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Design of a new simulative tribotest for warm forming applications having high contact pressure and surface enlargement

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Abstract. Many tribological tests have been developed in the last decades to emulate real cold forging processes at laboratory conditions and to obtain friction coefficients at different process conditions. In this paper a new tribotester is designed and numerically validated to reach extreme contact conditions, high normal contact pressure and surface enlargement, for warm temperature testing of lubricants starting from material in the form of thick sheets or precuts. The numerical simulations prove that this is possible by the use of a combined bending and ironing test.

Introduction

Fine blanking is a manufacturing process capable of producing sheet metal parts with completely smooth cutting surfaces [1]. The process is sometimes known by other names like fine stamping or precision cutting and like standard shear blanking processes, according to DIN 8580, fine blanking falls under the main category of material separation or parting processes, and is defined according to DIN 8588 under the sub-category dividing [2].

The main differences in comparison with the conventional blanking or punching process are the use of a counterpressure which enables to work in a more compressive stress state and decreases the cambering of the final product, the use of very small clearances (0.5-1% of the material thickness instead of 10-20% in conventional shearing) and the introduction of Vee-Rings in the pressure and/or blanking plates. The Vee-Ring is a physical V-shape feature that is located either in the pressure plate, the blanking plate or in both of them, which has the function to hold the punched material outside the blanking line and so prevents lateral flow of the material during the blanking process. In addition, it serves to apply compressive stress to the sheet metal, improving the flow process and delaying the fracture occurrence.

The main advantages of the process are the increased accuracy (smoother sheared surface and better geometrical tolerances) and the need of less production steps to produce high quality functional components that need to be manufactured by metal forming and final machining instead.

The disadvantages of the technology are the high tool wear of the active elements (punches, dies, plates), the high tool costs and the need of specific presses that are only used for fine blanking, as three actions (force application) are needed to run the process. A compound fine blanking die working principle during the blanking process is shown in Fig. 1.

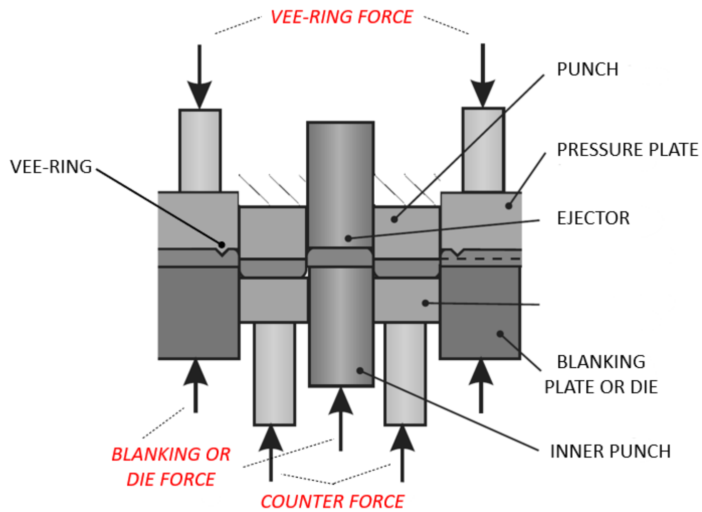

Fig. 1. Compound die set used in fine blanking (recreated from [2]).

Nevertheless, not all the aspects of the fine blanking technology are positive. The main materials that are fine blanked are steels (structural, case hardenable, heat treatable, etc.) which roughly represent the 80-90% of the produced parts all over the world. Other materials like aluminium, cooper and stainless steels are properly processed with the use of proper lubricants that avoid excessive adhesive wear. Anyhow, the elongation capacity of the materials needs to be high enough to guarantee the fine blanking capability of the cut material (complete smooth cutting surface) and this is reached by chemical composition adjustments, a proper thermos-mechanical processing and the soft annealing of the material prior to its processing. For example, in the case of the C45 steel, this annealing heat treatment changes the original microstructure that passes from a ferritic-perlitic typical microstructure to a microstructure that comprises a ferrite matrix with spheroidal cementite embedded in it. This spheroidized microstructure highly increases the fine blanking capability.

