H^2/2q\Delta H) \exp[-q(\Delta H/H^2)X^2] \right]
\]

more simply

\[
F_{fr} = (2\sqrt{3})\sigma f W \left[ \exp[q(\Delta H/H^2)L^2] - 1 \right]
\]  

and it comes

\[
\sigma f = (\sqrt{3}/2)F_{fr}/2WH \left[ \exp[q(\Delta H/H^2)L^2] - 1 \right]
\]  

or using \( F_{ver} = \int -W \sigma z \, dx \) we get:

\[
\sigma f = (\sqrt{3}/2)F_{ver}/2W \int \exp[q(\Delta H/H^2)(L^2 - X^2)] \, dx
\]

We can see than in this formula, \( \sigma f \) is expressed with \( q \), and \( q \) is a function of \( \sigma f \) than we can derive from I3.4.4:

we have

\[
\exp[q(\Delta H/H^2)L^2] = 1 + (\sqrt{3}/2)F_{fr}/2\sigma f WH
\]

then

\[
q = (H^2/\Delta H\cdot L^2) \cdot \ln[1 + (\sqrt{3}/2)F_{fr}/2\sigma f WH]
\]  

A semi-experimental way is used to derive \( q \):

1. From a Rastegaev test we get a flow curve of the material \( \sigma f(\varepsilon) \).
2. \( q \) is derived from formula I3.4.7 using Rastegaev \( \sigma f \).
3. A new \( \sigma f \) value is derived from I3.4.6 and used again to get a new friction coefficient \( q \).

The loop 2-3 is reiterated until the difference between Rastegaev \( \sigma f \) and new \( \sigma f \) is less than 1%.

I4. Presentation of the test.

A schema of the structure is presented in appendix 2.

The tribometer was designed by a chinese student, S. Wang, a schematic drawing of the tribometer is given in appendix 3.

Three signals are recorded. The vertical force is measured by mean of a strain gauge. The friction load is recorded via a kistler cell, a pressure-sensitive crystal. And the vertical displacement between tools is got using an inductive displacement sensor; the maximum course is about eight millimeters.
Most of the difficulties in the measurements are due to the setting of blocks and testpiece in the press, and also to the calibration of sensors. So I wrote a procedure to improve the repetability of the test's conditions, you can see it in appendix 4.

II. STANDART TESTS.

Keeping in mind I have to check the reliability of the plane strain compression test to get flow curves, it is clear that standarts tests have to be carried out. Their results will be compared with our apparatus ones.

Two tests are chosen: first tensile test because it is very commonly used and second a singular upsetting test defined by Rastegaev because it uses compression stress (like ours), and because the friction is very small. Next follows a short description of these two experiments.

III1. Tensile test.

This test is very commonly used because it is quite easy to handle but it has some drawbacks. Indeed because of necking, it is difficult to get high strains, a true strain of 0.5 is about the maximum it is possible to get for very ductil materials like electrolytic copper. A result of this is that testpieces have to be machined very accurately to avoid a fast necking due to a weakest section (crack of cutting for example). The drawing of the testpieces I used is given in appendix 5 with the usual flow curve form obtained.

III2. Rastegaev test.

This is an upsetting test so it is closer to the plane strain compression experiment than tensile test but the main difference is that the friction is reduced to very small values by using a special design. Indeed two flat recesses are machined on both end faces of the cylindrical testpiece, and these holes are filled with a lubricant. Then during the cylinder upsetting, the lubricant carries most of the pressure so that the friction is very low. A Rastegaev specimen is drawn in appendix 5 with the optimum dimensions usually used.

The main advantage of this test is that high strains can be obtained.

When a cylindrical piece is compressed between parallel dies, the equivalent strain, according to Tresca criterion, is given by the equation:
\[ \varepsilon(F) = \ln \frac{H(F)}{H_0} \quad (<0) \]

and flow stress is

\[ \sigma_\tau(F) = \frac{F[H_0 - \Delta H(F)]}{\pi r_0^2 H_0} \]

Much care has to be taken because if the friction is low enough, the specimen doesn’t remain cylindrical. The contour of barelling must be measured for a correction of the results. This causes an additional error which propagates into the calculated flow curve.

III. RELIABILITY OF THE TRIBOMETER.

III.1. Materials tested.

III.1.1. Choice.

The plane strain compression test has to be checked on reliability to get flow curves for several materials. Every material doesn’t have the same plastic behaviour, so it was interesting to lead some experiments on different materials. Then five common ones were chosen according to the laboratory’s availabilities: steel St37, brass Ms58, electrolytic copper, aluminium St51 and aluminium A99.5. Their characteristics are given in appendix 6.

Indeed, we can justify this choice because brass and copper are well known for their singular strain hardening:

Until a certain limit \( \delta \), an usual parabolic law is observed, \( \sigma = C(\varepsilon + \varepsilon_0)^n \), but then there is logarithmic strain hardening, \( \sigma = B + m \ln(\varepsilon + \varepsilon_0) \). This phenomenon can be well observed only if the deformation is high enough.

On the contrary, for steels and aluminium, an usual parabolic strain hardening is usually got.

