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MODERN METHODS FOR FABRICATION OF ULTRAFINE-GRAINED METAL SHEETS

Stefan K. Stefanov
Department of Material Science and Technology
University of Ruse „Angel Kanchev"
e-mail: ststefanov@uni-ruse.bg

Abstract: *For the past 35 years, the topic of ultrafine-grained materials and their production has been compelling researchers to explore further. A short summary of some of the most feasible methods of ultrafine-grained sheet metal production has been carried out.*

Keywords: *ultrafine-grained materials; severe plastic deformation; asymmetric rolling; cryorolling; accumulated roll-bonding; repeated corrugation and straightening.*

INTRODUCTION:

In material science, ultrafine-grained (UFG) materials, defined as polycrystalline materials with grain size between 100 and 1000 nm [1], have attracted increased interest towards them because of their potential application in a multitude of industries and their importance to society. Thanks to the increased homogeneity of their microstructure, they possess improved physical-mechanical properties, compared to conventional materials, examples of which are higher tensile strength, fatigue wear resistance and hardness [2] [3] strength to strain ratio [4], as well as the ability to enter a state of superplasticity under specific circumstances [5].

Despite over 35 years of research in the field and the proven benefit of the UFG structure, its fabrication outside of laboratory conditions still presents a significant technological obstacle to the introduction of such materials in modern industry, hence the insufficient familiarity with such materials among the general public and industry professionals.

It is possible to produce materials possessing UFG structure via chemical synthesis methods (bottom-up method), but from an engineering standpoint, the more interesting approach is the method of fabrication via undergoing of severe plastic deformation (SPD) (top-down method), which generates shearing stresses under the large forces the material is being subjected to, leading to grain refinement on a microstructural level. In order to achieve the desired effect, it is necessary for the plastic deformation to reach 600% - 800%, which is possible by subjecting the materials multiple times to SPD [6].

Depending on the type of UFG samples produced, SPD methods are conditionally divided into three groups:

- discrete.
- semi-continuous.
- continuous – used for fabrication of sheet metals, plates and profiles.

This article aims to familiarize the reader with the continuous methods for UFG sample production and those concerning sheet metals in particular. Furthermore, those approaches selected are the ones with the highest potential for utilization at manufacturing scale. Most of the processes described are modifications of the existing one of rolling, granted its efficiency in sheet metal processing as well as the possibility to exert forces with high magnitude onto the material, generating the necessary shearing stress as a result, leading to the desired refinement of the material structure.

AREAS OF APPLICATION OF UFG METAL MATERIALS

UFG materials and their deriving products are commercially viable because of their increased mechanical and physical properties and their efficient production [7] [8], thus their potential application is broad.

In the biomedical sphere, UFG materials are used for non-integrated medical devices, shown in Figure 1 and especially in medical implants [9], where the increased strength and hardness of the material allow production of more durable, stronger and/or lighter prostheses. Furthermore, the finer the microstructure of the material, the better detail of the produced part, which is beneficial to small implants.

Figure 1: Non-integrated medical devices, produced from UFG Titanium [9]

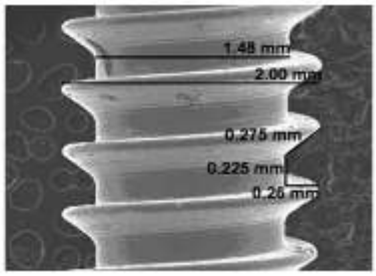

Figure 2: Dimensions of a miniscrew for orthodontic Anchorage, made of UFG material [9]

To further carry on to the advantage of the finer grain microstructure of UFG materials that they can be used in microforming applications is that they allow the possibility of production of parts which detail is smaller than that of the grain size of conventional materials. An example is given on Figure 3, where a microturbine is formed from an ultrafine-grained piece of aluminium [10].