Currently, the ultimate tensile strength of fine blanked materials is around 550-600 MPa, both for steel and stainless steels. The current needs for structural lightweighting, especially in the transport industry, are forcing the fine blanking companies to push these material boundaries and to process higher steel grades. Although many attempts have been made by different companies to be able to cut high strength materials, the warm assisted fine blanking seems the most suitable technological approach for this, still causing big challenges to be implemented in serial production.

Warm Assisted Fine Blanking

It is well known that heating of metallic alloys improves their ductility in the absence of blue brittleness or other similar fragility mechanisms. For these reasons, four different research institutes and companies have performed initial fine blanking tests to develop the warm assisted fine blanking process.

Up to the authors best knowledge, researchers of the University of Shanghai were the first ones reporting experimental values in 2020. In their work, aiming to widen the application of the fine-blanking process, the heat-assisted fine-blanking process of AISI 304 stainless steel grade was performed. The cutting of a dog-bone shape component showed that the increase in temperature was beneficial for the final quality of the fine blanked component, being 250ºC the optimal temperature for a cutting quality improvement [3].

Later in 2020, Feintool company together with ETH Zurich published an online web publication about their recently developed Thermo-FineBlanking. Unlike the previous work, both the blank material and the tool inserts were heated and the aim of the result was to check if conventional steels could be fine blanked without a laborious and expensive heat treatment with a carbide spheroidization level of more than 90%. The cutting force was reduced in a 30% in comparison to the room temperature cutting and fine blanking capability was considerably improved with increased temperature for the 42CrMo4 and 1.4301 (AISI 304) materials [4]. In the same work, authors claimed that new lubricant developments were needed so that a proper tribological condition is obtained with temperatures above 200ºC, the limit for conventional fine blanking mineral-oil based lubricants.

Lastly, researchers of the laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University have published three works where they showed preliminary results of the newly developed warm assisted fine blanking process. In Shemet 2021, the authors presented final microhardness values obtained after fine blanking S700MC, 42CrMo4 and 16MnCr5 steels [5]. Later in Esaform 2021, same group presented the cutting forces at different temperatures for the X5CrNi18-10 (AISI 304) stainless steel. In the same paper, final product tolerances and cutting surface quality of different temperatures were also analysed [6]. Finally, in Esaform 2022, the same research group, presented the results obtained when fine blanking a star shape component and the 40MnB4 and 42CrMo4 steels. The process forces were evaluated depending on the sheet metal temperature and a good fine blanking capability of 40MnB4 was confirmed. Moreover, results showed that process forces and product quality were comparable to 42CrMo4 steel [7].

Following the findings of the previous researchers, Mondragon University, together with the Elay company, has recently performed warm forming fine blanking tests using an industrial Mori hydraulic fine blanking press. Different tests were performed by heating the raw material up to 300ºC and the results of precedent authors were confirmed by cutting a real component. As stated by Zheng et al. from Shanghai University, the critical point of the industrial application of the process is, among others, the loss of properties of conventional lubricants used in fine blanking and thus, the premature tool wear. For this reason, the main objective of the present paper is to develop a new tribotester that can emulate the fine blanking conditions, extreme contact pressures and surface expansions, at warm temperatures, so that the test results can be used for new lubricants screening and new lubricant formulation optimization.

Tribotesters for Extreme Contact Conditions

Several tribotesters have been developed during the last decades to emulate sheet metal forming and forging processes. Among others the ring test for forging and the strip drawing test for sheet metal forming are the most used tests to estimate the coefficient of friction and for the testing of new lubricants.

Groche et al. compared six different well established friction tests for cold forging operations using one state of the art industrial tribosystem, the contact between the 16MnCrS5 steel and tools made of M2 grade steel with a hardness of 61–63 HRC [8]. The tool surfaces were coated with an AlCrN based coating (Balinit Alcrona Pro) and polished to a roughness of Ra < 0.2 mm. In the same study, the different tribotests were numerically simulated and the basic tribological loads, the contact normal pressure, the surface enlargement, the relative sliding velocity and temperature at the interface were compared.

Due to the individual frictional test setups, it is clearly observed that not all the mentioned tribological loads can be set independently. Each of the tribotest has its own characteristic working window and the Sliding Compression Test seems to be the most flexible option to tune the test and get the desired range of contact conditions. All in all, the tribological conditions found in fine blanking and shearing in general are very aggressive [9-10]. Contact pressure can reach levels as high as 5 GPa and surface enlargements bigger than 50 are locally found in the sheared zone for a fine blanking of 8 mm thick S700MC steel. A summary of the numerical results obtained by the authors is shown in Table 1.