III.1.2. Precautions.

We have to take much care using new materials in the new apparatus because even thought the tools are hard enough to endure high pressures, the design of the system doesn’t allow us to get very high pressures:
Indeed the piece 1 is not strong enough to endure sresses up to 400 MPa. So with the pieces initial dimensions, we get the maximum force which can be used:

\[ S = 50 \times 25 = 1250 \text{ mm}^2 \text{ then } F_{\text{max}} = 500 \text{ KN} \]

So during experiment, we have to stop the measures before reaching this load to avoid tools damages.

During Rastegaev test, different tools are used and their basic design gives us the possibility to get very high pressures. Tools elastic strength \( R_E \) is about 2800 MPa so that, using a security factor of 2, the maximal stress is about **1400 MPa** and we get, with pieces initial dimensions, the maximal force which can be used:

With \( S = \pi \times 10^2 = 320 \text{ mm}^2 \) then \( F_{\text{max}} = 450 \text{ KN} \)

So in this experiment, each material can be tested under high stresses.

During tensile tests, when necking occurs, the acquisition program automatically stops the measures otherwise it can 't calculate the flow curve. And even without any necking, the force can 't be up to 20 KN because of amplifiers and calibrations used. The maximal stress which is obtained is about **600 MPa**, but of course, it depends of the piece final area.

### III.2. Measured flow curves.

#### III.2.1. Aluminium St51.

In the following graph, aluminium St51 flow curve was obtained using each test.
First, you can see that the curve could be got only for low strains. Indeed, I saw that this material was very hard during tensile test because a very fast necking occurred. And during both upsetting tests, I had to stop the measures as soon as the maximal pressure was reached.

Otherwhere, in the strain range I got, there is a quite good agreement between all three tests. Indeed the difference observed between plane strain test and both other ones is small, less than 5%.

According to the tensile test, the flow curve equation is

\[ \sigma_f = 377 \epsilon^{0.082} \]

III.2.2. Pure aluminium A99.5.

I was expecting better results with this very soft material than those obtained with aluminium St51. These are the results.

\[ \sigma = F(\epsilon) \]

As expected, the deformation range got from tensile test is smaller than those obtained from both upsetting tests. Of course, this is due to necking.

It can be also noticed that these results agree better with literature than previous ones. Indeed, a difference is usually observed between tensile and upsetting tests: for a given strain, the stress is higher in compression than in tensile tests. The main reason of this phenomenon is that metals plastic behaviour depends on the strain path.

Furthermore, it can be seen that the difference between both upsetting tests is not constant. Indeed, for low strains, the biggest difference is observed. This can be explained because
friction is neglected in Rastegaev experiment and at the beginning of this test, the lubricant doesn't carry yet the pressure so that, due to the contact metal/metal, the friction is not neglectable.

But, we shouldn't forget that the difference is small, less than 8 %, so globally, there is a good agreement between plane strain compression test and standard ones.

**III.2.3. Electrolytic copper.**

A first serie of tensile tests was carried out using this material but then a very fast necking occurred revealing the hardness of this copper. Then I annealed new test pieces to get better results.

Then the following flow curves were obtained:

\[
\sigma = F(\varepsilon)
\]

Electrolytic copper

There is a very good agreement between both standard tests. But the flow curve measured in the new apparatus is below these two last ones with a maximal difference of about 20 %. This difference can't be explained only by measurements unaccuracy. A possible explanation is that the displacement sensor calibration was wrong so that the curve should be moved on the left. This possible explanation couldn't be checked because the calibrations were modified after these tests.

**III.2.4. Steel St37 and brass Ms58.**

These two materials are considered together because they showed the same problem: they are too hard to be tested on plane strain compression experiment. However, let see the results of
standard tests first for steel:

\[ \sigma = F(\epsilon_{\text{ion}}) \]

Steel st37

<table>
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<tr>
<th>\epsilon_{\text{ion}}</th>
<th>0</th>
<th>0.1</th>
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<th>0.3</th>
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<td>\sigma</td>
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\[ \times \text{ tensile test} \quad \bullet \text{ Rastegaev test} \]

It can be see again that, in the small strain range got in tensile test, there is a very good agreement of both curves.

For brass, the following flow curves were got:

\[ \sigma = F(\epsilon_{\text{ion}}) \]

Brass ms58

<table>
<thead>
<tr>
<th>\epsilon_{\text{ion}}</th>
<th>0</th>
<th>0.05</th>
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<td>\sigma</td>
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\[ \bullet \text{ tensile test} \quad \times \text{ Rastegaev test} \]

Excepted the very good agreement of both experimental results, the singuliar plastic behaviour of brass is interesting to see. In appendix 7, flow curves of different materials are
presented on double logarithmic scaling graphs to illustrate these different plastic behaviours. Then for copper, the two parts are easy to see: first a parabolic law and next a logarithmic one.

III.3. Concluding remarks.

Good agreements were always obtained between standard tests so their choice as a reference is justified.

For steel and brass, any comparison could be made, for technical reasons I already explained, plane strain compression experiment couldn't be carried out on these two too hard materials.