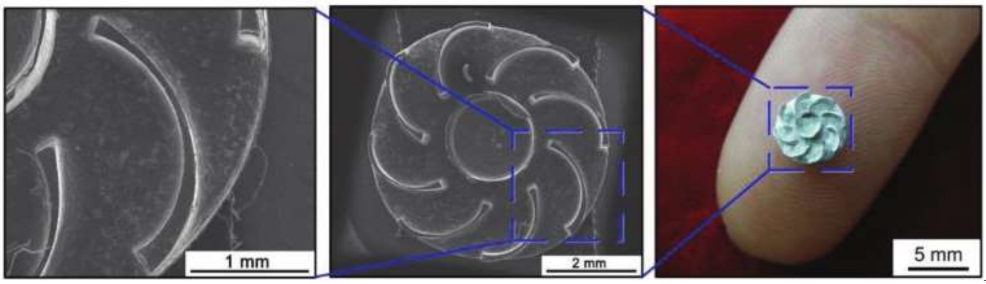

Figure 3: Microturbine of UFG Aluminium [10]

In addition to miniature components, UFG materials could be extensively used in manufacturing of construction materials, such as fasteners – the stronger material will improve the quality of the fasteners. Furthermore, the higher wear resistance would be beneficial to manufacturing of construction profiles and different types of chassis, which can further be subjected to weight optimization, as the material would allow it. Wear resistance of UFG materials would make them an ideal choice for consumer products where the improvement in lasting appearance will be appreciated and necessary.

All these possible applications are valid for sheet metals as well, as their multi-purpose utilization can benefit from the superior mechanical properties of UFG materials

METHODS FOR FABRICATION OF UFG SHEET METAL SAMPLES

Asymmetric Rolling (AR)

Asymmetric Rolling is a modification of conventional rolling process, also known as symmetric rolling and is one of the most popular means of producing materials with ultrafine-grained microstructure. The rolling asymmetry is expressed in one or in combination of three ways:

- feeding the sample between rolls with different diameters, shown in Figure 4.
- feeding the sample between rolls with different angular velocities, shown in Figure 5.
- feeding the sample between rolls with different friction coefficients

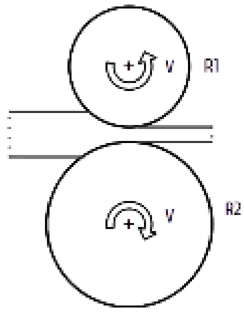

Figure 1: Asymmetric rolling via different diameters of the rolls

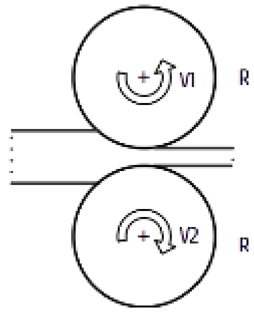

Figure 2: Asymmetric rolling via different angular velocities of the rolls

The difference in those three technological parameters is the premise for irregular deformation of the rolled sheets as the shearing stress is larger in those layers of the material that come in contact with the rolls possessing greater diameter, angular speed and/or coefficient of surface friction. It is experimentally proven that a combination of the three leads to better results than if only one of the techniques is used.

It is shown via experimental means that in asymmetric rolling of pure aluminium (Figure 6), if a reduction of 90% of the specimen's thickness is achieved, there is an increase of its tensile strength in approximately 2/3 times more than if the specimen was subjected to symmetric rolling instead (Figure 7). The reason for the increase is the forming of ultrafine-grained microstructure as a result of the refinement taking place because of the shearing stresses acting on the sheets [11].