Table 1. Summary of the numerical results obtained in [8].

Tribological tests	Contact pressure	Surface expansion	Relative sliding velocity	Temperature
Ring Compression	Low	Low	Low	Low
Combined Forward Rod Backward Can Estrusion	Medium	Low	Medium	Medium
Backward Can Extrusion	Medium-High	High	High	High
Backward Can Extrusion with rotation	High	High	Medium	Medium
Upsetting sliding	Medium	Low	Set value	Low
Sliding compression	Medium	Medium	Set value	Medium

For these limitations, also found in cold forging, and to evaluate different lubricants and surface finishings, Hirose et al. developed an Upsetting-Ironing type tribometer for evaluating the tribological performance of lubrication coatings for cold forging [11]. Numerical simulations of the test prove that the test is able to reach a surface enlargement up to 500 and a contact pressure of around 2GPa for a SWRM 10K steel (tensile strength of 480 MPa). During the test a cylindrical billet is first upset for being later deformed by ironing using three ball bearing made of high chromium steel (SUJ2) of diameter 12 mm. Following this idea, a new tribotester is presented in this work for testing thick sheets and to emulate warm fine blanking conditions.

Design of a New Tribostester

The new tribotester that is proposed for fine blanking is shown in Fig. 2. As in the concept presented by Hirose et al. the test is divided in two steps [11]. First, the initial flat blank is bent to obtain an U-shape. Then punch stroke continues and the ironing phase starts. The U-shaped blank, which has been bent with a clearance of 0.5 mm between the punch and the die (per side) is deformed against bearing balls made by SUJ2 steel of diameter 12 mm. At this moment, a build-up of contact pressure and surface enlargement occurs in the desired contact zone. The ball bearings can be exchanged at every new test due to their low cost and the galling can be studied on them, as well as in the tested sample, following the procedure defined by Hirose et al. Chromium tends to adhere in the tested sample and this is used to determine when the galling starts using an SEM microscope.

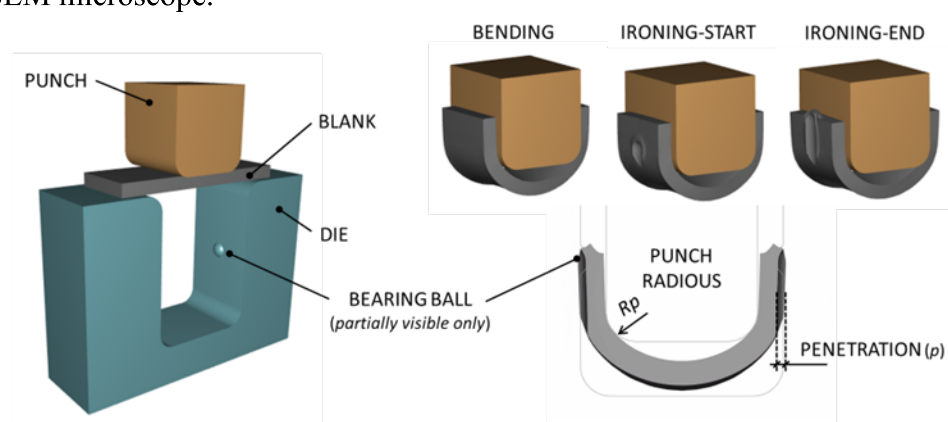

Fig. 2. New tribotester for thick sheet material and extreme tribological conditions.

The parameters that can be changed during the test are the blank temperature, which can be previously heated in a furnace, the ball penetration (see Fig. 2) and the press speed.

Numerical Modelling of the Test

The new testing concept and set-up has been numerically studied to evaluate the contact conditions reached with different testing conditions, varying the penetration (p) and punch radius (R_p). FORGE NxT 3.2 software has been used for running the numerical simulations and the tools have been considered rigid. The blank material is a S700MC steel which has been modelled using solid tetrahedral elements and a simplified Hensel-Spittel hardening law considered as isotropic (r values close to 1 in different directions). Only one half of the blank has been modelled in the study (see symmetry plane in Fig. 3). Young modulus of 210 GPa and a Poisson coefficient of 0.3 were employed. The material temperature has been fixed to room temperature and no temperature influence has been studied in this work. The different simulation conditions are shown in Table 2 and the numerical model is further detailed in Fig. 3.