For both aluminium, good agreements were got between each test. But there is a number of different causes from which these differences can originate. They can be classified with respect to their backgrounds in experimental, theoretical and metallurgical causes.

III.3.1. Experimental considerations.

It is clear that the determination of accurate experimental information depends highly on a solid experimental procedure. First, this requires a proper experimental set-up. The Rastegaev test is a suitable means. As a result of the excellent lubricating conditions, the cylindrical shape of the specimen is preserved (there is no barreling) up to high deformations. The accuracy of its results can be improved measuring directly the diameter instead of the height.

For the tension test, the deformation is uniform by its nature, uni-axial stress state, at least before necking occurs. Some methods such as Bridgman can be used to extend the explored strain range correcting the non-uniaxiality due to necking.

For plane strain compression test, the specimens often don't remain plane, then the presence of barreling causes inaccuracies in the derivation of flow curves. But the main problem in this test is the necessary use of calibrated testing equipment. This expresses the importance of an accurate measurement of all quantities involved in the calculation of flow curves (dimension, loads, displacement, ...). But these causes can't explain the important difference observed for copper. And mostly because this difference wasn't observed for both aluminium.

The homogeneity of the materials is also important. To assure good reproducibility within the sets of experiments, the specimens for each material should be taken from the same rod. This condition wasn't respected in my experiments. Indeed the test piece is not cylindrical so it was cut from another block than tensile and Rastegaev test pieces. Then after annealing treatment, it is possible that microstructures and grain sizes
in both longitudinal and transverse directions were not the same.

**III.3.2. Theoretical considerations.**

Theoretical backgrounds also play a role in the comparison of flow curves derived from the different tests. Indeed, this category involves the assumption of a yield criterion. In all three applications, the Von Mises Yield criterion is used. Usually inaccuracies due to these considerations are of secondary importance.

**III.3.3. Metallurgical causes.**

Metallurgical effects can induce a different flow behaviour. This is supported by many investigations. Differences between the flow curves can be explained from the development of different microstructures, different textures in the deforming material.

Herbertz and Wiegels led many studies on this topic and concluded that the compression and tension flow curves cannot be brought into coincidence for certain materials such as steel C22.

Finally, the plastic behaviour of metals is so complex that it seems difficult to bring an absolutely right explanation to the differences observed with copper. This shows that such experiments need much care to master most of the parameters.

So more experiments should be carried out with copper to check the results got previously.

However, the study of friction during plane strain compression test has to be considered.
IV. FRICTION DURING FORMING.

For a long time, friction forces have been neglected in the analysis of the stresses during forming. But in reality, friction is a very important factor which has to be taken into account to master these processes.

As already shown, different models are commonly used to describe friction during forming. Coulomb’s model considers a sliding friction concept whereas Von Mises supposes that the interface has a proper shear strength, this is an adhesive friction concept. But during cold forming processes, Coulomb’s model is most commonly used.

Friction is a very complex parameter to study. I didn’t have enough time during this project to study it in details. So the following part is just to give some ideas about friction during forming.

The agreement of three friction models with the reality will be considered. Lubrication and roughness effects will be also observed.

IV.1. Comparison of models.

The tribometer’s reproducibility was successfully tested on pure aluminium test pieces using tallow as lubricant.

IV.1.1. Friction coefficients.

Let have a look on the friction coefficients derived from the recorded datas and using each model.
You can notice that friction coefficients are not constant during the experiment. $\mu$ and $m$ increase with the punch travel whereas $q$ first rises fastly up and then decreases. So the three models run into difficulties when used in forming processes. Indeed, it is expected that the friction stress increases with the slip ratio $Us/Vt$ between the tools and the workpiece.

That's why Ramaekers-Kals friction model was modified to take into account this slip ratio. It becomes:

$$r_{fr} = q_1 \cdot p \cdot (Us/Vt) \cdot (A/A_0)$$

Then the friction coefficient $q_1$ is now dimensionless.

Finally, you can see that $q_1$ increases fastly with the punch travel at first due to adherence and then is nairly constant.

**IV.1.2. Deformation load.**

Using experimental friction coefficients and the derivation by slab method, we get load versus punch travel curves which can be compared to experimental one:

First the differences between each model are small. But the values showed that Ramaekers-kals model (modified one) agrees the
best with experiment. In fact both other ones underestimate the deformation load.

IV.1.3. Friction and normal pressure distribution.

It is interesting to consider friction and normal pressure distributions. They are given for $\delta H = 3$ mm, $\epsilon = 0.16$.

The integration of friction and normal pressure over the contact area has to to be equal to the total friction and
vertical forces measured. But in fact, the sum of the areas between the curves corresponding to each model are not the same. This result could be easily expected from the previous ones (§IV.1.2.). Indeed, by using slab method, the vertical force and friction force are all functions of friction coefficients, so the results could only be good when the model agrees well with the reality.

IV.2. Lubricants effects.

One of the many possibilities the tribometer can offer is the test of different lubricants properties.

Let see in the following graph the effects of lubrication on the flow curve of a pure aluminium. The roughness of pieces surfaces was about 3 μm.