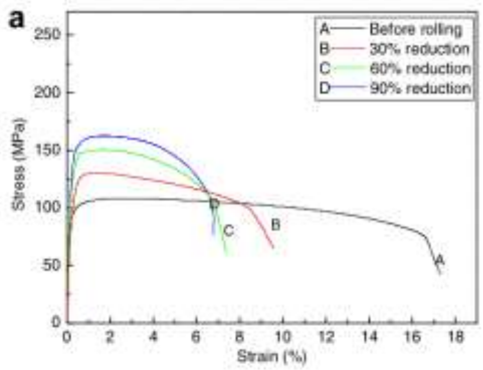

Figure 6: Stress-Strain diagram of an aluminium specimen undergoing symmetric rolling [11]

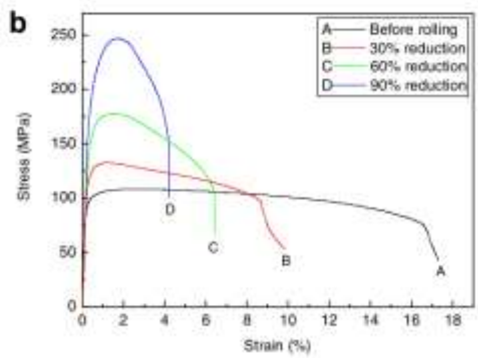

Figure 7: Stress-Strain diagram of an aluminium specimen undergoing asymmetric rolling [11]

A similar experiment was conducted using blanks made of magnesium alloy. The cross-section is reduced by 25% during both the symmetric and asymmetric methods of rolling. In the results shown in Figure 8, the tensile strength, yield strength and the deformation the material is capable of sustaining before failure are increased [12].

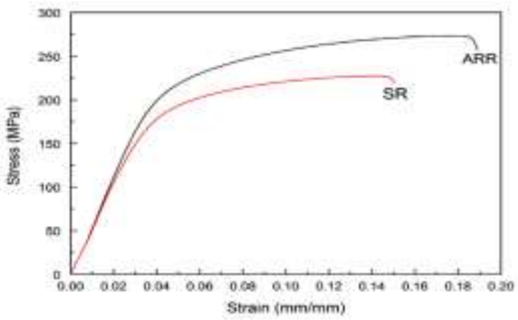

Figure 8: Stress-Strain diagram of blanks made of AZ31, undergoing symmetric (SR) and asymmetric (ARR) rolling [12]

From a technological point of view, AR is easy to implement because of the possibility to most easily alter the symmetric rolling process by changing the smallest number of parameters. Despite the conceptual and experimental proof of the increase in mechanical properties of the material, the process is considered to be unstable because of the phenomenon of roller slipping which is examined during AR [13].

Cryorolling (CR)

Another modification of the existing conventional method, shown on Figure 9, this type of rolling is taking place in conditions that permit reaching of cryogenic temperature [14]. The process consists of initial submerging of the material in a container full of cooling liquid, most often that being liquid nitrogen, and afterwards subjecting it to symmetric rolling. After the blank is rolled, it is submerged into the container again. As a result, the natural recovery processes in the material are suppressed, which leads to the refinement of its microstructure thus increasing its strength and plasticity.

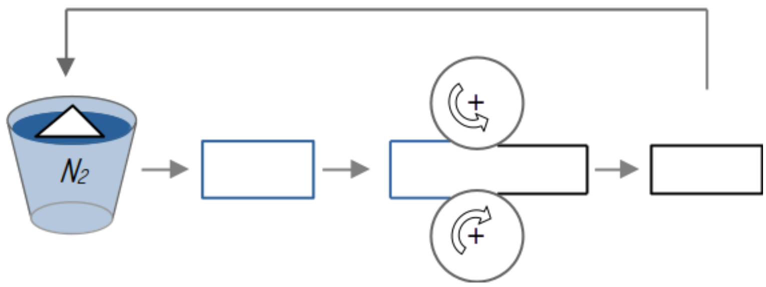

Figure 9: A simplified depiction of the cryorolling technological process

The physical and mechanical properties of cryorolled samples are subjected to testing, as shown in Figure 10. In it, the stress-strain diagram of samples rolled alongside the grain and across it both in room temperature and in cryogenic conditions is shown. The values lead to the conclusion that compared to materials subjected to conventional rolling, their cryorolled counterparts exhibit increased yield strength and ultimate tensile strength as improvement of up to 30% is possible [15].