Table 2. Different simulation conditions.

Material model – Hensel Spittel (MPa)	$\sigma = 1127 \cdot e^{-0.0009 \cdot T} \cdot (\varepsilon - 0.01354)^{0.0833}$
Friction coefficient (Tresca shear model)	0.05, 0.1, 0.2, 0.3
Penetration (p) - mm	2, 3, 4
Punch radious (R_p) - mm	10, 17.5, 25

The main objectives of varying the selected parameters are:

1. To evaluate the sensitivity of the test to different friction coefficients using different test conditions – a higher force increment when changing the friction coefficient is desirable to perform a screening of different lubricants that are suitable for warm fine blanking
2. To evaluate how the penetration changes the contact pressure and surface enlargement
3. To optimize the punch radius value to avoid excessive curving of the tested sample before the ironing phase

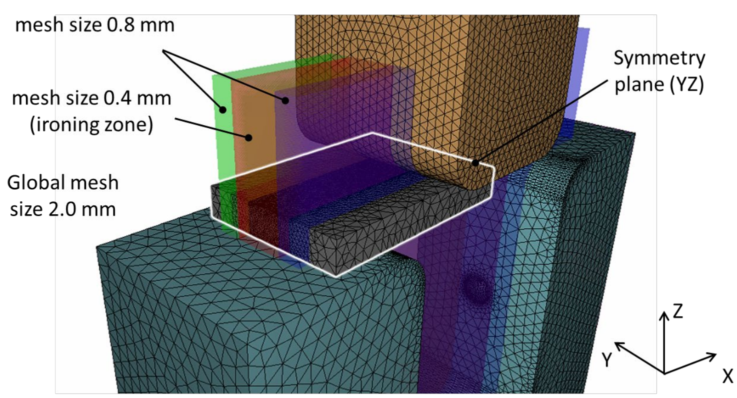

Fig. 3. Numerical model of the bending-ironing tribological test (R10 and p2).

With the purpose of selecting the best tool dimensions of the new tribotester the force evolution curves, surface enlargement variation and the maximum normal contact pressures for each of the simulated case have been evaluated.

A typical force-displacement curve of the punch is shown in Fig. 4a. The curve shows a double dome shape with two force peaks corresponding to the initial bending force and the ironing force respectively. If we solely consider the ironing force, ΔF is defined as the force difference between the peak forces taking as a reference the m0.05 friction case. A higher force change means a higher sensitivity to detect different friction coefficients and thus to do a proper evaluation of the new lubricants for fine blanking. Fig. 4b clearly shows that sensitivity of the test increases when the punch radius decreases and the penetration increases. Thus, the best testing parameters in terms of friction sensitivity are R_p=10 mm in combination with p=4 mm.