![Flow Curves of Pure Aluminium Lubrication Effects](image)

First, the friction is higher without lubricant than using tallow because of adherence. But then for strains between 0.1 and 0.5 the friction is lower without lubrication. And it seems that for deformations up to 0.5 the contrary would be observed. Using no lubricant, it seems that there is a succession of adhesive and sliding contacts between tools and piece. But it is quite sure that for strains up to 0.5, the friction increases much more without than with lubricant.

For forming applications, the lubricant to use has to be chosen carefully because this parameter has a strong influence on friction so on the products quality, but also on the tools life, on the necessary energy.
IV.3. Roughness effects.

Roughness is usually a parameter which has some effects on friction. In the following graph, two tests were carried out on pure aluminium pieces of different roughnesses, 3 and 9 μm. In both experiments, tallow lubricant was used.

It can be noticed that with the roughness of 9 μm, the flow stress is lower than with Ra = 3 μm. This can be easily explained because a minimal roughness is required to hold the lubricant between areas in contact.
CONCLUSION

First, I would say, because it makes me a bit frustrated, that a three month project is too short for this kind of research. Indeed, First I had to be familiar with the subject and also with a new way of working and with the use of English in daily work situations. Then I met some practical difficulties for example with the acquisition program which had to be modified. Furthermore, the staff I used for my experiments wasn't only mine and I should share it with other students. But I know these problems are commonly met during such a project. And if most of these difficulties were solved, the time I could spend for pure research was shortened.

Despite of this, I got some interesting results about forming technology and before this project I couldn't expect the existence of Ramaekers-Kals friction model which seems to agree better than usual models in cold forming applications.

I also showed that plane strain compression test could be used to determine at least aluminium flow curves. It's a shame that the design of this apparatus isn't strong enough to measure steel and brass flow curves. Indeed it could have brought an explanation to the results we got with copper.

It is also important to say that a flow curve is absolutely not a constant of a given material. Indeed, it depends of an enormous variety of parameters which main ones are temperature, strain rate, lubrication, roughness, hardness of tools but also the kind of process itself.

The last point can be explained, in part, by the fact that flow stress depends on the strain path. And a consequence of this is that the test to choose depends mainly on the process to describe. If a tensile test can describe deep drawing, it is better to use an upsetting test to simulate rolling or free forging.

Finally, this project aboard was a rich experience for me, first because the job was interesting but also because the atmosphere in the forming technology department was very friendly. I hope I will meet such working conditions in my future career.
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Reliability of Plane Strain Compression Test
and a note on friction during forming

Eric Tricaud
Ecole Nationale d’Ingénieurs de Tarbes
2 June 1994
WPA 120013

French Summary

Mentor in TUE: dr. ir. J.A.H. Ramaekers
Project leader in ENIT: Pr. Boutoleau
Trainee: E. Tricaud option: Materials Engineering

University year 1993-1994
Préliminaire

Le présent document ne saurait être présenté comme une traduction du rapport que j’ai rédigé en anglais. Il s’agit sinon d’un résumé, d’un rappel des grandes lignes du projet ainsi que des principaux résultats.

Trois parties sont développées suivant le plan du rapport de stage. Une description rapide du tribomètre développé au laboratoire est donnée. Suit le test de ce tribomètre pour définir son aptitude à fournir les courbes d’écoulement de divers métaux. Et une analyse de la friction au cours de la mise en forme est finalement présentée.

A. Présentation du tribomètre

L’étude et la prise en compte des phénomènes de frottement accompagnant la mise en forme sont récentes. Au laboratoire de mise en forme de l’Université d’Eindhoven, c’est un problème auquel on s’intéresse depuis déjà de nombreuses années au point qu’un modèle de friction a été développé au sein de cette équipe, par Messieurs F. Ramaekers et J. Kals. Mais pour vérifier la validité de ce modèle, un tribomètre intégré dans un procédé de mise en forme a développé.

A.1. Le tribomètre

Etant donné que les procédés de mise en forme par compression sont nettement prédominants, la solution du tribomètre intégré à un test de compression a été choisie. Les éprouvettes sont comprimées en déformation plane pour simplifier la détermination des courbes d’écoulement. De plus, l’écoulement ainsi obtenu est alors similaire à de nombreux procédés de mise en forme à froid : emboutissage, forgeage, roulage, etc...

voir rapport figure 6.1.

Une représentation schématique de l’ensemble de la structure du test est représentée en annexe p3. Trois données sont mesurées lors des tests : force verticale, force horizontale (friction) et déplacement vertical.

L’obtention des courbes d’écoulement à partir de ces données est illustrée par un synoptique pour trois modèles de friction auxquels on s’intéresse (Coulomb, Von Mises et Ramaekers-Kals) en annexe p1 et 2. Le détail des calculs peut également être consulté dans le rapport aux pages 5 à 9.
En annexe p4, est présenté le dessin de la partie mécanique du test, l’ensemble est évidemment installé sur une presse hydraulique.