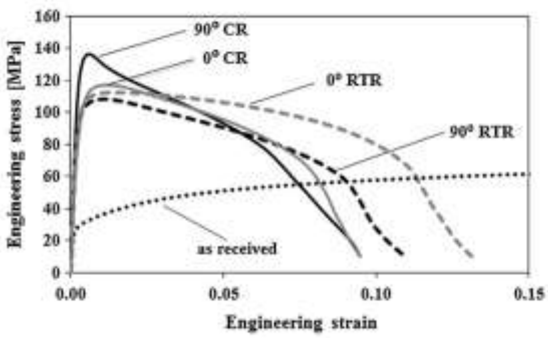

Figure 10: Stress-Strain diagram of blanks made of 99.6% aluminium, rolled alongside the grain and perpendicularly across the grain both in room temperature (RTR) and cryogenic temperature (CR) [15]

Being conceptually simple to adapt and in combination with the relatively high increase in mechanical properties of the sheet metals produced by it, make cryorolling a compelling method to be further researched. Considerations on if and how containers of liquid nitrogen can be implemented and stored in manufacturing sites remains a factor.

Accumulated Roll-Bonding (ARB) and Cross-Accumulated Roll Bonding (CARB)

One of the earliest methods for fabrication of UFG materials, the accumulated roll-bonding (ARB), shown on Figure 11, uses unmodified rolling mills. The metal sheets are prepared by its surfaces being subjected to abrasive wear and are afterwards stacked on top of each other before being fed into the rolls. The rolling process conjoins them together, halving their cross-section in half. The new sheet is then cut into two pieces ready to have the whole sequence of operations performed again as many times as it is deemed necessary.

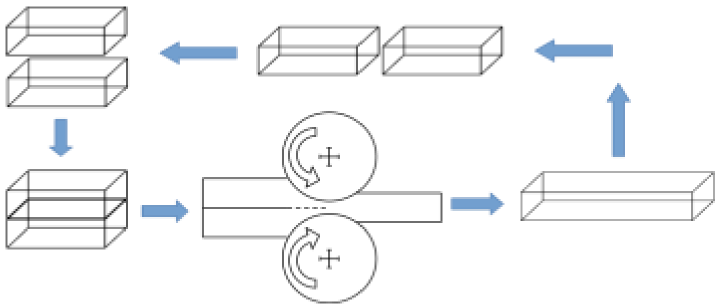

Figure 11: A simplified depiction of the accumulated roll-bonding technological process (ARB)

Despite the theoretical and practical possibility for endless iterations of the ARB process on a single sheet of paper, from a rational point of view, it is applicable with the most distinctive results in terms of change in its physical and mechanical properties only a few times because of diminishing returns. On Figure 12 are shown the results of an experiment conducted by R. Radev [16], where a piece of sheet metal alloy AA 1050 is subjected to 8 ARB passes and the values of the hardness of the alloy and its grain size have been recorded. The numbers show a tendency to reach a plateau-like trajectory starting from the 6-th pass onward. A similar experiment is carried out by measuring the tensile strength and the elongation of the material [17], as interpretation of the values leads to a similar conclusion.

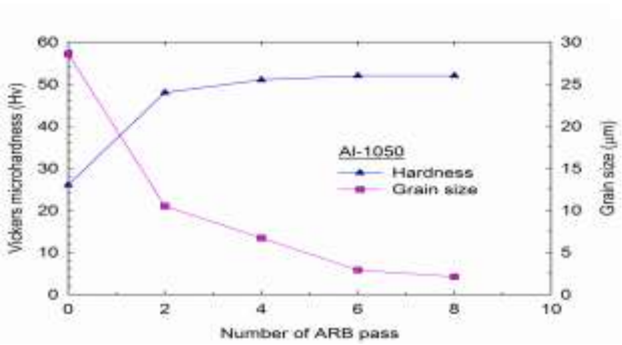

Figure 12: Dependency between the ARB passes, the hardness of the material and the grain size of aluminium alloy AA 1050 [16]