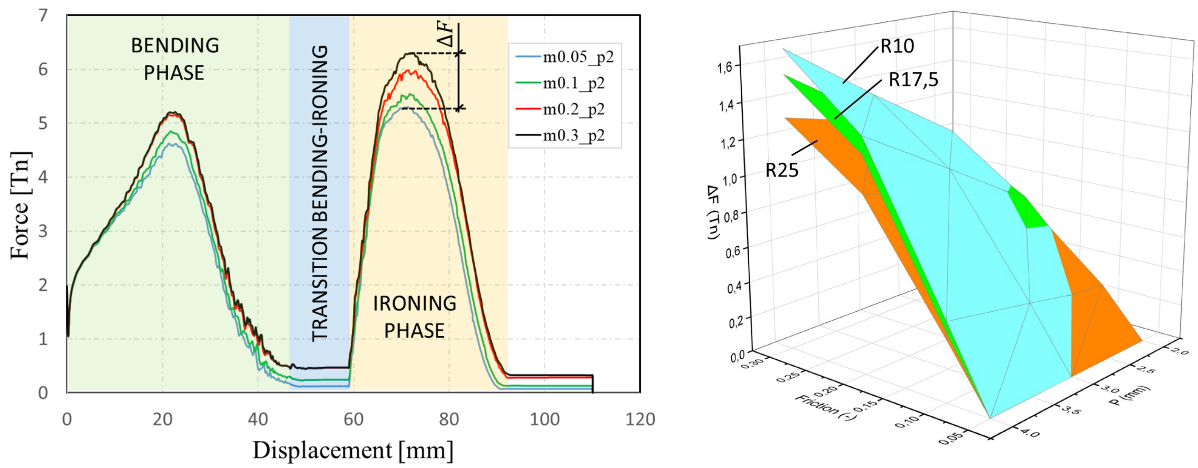

Fig. 4. a) Typical punch Force-Displacement curve for penetration 2 mm and different friction values and b) comparison of ΔF for different configurations.

An example of the numerical results obtained for the field variables maximum surface enlargement and maximum normal contact pressure is shown in Fig. 5a and Fig. 5b respectively. Here, the surface enlargement (named as DSURF) is defined as follows:

$$DSURF = \frac{Surf - Surf_0}{Surf_0} = \frac{Surf}{Surf_0} - 1 \tag{1}$$

where *Surf* is the new expanded surface and $Surf_0$ is the initial surface. Consequently, a DSURF value of 3 means that the new surface is four times greater than the original one.

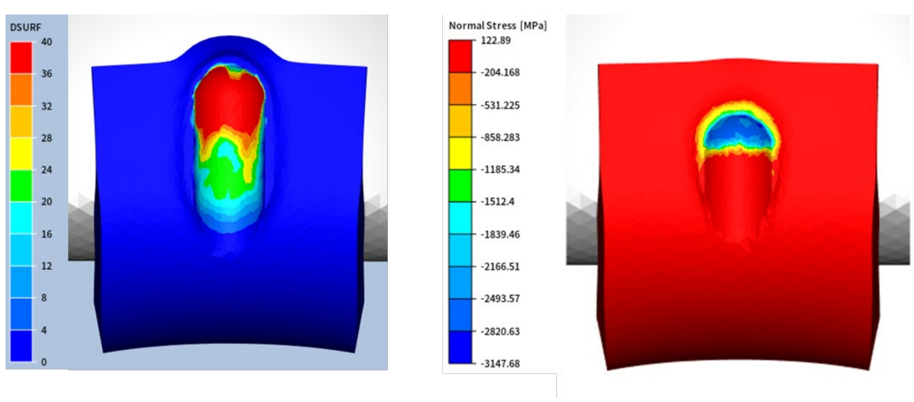

Fig. 5. Example of numerical results for a) Surface enlargement and b) Normal contact pressure.

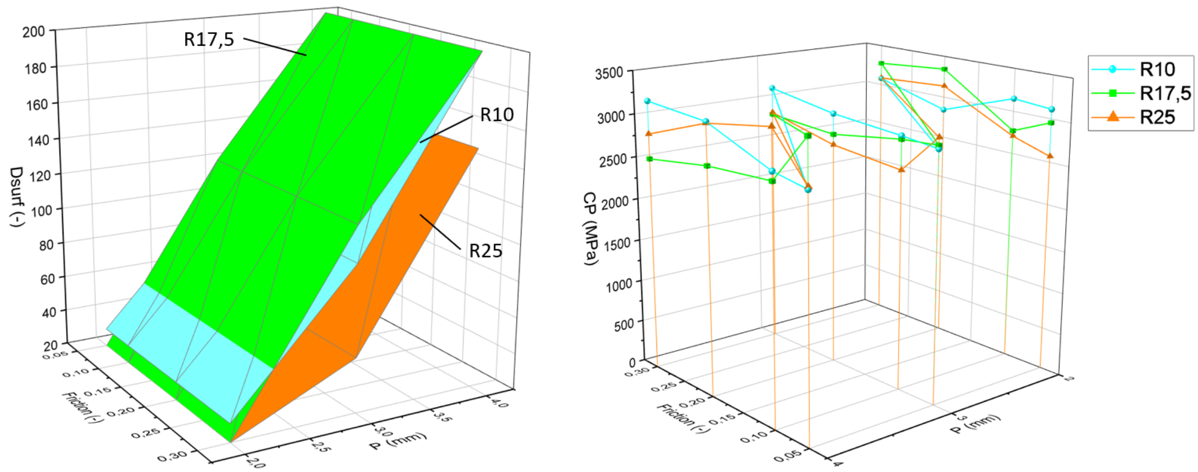

Fig. 6. Influence of parameters on a) Surface enlargement and b) Normal contact pressure.