A.2. Test standards

Pour ma part, le contrôle de la validité du tribomètre lui même à la détermination de courbes d’écoulement passait par la comparaison avec des tests standards effectués sur les mêmes matériaux.
Deux tests très couramment utilisés sont choisis: le test de traction et un test de compression défini par Rastegaev.

A.2.1. traction

Ce test s’il est couramment utilisé en raison de sa relative simplicité de mise en œuvre, il souffre malgré tout d’un inconvénient majeur: la striction.
En effet celle-ci limite largement le domaine de déformation sur lequel peut être définie la courbe d’écoulement.
On obtient généralement 0,2 à 0,3 de déformation vraie pour des matériaux ductiles.
Habituellement les tests peuvent être exploités après le début de la striction. Une correction (Bridgmann par exemple) permettant de palier la non uniaxialité de l’écoulement.
Une conséquence de cette striction est qu’il est souhaitable d’usiner avec beaucoup de soin les éprouvettes. Toute réduction de section dû à une strie d’usinage ou autre défaut pouvant entrainer une striction prématurée.

Le principal avantage de ce test est l’absence de frottement, ainsi toute erreur dûe à une mauvaise estimation de ce dernier est évitée.
Cependant il paraît plus juste de comparer notre test avec une expérience utilisant le même type de sollicitation: la compression.

A.2.2. Rastegaev

La particularité de la conception des éprouvettes dans ce test conduit à une réduction très nette de la friction tant et si bien qu’elle est négligée.
En effet aux deux extrémités d’un cylindre sont usinés des logements qui serviront de véritables "chambres de lubrification". Remplies de lubrifiant, elles assureront une véritable portance hydrostatique de la pression exercée sur la pièce. Le contact métal/métal étant ainsi réduit fortement et par conséquence le frottement aussi.
B. Contrôle du tribomètre

Ce tribomètre doit conduire à l’obtention de courbes d’écoulement de divers matériaux. Aussi des tests standards seront conduits sur les mêmes matériaux.

B.1. choix des matériaux

Le choix de ces matériaux est problématique: on souhaite des matériaux variés, de comportements plastiques bien différents. Une contrainte cependant est d’utiliser des matériaux ductiles et pas trop durs pour obtenir de grandes déformations et des contraintes limitées pour ne pas endommager les outils et le tribomètre lui-même. Toutefois une autre contrainte est de se fournir parmi les matériaux dont dispose le laboratoire, avec les avantages mais aussi les risques que cela comporte. Le principal avantage est la rapidité de la disponibilité des matériaux, par contre on peut déplorer la méconnaissance, parfois, des nuances exactes fournies ou des traitements subis; trempes et durcissements seraient naturellement à proscrire pour de tels essais de formabilité.

Finalement cinq matériaux sont donnés :
- pur aluminium A99,5
- aluminium st51
- acier Ust37
- laiton à 58% Zn
- cuivre électrolytique

Lorsque les tests de traction sont réalisés sur chacun des matériaux, il apparaît rapidement que laiton et acier ne pourront être testés sur le tribomètre sous peine de l’endommager.

Effectivement ces deux matériaux sont jugés trop durs. Toutefois les tests de Rastegaev sont menés sur tous les matériaux afin de juger de la concordance des résultats entre les deux tests standards.

Donc sur le tribomètre seront testés Aluminium st51, A99,5 et cuivre électrolytique.

B.2. Résultats.

B.2.1. Aluminium St51.

voir courbes p12 du rapport.

Il faut noter que de faibles déformations ont été obtenues pour cet aluminium qui s’est révélé très peu ductile.

Cependant, les résultats obtenus sur chacun des trois tests sont très
proches, l’ écart ne dépasse jamais 5 %.

**B.2.2. Aluminium A99.5.**

voir courbes p13 du rapport.

L’ avantage de ce métal est sa bonne ductilité qui permet d’obtenir de grandes déformations sous de faibles contraintes. Ceci est tout à fait souhaitable pour le tribomètre en particulier.

Logiquement, de plus faibles déformations sont obtenues en traction qu’en compression à cause de la striction.

On peut également noter que la contrainte d’écoulement en compression est supérieure à celle obtenue en traction. Ceci n’est pas forcément dû à des imprécisions dans les mesures. En effet, j’ai pu relever dans certains ouvrages que la courbe d’écoulement de certains matériaux pouvait varier selon le type de sollicitation. Ceci semble prouver la dépendance de la contrainte d’écoulement vis à vis du chemin de déformation suivi.

Mais bien sûr, il ne faut pas perdre de vue que les différences obtenues sont très faibles et les résultats encourageants.

**B.2.3. Cuivre électrolytique.**

voir courbes p14 du rapport.

Ces résultats justifient pleinement le choix des tests standards qui donnent toujours des contraintes très proches.

En revanche, il est plus surprenant que la contrainte obtenue avec le tribomètre soit si faible, 10 à 20 % inférieure aux deux autres. Évidemment il est possible d’avancer un certain nombre d’hypothèses pouvant expliquer ce résultat. Toutefois, il faut rester humble avec des phénomènes aussi complexes. En effet, il est également possible qu’une mauvaise calibration du capteur de déplacement soit la source d’une erreur.