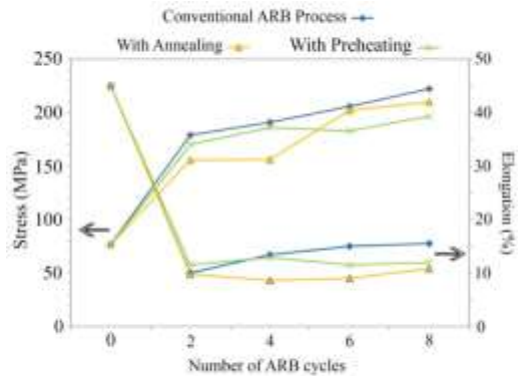

Figure 13: Dependency between the ARB passes, the tensile strength and the elongation of aluminium alloy AA 1050 [17]

ARB also creates a premise for the occurrence of plastic anisotropy in the material, which is due to the multiple rolling in the same direction, which further elongates the grains. This is visible on Figure 14, depicting pictures taken by microscope, showing the longitudinal cross-section of a steel strip that has undergone multiple ARB passes and the respective grain elongation after the operations [18].

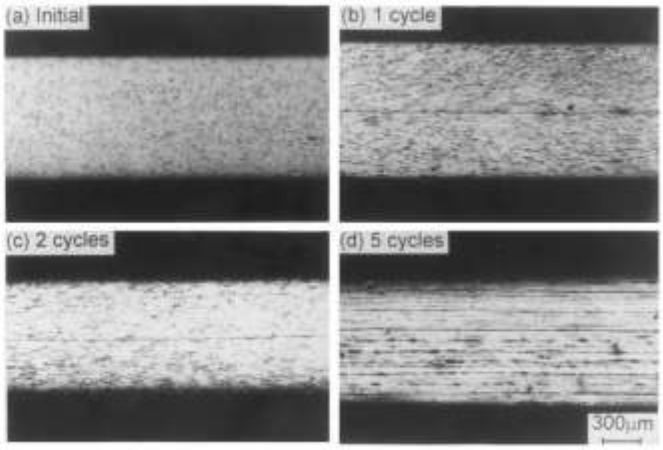

Figure 14: Longitudinal cross-section of a steel strip subjected to ARB and examined under microscope [18]

In order to reduce plastic anisotropy, a small change in this method is introduced. Displayed on Figure 15 is the principal scheme of the cross-accumulated roll bonding (CARB) process, which does not differ from ARB except from the added rotation of the sheets by 90 degrees before them being fed between the rolls. This way every next rolling operation will be carried out perpendicularly to the direction of the previous one [19].

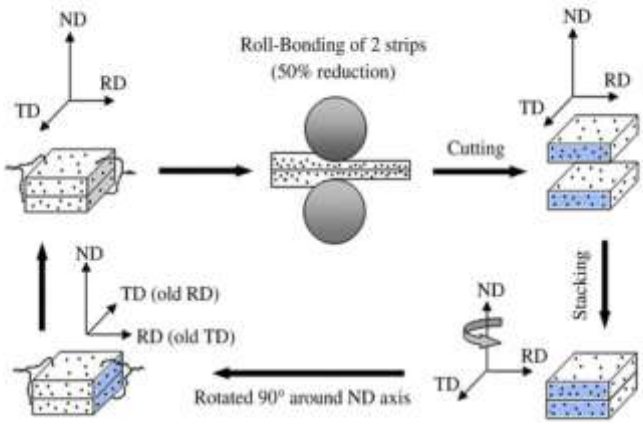

Figure 15: A simplified depiction of the cross-accumulated roll-bonding (CARB) [19]

It is experimentally proven that sheets subjected to CARB possess greater yield and tensile strength and hardness compared to those under ARB in both aluminium composites [20], and aluminium alloys [21].