As it can be observed in Fig. 6a, the maximum surface expansion is mainly dominated by the penetration. Higher penetration results in a higher surface enlargement as already shown by Hirosi et al. where higher amount of upsetting and subsequent ironing achieved higher surface enlargement values. On the contrary, the maximum contact pressure is around 3GPa for all the cases (Fig. 6b). This is probably because the hardening of the material tends to saturate at high strain levels. Nevertheless, both the surface enlargement values and contact pressures are representative of extreme contact conditions and suitable to emulate the fine blanking situation.

Summary

A new tribotester to test lubricants for warm fine blanking has been conceptually defined and numerically validated. The new testing device is simple, can achieve high contact pressures and surface enlargements and uses ball bearings that are cheap and easily exchangeable to analyse wear mechanisms.

The numerical parametric study of the most relevant design dimensions, the ironing penetration (*p*) and punch radius (R_p), has clearly shown the effect of them on the maximum surface enlargement and contact pressure. The surface enlargement increases with the penetration while the surface enlargement follows a different trend. Similar surface expansion values are obtained for R17.5 and R10 while lower values are observed with R25. This can be probably explained by the fact that using this high punch radius and same sample length, the total extruded length is notably decreased in comparison to the other two cases.

The friction force different between the studied conditions shows that sensitivity to contact condition changes is higher when penetration increases.

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References

[1] R.A. Schmidt, Cold forming and fineblanking, Feintool, Buderus, Wälzholz, Hoesch Hohenlimburg, Germany, 2007.

[2] T. Altan, Metal Forming Handbook /Schuler, Springer-Verlag Berlin Heidelberg, 1998.

[3] Q. Zheng, X. Zhuang, J. Hu, Z. Zhao, Formability of the heat-assisted fine-blanking process for 304 stainless steel plates, Mater. Charact. 166 (2020) 110452. http://doi.org/10.1016/j.matchar.2020.110452

[4] C. Maurer, Development project: Thermo-fineblanking, Feintool, IEPA, 2018. https://blog.feintool.com/en/thermo-fineblanking

[5] I.F. Weiser, A. Feuerhack, T. Bergs, Investigation of the Micro Hardness at the Cut Surface of Fine Blanked Parts with Variation of Sheet Material and Cutting Temperature, Key Eng. Mater. 883 (2021) 269-276.

[6] I.F. Weiser, R. Mannens, A. Feuerhack, T. Bergs, Experimental Investigation of Process Forces and Part Quality for Fine Blanking of Stainless Steel with Inductive Heating, ESAFORM 2021. https://popups.uliege.be/esaform21/index.php?id=2575

[7] I.F. Weiser, T. Herrig, T. Bergs, Fine Blanking Limits of Manganese-Boron-Steel in Fine Blanking Compared to Tempered Steel with Variation of Sheet Metal Temperature, Key Eng. Mater. 926 (2022) 1122-1130. https://doi.org/10.4028/p-7cwhpb

[8] P. Groche, P. Kramer, N. Bay, P. Christiansen, L. Dubar, K. Hayakawa, c. Hu, K. Kitamura, P. Moreau, Friction coefficients in cold forging: A global perspective, CIRP Annals 67 (2018) 261-264. https://doi.org/10.1016/j.cirp.2018.04.106

[9] Y. Abe, R. Yonekawa, K. Sedoguchi, K.I. Mori, Shearing of ultra-high strength steel sheets with step punch, Procedia Manuf. 15 (2018) 597-604. https://doi.org/10.1016/j.promfg.2018.07.283

[10] K.I. Mori, Review of shearing processes of high strength steel sheets, J. Manuf. Mater. Process. 4 (2020) 54. https://doi.org/10.3390/jmmp4020054

[11] M. Hirose, Z.G. Wang, S. Komiyama, An upsetting-ironing type tribo-meter for evaluating tribological performance of lubrication coatings for cold forging, Key Eng. Mater. 535 (2013) 243-246. http://doi.org/10.4028/www.scientific.net/KEM.535-536.243