Quelques tests supplémentaires auraient bien sûr pu apporter une explication mais un étudiant avait besoin de la presse avec différents outils m’interdisant tout nouvel essai jusqu’à ce que les outils puissent être remplaçés à nouveau.
B.2.4. Acier St37 et laiton Ms58.

voir courbes p15 du rapport.

Chacun de ces deux tests confirme l’excellente concordance entre les résultats obtenus en traction et avec le test de Rastegaev.

Il est également intéressant de constater que la loi d’écrouissage de chacun de ces deux métaux n’est pas la même. Effectivement, en annexe 7 les courbes d’écoulement portés en échelle log/log montrent qu’une loi parabolique du type Hollomon ou Krupkovski décrit bien le durcissement par écouissage de l’acier. Par contre, le comportement plastique du laiton est différent, dans un premier temps, le durcissement suit une loi parabolique puis change progressivement pour suivre une loi logarithmique.

C. Le frottement en mise en forme.

C.1. Coefficients de frottement.

voir courbes p18 du rapport.

Aucun des coefficients de frottement obtenus par chacun des trois modèles n’est constant au cours de la déformation. Pour Coulomb μ, et pour Von Mises m, il augmente avec la déformation. Pour Ramaekers-Kals q, il augmente d’abord rapidement puis diminue progressivement. Ils semblent donc ne pas très bien décrire le frottement au cours de ce test. En effet, ce coefficient devrait être fonction du déplacement relatif à l’interface outil/pièce.

En partant de la précédente considération, le modèle développé par MM. Ramaekers et Kals a été modifié pour prendre en compte le glissement à l’interface us/vt, il devient :

\[ \mu_{fr} = q1.p.(us/vt).(A/A0) \]

Alors, on peut voir que le nouveau coefficient de frottement q1 augmente d’abord rapidement en raison de l’adhérence, puis il demeure à peu près constant. Donc ce modèle semble plus cohérent.

C.2. Force de déformation.

voir courbes p19 du rapport.

Les forces de déformation obtenues avec chaque modèle sont très proches. En effet, en présence d’une bonne lubrification, l’influence du frotte-
ment et encore plus du modèle utilisé pour le décrire est difficiles à appréhender.

Cependant, d’après les valeurs relevées, c’est le modèle de Ramaekers-Kals qui approche au mieux la force de déformation expérimentale. Coulomb et Von Mises la sous_estiment.

C.3.Distributions de la pression normale et du frottement.

voir courbes p20 du rapport.

Les modèles de Von Mises et de Coulomb sont simplistes, considérant une répartition constante ou presque du frottement. Au contraire le modèle de Ramaekers-Kals penne en considération que pour \( X = 0 \), il n’y a pas de déplacement entre pièce et outil, donc il ne peut y avoir de frottement.

On peut aussi noter que chacun des 3 modèles ne donnent pas la même force de déformation car pour chaque modèle, la somme des aires décrites par les 2 courbes de distribution est différente.

C.4.Lubrification.

voir courbes p21 du rapport.

Au début, le frottement est supérieur sans lubrification mais pour les déformations comprises entre 0.1 et 0.5, le contraire est observé. Il semble en fait que pour les relativement faibles déformations, sans lubrifiant, une succession de phases d’adhésion et de glissement se produit à l’interface. Par contre, il est quasi certain qu’aux grandes déformations, le frottement serait supérieur sans lubrifiant avec un écart de plus en plus significatif. C’est ce qui peut être tiré de la littérature.

C.5.Rugosité.

voir courbes p22 du rapport.

Le frottement est plus faible en utilisant une rugosité de 9 \( \mu m \) qu’avec 3 \( \mu m \), ceci s’explique par le fait que la lubrification requiert un minimum de relief pour retenir le lubrifiant à l’interface.

Par ailleurs, notons que le tribomètre serait un excellent outil pour comparer diverses qualités de lubrifiants ou encore pour déterminer la rugosité permettant d’optimiser la réduction du frottement pour un couple de matériaux donnés.
RELIABILITY OF PLANE STRAIN
COMPRESSION TEST
and a note on friction during forming

Eric TRICAUD
Ecole Nationale d'Ingénieurs
de Tarbes
2 June 1994
WPA 120013

APPENDICES

Mentor in TUE:  dr. ir. J.A.H. Ramaekers

Project leader in ENIT:  Pr. Boutoleau

Trainee:  E. Tricaud  option: Materials Engineering

university year 1993-1994
APPENDIX 1

FLOW CHART: GETTING FLOW STRESS 
USING VON MISES FRICTION MODEL $t = mK$

Using slab method, we get equilibrium equation 
\[ \sigma_y = \frac{X-L}{H} \]

Von Mises yield criterion under plane strain conditions gives: 
\[ \sigma_x - \sigma_z = \frac{2}{\sqrt{3}} \sigma_f \]

Von Mises friction model is: 
\[ t = mK \]