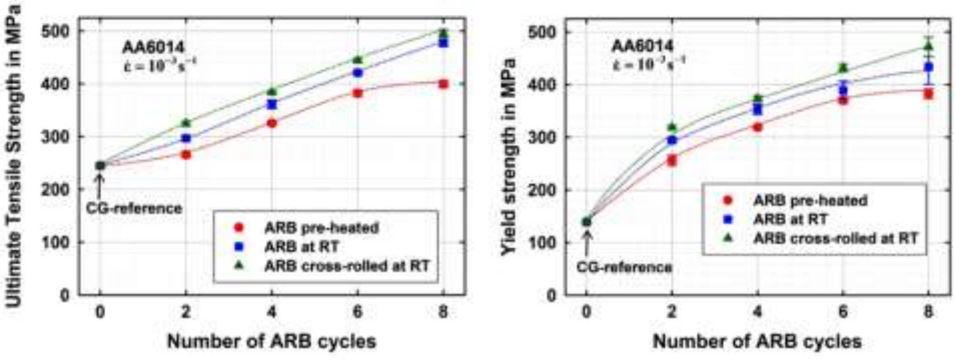

Figure 16: Dependency between the tensile strength of sheets of alloy AA 6014, subjected to ARB and CARB, and the number of passes [21]

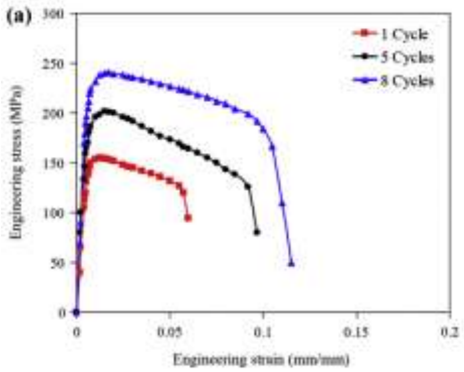

Figure 17: Dependency between the tensile strength of sheets of composite Al-Al_2O_3, subjected to ARB and its ductility [20]

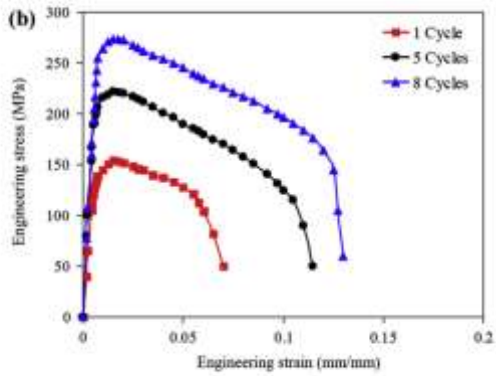

Figure 18: Dependency between the tensile strength of sheets of composite Al-Al_2O_3, subjected to CARB and its ductility [20]

Even though the sheets made by CARB have increased physical and mechanical properties, their production on manufacturing scale is more difficult from a technological point of view due to the method's requirement of sheet rotation. This condition can grow into a more serious problem with the increase in size of the blanks.

Repeated Corrugation and Straightening via Rolling (RCSR)

Shown on Figure 19, in this method, the sheet is fed between rolls with non-cylindrical shapes, thus deforming the sheet in a wavy pattern and creating shearing, compression and tensile stresses in different areas of it as a result. After passing through that set of rolls, the sheet is fed into another set of cylindrical rolls, which straighten its shape. Afterwards, the specimen is either flipped by 180° and the steps are repeated, or it is fed into rolls with a mirrored shape, aiming to subject the areas of the sheet previously under compression stress to tension and vice-versa [22].

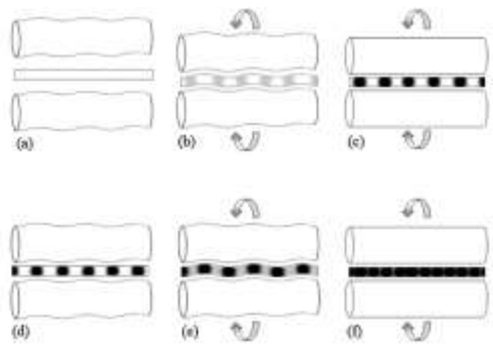

Figure 19: Principle of operation of the RCSR process [22]

Of all aforementioned severe plastic deformation techniques, this one is the most applicable for producing large metal sheets because of the simplicity of the rolling mills and the capability for implementation in large manufacturing sites [4], but a serious disadvantage is the less homogeneous structure of the material and its failure likelihood because of its subjection to both compression and tension at the same time.