Measuring $F_v = \iint -w \sigma_z \, dx$ 
$F_{fr} = 2\mu F_v$ and $H$

Deriving 
\[ \sigma_z = \frac{-2 \sigma_f + 2(L-x)^2}{\sqrt{3}} \]

Finally it comes: 
\[ \sigma_y = \sqrt{3} \frac{F_v - F_{fr}}{2} \]

FLOW CHART: GETTING FLOW STRESS 
USING COULOMB FRICTION MODEL $t = mK$

Using slab method, we get equilibrium equation 
\[ \sigma_z = \frac{2\mu F_v}{H} \]

Von Mises yield criterion under plane strain conditions gives: 
\[ \sigma_x - \sigma_z = \frac{2}{\sqrt{3}} \sigma_f \]

Coulomb friction model is: 
\[ t = -\mu \sigma_z \]

Measuring $F_v = \iint -w \sigma_z \, dx$ 
$F_{fr} = 2\mu F_v$ and $H$

Deriving 
\[ \sigma_z = -\frac{2 \sigma_f \exp[2\mu(L-x)]}{\sqrt{3} H} \]

Finally it comes 
\[ \sigma_y = \frac{\sqrt{3} F_v}{2WH} \frac{F_{fr} + 1}{F_{fr} - 1} \]
FLOW CHART: GETTING FLOW STRESS USING R-K FRICTION MODEL $\tau = mK$

Using slab method, we get equilibrium equation

$$dz = \frac{2dx}{H}$$

Von Mises yield criterion under plane strain conditions gives:

$$\sigma_x - \sigma_z = \frac{2}{\sqrt{3}}$$

R-K friction model is:

$$\tau = -q_0z\sigma$$

Measuring $F_v = \int -Wozdx$ and $H$

Deriving $\sigma_z = \frac{2}{\sqrt{3}}$ of $\exp[\frac{qH(L^2-H^2)}{H}]$

Measuring $F_{fr} = 2W/dx$

From a standard Rastegaev test, we use $\sigma_{ref}$

Then we derive a friction coefficient:

$$q = \frac{H^2}{\Delta H^2} \ln[1 + \sqrt{3} F_{fr}]$$

So it comes

$$\sigma_{exp} = \frac{\sqrt{3} F_v}{2W \exp[\frac{qH(L^2-X^2)}{H^2}]dx}$$

$$|\sigma_{exp} - \sigma_{ref}| \leq 1\%$$

$\sigma_{ref}$ becomes $\sigma_{exp}$ to calculate a new friction coefficient

Finally $\sigma_f = \sigma_{exp}$
For more information about the overall structure, see Shunlong Wang's report: "Development of a plane strain compression tribometer".
Schematic drawing of the tribometer.
1. die base.  2, 6. steel blocks.  3. upper tool.  4. testpiece.
5. lower tool.  7. Kistler cell.  8. adjustable side platens.
9. side platen.  10. pre-stress screw.  11. position fix screw.
APPENDIX 4

PLANE STRAIN COMPRESSION SEQUENCE

1. Preparation and setting of workpiece.
   a. measure the piece: W, L, H.
   b. clean every block with acetone.
   c. lubricate every workpiece's faces with tallow or other lubricant.
   d. put teflon foils (about 60 x 35) on both sides of workpiece in the Y direction.
   e. reset kistler cell, then turn screw 11 till +00.
   f. pre-stress strongly screw 10 to insure plane strain deformation.

2. Calibration of sensors.

   This phase has not to be done before each test, it is only necessary to check the calibrations sometimes.

   The calibrations of both vertical displacement and vertical load have to be done simultaneously.

   a. first check the punch velocity the mechanic displacement sensor of the press and a clock. If not good, adjust it by screwing the oil flow mollet. The 3 engines should be always all in charge.
   b. put the die up using the two green buttons on the press.
   c. assure contact of both lower and upper tools using incremental displacement (yellow button). Consider there is contact only when the vertical force is 0.01.
   d. the vertical displacement should be of -4 V on the display (0 mm). If no, adjust it by mean of the amplifier.
   e. apply the effort until 500 KN.
   f. adjust, with the amplifier, the force to 4 V on the display (500 KN).
   g. release the effort, put again in contact, if the values don't remain the same that at first, then it is necessary to repeat this sequence.
3. Acquisition.

a. check the connexions of the PCL 718 card with computer and with amplifiers.
b. on the computer, choose C:\ERIC\ECDADE, then EXPERIMENT, PLANE STRAIN, DATA NAME :xxxxxx, EDIT, VELOCITY : 0.017 (about 1mm/mn), CYLINDER TRAVEL : 8 (at maximum).
c. then be sure that the displacement value displayed is less than -4.00, if no adjust it to about -4.02 because the acquisition of datas starts when this value goes down to -4.00.
d. choose ACQUISITION and press an arrow key 4 (to see when the acquisition of datas is finished, otherwise you can’t guess it).
e. immediately start the press displacement.
f. check on the display that a friction force appears in first twenty minutes of experiment, otherwise it means that the position of the workpiece is bad, not in good contact with block 6. Then stop the experiment (at this moment, only elastic deformation occurs).
g. when finished, stop the press displacement and all three engines, read the displacement data, release slowly the vertical force, when it is nul, read the displacement value to get the elastic deformation.
h. press PROCESS, you get the curves of the three recorded datas so that it is possible to have an idea about the test.