CONCLUSION

In this article have been described a small number of methods for fabrication of ultrafine-grained structured materials, focusing on the most recent and the most established techniques for sheet metal production. Despite their implementation on a manufacturing scale not being possible at this point, because of the practical considerations that those methods require, progress has been made in terms of the conceptual ideas and the conducted experiments, which are promising enough to be further researched on the possibility to remove or mitigate their disadvantages.

REFERENCES

1: Ruslan Z. Valiev, Yuri Estrin, Zenji Horita, Terence G. Langdon, Michael J. Zehetbauer, Yuntian T. Zhu, Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation, 2006
2: Xie Ju et.al., Hardness homogeneity and micro-tensile behavior in a magnesium AZ31 alloy processed by equal-channel angular pressing, 2013
3: J. Wongsa-Ngam et. al., The development of hardness homogeneity in a Cu–Zr alloy processed by equal-channel angular pressing, 2012
4: Ghader Faraji, Hesam Torabzadeh, An Overview on the Continuous Severe Plastic Deformation Methods, 2019
5: R. B. Figueiredo, T. G. Langdon, Record Superplastic Ductility in a Magnesium Alloy Processed by Equal-Channel Angular Pressing, 2008
6: Rossen Radev, Valentin Gagov, Danail Gospodinov, Emil Yankov, Contemporary Methods For Fabricating Of Nanostructured And Ultrafine-grained Metals By Severe Plastic Deformation, 2010
7: Jie Xu, Bin Guo,Debin Shan, Innovative Applications of Ultrafine-Grained Materials, 2017
8: J. Xu et. al., Microhardness, microstructure and tensile behavior of an AZ31 magnesium alloy processed by high-pressure torsion, 2015
9: C. N. Elias et. al., Ultrafine grained titanium for biomedical applications: An overview of performance, 2013
10: J. Xu et. al., Micro-Forming Using Ultrafine-Grained Aluminum Processed by Equal-Channel Angular Pressing, 2015
11: J.Jiang et al., Mechanical properties and microstructures of ultrafine-grained pure aluminum by asymmetric rolling, 2009
12: R. Ma, L. Wang, Y.N. Wang, D.Z. Zhou, Microstructure and mechanical properties of the AZ31 magnesium alloy sheets processed by asymmetric reduction rolling, 2015
13: Y.H. Ji, J.J. Park, Development of severe plastic deformation by various asymmetric rolling processes, 2009
14: Ruby Pant, Shushant Singh, Amit Joshi , Mechanical performance and characteristics evaluation of material through Cryo rolling process: A review, 2022
15: J. Marnette, M. Weiss, P.D. Hodgson, Roll-formability of cryo-rolled ultrafine aluminium sheet, 2014
16: R. Radev, personal communication, 2024
17: H. Roghani et al., Effect of concurrent accumulative roll bonding (ARB) process and various heat treatment on the microstructure, texture and mechanical properties of AA1050 sheets, 2022
18: Y. Saito et al., Novel Ultra-high Straining Process for Bulk Materials - Development of the Accumulative Roll-Bonding (ARB) Process, 1999
19: M. Alizadeh, Processing of Al/B4C composites by cross-roll accumulative roll bonding, 2010
20: M. Alizadeh, E. Salahinejad, A comparative study on metal–matrix composites fabricated by conventional and cross accumulative roll-bonding processes, 2015
21: M.Ruppert et al., Influence of cross-rolling on the mechanical properties of an accumulative roll bonded aluminum alloy AA6014, 2014
22: A. Mirsepasi et.al., Microstructure and mechanical behavior of martensitic steel severely deformed by the novel technique of repetitive corrugation and straightening by rolling, 2012