4. Processing datas using DATA-PRO.

a. copy the data file xxxxxx.dat as xxxxxx.org.
b. then remove the text out of the file (displacement...).
c. replace negative load values by small positive ones.
d. some constants have to be changed in the program :
   _ piece initial dimensions.
   _ the constant value necessary to replace recorded displacements by real displacements ( -4 to 0,...).
e. then choose RUN, and you can choose each option to get flow curves, friction coefficients, etc...
f. every files which are obtained are ASCII files so that it is possible to process them with many programs (lotus, wp, grapher,...).
TENSILE TEST PIECE DIMENSIONS.

Remarks:

Tensile test were carried out on a well automated apparatus so that a good reproducibility was obtained.

The processing program used to derive flow curves is used for sheet metals, then a program had to be used to change from rectangular to round section.
Remarks:

The optimum dimensions of the rings at the end faces have been determined experimentally by Krokha. According to him, the specimens retains a cylindrical shape up to the highest strain if the next conditions are fulfilled:

\[ h_0 \leq 2r_0 \] to avoid skewing.

\[ t_0 = 0.4u_0 \]

where \( t_0 \) is the initial height, and \( u_0 \) the initial width of the ring.
According to standard DIN 1712/1745

Designation

Al 99,5

Name: Aluminium 1 S-HH-Half Hard.

Form: Sheet, rod.

CHEMICAL COMPOSITION IN WEIGHT %

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
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<tbody>
<tr>
<td></td>
<td>99-99.5</td>
<td>0.3</td>
<td>0.4</td>
<td>0.05</td>
<td>0.03</td>
<td>0.07</td>
<td>0.05</td>
</tr>
</tbody>
</table>

PROPERTIES

Tensile strength 100 MPa

Elasticity modullus 70 000 MPa

0.2 yield point 70 MPa

Hardness 300 HB

Elongation A % 6 %

Density 2710 Kg/cm³

Melting point 658 °c
According to standard DIN 1746/1747

Name: Aluminium 51 St

Form: Sheet, rod, round rod, pipe, U profile.

CHEMICAL COMPOSITION IN WEIGHT %

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Mn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8-1.2</td>
<td>0.9</td>
<td>0.15</td>
<td>0.7</td>
<td>rest.</td>
<td></td>
</tr>
</tbody>
</table>

PROPERTIES

- Tensile strength: 320 MPa
- Elasticity modulus: 70 000 MPa
- 0.2 yield point: 280 MPa
- Hardness: 950 HB
- Elongation A %: 18 %
- Density: 2710 Kg/cm³
- Melting point: 590-665 °C
COPPER

According to standard DIN

Name: Electrolytic copper.
Form: Sheet, rod, round rod.

CHEMICAL COMPOSITION IN WEIGHT %

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>99.9</td>
</tr>
</tbody>
</table>

PROPERTIES

Tensile strength 220 MPa
Elasticity modullus 120 000 MPa
0.2 yield point 50 MPa
Hardness 450 HB
Elongation A % 48 %
Density 8900 Kg/cm³
Melting point 1083 °c
T.U.E. INTERNAL STANDARD Nr 12.2.3

NON FERRO MESSING

According to standard DIN 17670/71

Designation
CuZn40Pb3

Name: Messing Ms 58.

Form: Sheet, round rod, profiles.

CHEMICAL COMPOSITION IN WEIGHT %

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Zn</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>58-60</td>
<td>39.5</td>
<td>2-2.5</td>
</tr>
</tbody>
</table>

PROPERTIES

Hard quality

Tensile strength 450 MPa
Elasticity modullus 97 000 MPa
0.2 yield point 300 MPa
Hardness 1200 HB
Elongation A % 20 %
Density 8500 Kg/cm³
Melting point 890 °c
According to standard DIN 17100

Designation
St 37.2

Name: Steel St37.2.

Form: Sheet, rod.

CHEMICAL COMPOSITION IN WEIGHT %

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Fe rest.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
<td>0.2-0.5</td>
<td>0.06</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

PROPERTIES

Tensile strength 360-470 MPa
Elasticity modullus 210 000 MPa
0.2 yield point 230 MPa
Hardness 1100 HB
Elongation A % 25 %
Density 7850 Kg/cm³
Melting point 1500 °c
APPENDIX 7

Steel ST37 from Rastegaev test:

\[ \sigma_f = 915 (\epsilon + 0.049)^{0.186} \]

Aluminium ST51 from Rastegaev test:

\[ \sigma_f = 377 \epsilon^{0.082} \]
Brass MS58 from tensile test:

\[ \sigma_f = 790 (\varepsilon + 0.016)^{0.24} \]

Electrolytic copper from Rastegaev test:

\[ \sigma_f = 588 \varepsilon^{0.5} \]
Pure aluminium from plane strain compression test:

Electrolytic copper from tensile test:

\[
\sigma_f = 123 e^{0.27}
\]