REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
03-12-2018	Final Report	15-May-2017 - 1-Sep-2018

4. TITLE AND SUBTITLE
Final Report: Acquisition of a Multi-Physics Materials Processing Equipment to Investigate Magnetic Field Effects

5a. CONTRACT NUMBER
W911NF-17-1-0269

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
70079-MS-RIP.2

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER
UU	UU	UU	UU		Rajiv Mishra / 940-565-2316

RPPR Final Report
as of 03-Dec-2018

Agency Code:

Proposal Number: 70079MSRIP **Agreement Number: W911NF-17-1-0269**

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DUNS Number: 614168995 EIN: 756002149
Report Date: 01-Dec-2018 Date Received: 03-Dec-2018
Final Report for Period Beginning 15-May-2017 and Ending 01-Sep-2018
Title: Acquisition of a Multi-Physics Materials Processing Equipment to Investigate Magnetic Field Effects
Begin Performance Period: 15-May-2017 **End Performance Period:** 01-Sep-2018
Report Term: 0-Other
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:**

Major Goals: The objective of this proposal is to acquire a unique equipment that integrates application of magnetic field with concurrent temperature dependent deformation. The equipment will allow study of magnetic field effects during solid state deformation and phase transformation up to magnetic field strength of 3 T (load capacity of 110 kip). This equipment will serve as a discovery tool to expand the microstructural pathways for enhanced performance in steels, aluminum alloys, titanium alloys and magnesium alloys.

Accomplishments: This document details the acquisition of a multi-physics processing system which include the effect of high pulsed magnetic field. The high magnetic field is integrated with a servo-hydraulic platform for flexibility of tensile, compression and cyclic loading. The mechanical frame has capacity of 110 kip while a maximum of 3 T magnetic field can be obtained. The effect of this high magnetic field on initial compression test properties and microstructure is reported. The applied external field changes the mechanical response of paramagnetic materials via the magneto plasticity effect (MPE). The equipment will allow study of quantum effects in mechanical response of materials. In long run, the equipment will facilitate research on processing of metallic materials to obtain unique microstructure because of superimposed effects of magnetic field, strain and temperature.

Training Opportunities: Hitesh Adhikari and Michael Frank were trained to operate the magnetic field processing equipment.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: The PI is interacting with Dr. Heather Murdoch, Research Scientist, Lightweight and Specialty Metals Branch, U.S. Army Research Lab. He has an active collaborative research with her.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Rajiv S. Mishra

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Hitesh Adhikari
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

WEBSITES:

URL: https://cfsp.unt.edu/mts-attached-gmw-magnetic
Date Received: 03-Dec-2018
Title: Magnetic Field Processing Equipment
Description: This is a setup to explore magnetic field effects on plasticity of metallic materials. It can be used to process materials with unique microstructure.

Final Project Report on

Acquisition of a multi-physics materials processing system to investigate magnetic field effects

Award # W911NF-17-1-0269

Prepared by

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Period of Performance

15 May 2017 – 01 September 2018

Executive summary

This document details the acquisition of a multi-physics processing system which include the effect of high pulsed magnetic field. The high magnetic field is integrated with a servo-hydraulic platform for flexibility of tensile, compression and cyclic loading. The mechanical frame has capacity of 110 kip while a maximum of 3 T magnetic field can be obtained. The effect of this high magnetic field on initial compression test properties and microstructure is reported. The applied external field changes the mechanical response of paramagnetic materials via the magneto plasticity effect (MPE). The equipment will allow study of quantum effects in mechanical response of materials. In long run, the equipment will facilitate research on processing of metallic materials to obtain unique microstructure because of superimposed effects of magnetic field, strain and temperature.

1. Introduction

1.1 Basics behind introduction of magnetic field

In the recent years, the advancement of technology about physical fields have focused more in materials applications. Such physical fields are ultrasonic microwave field, electromagnetic field and magnetic field. Due to such effects, the material properties change dramatically, improving both the reaction efficiency as well as the output capacity. Specifically, the strong pulsed electromagnetic field exhibited comprehensive advantages of super high energy and quantum scale effect, which provided a new path for microstructural engineering and property enhancement of materials [**1**].

Faraday's Law of Magnetic Induction states that when a material is exposed to a magnetic field, the magnetic forces of the material's electrons are affected. Although, the effect varies depending upon factors such as structure of material and net magnetic field atomic-scale interactions. In most of the atoms, there is zero net magnetic field because pair electrons cancel their magnetic fields since electrons in pair spin are in opposite direction in nature. Although, there are conditions that unpaired electrons will have net magnetic field which in term can be expected to react differently when exposed to an external magnetic field.

Most elements are classified as diamagnetic, paramagnetic and ferromagnetic. Although, here our preliminary investigation focuses solely on paramagnetic materials due to the hypothesis of the magneto plasticity effect (MPE) on mechanical response of paramagnetic alloys. In a paramagnetic material each individual atom possesses a permanent magnetic moment (M) but due to thermal agitation there is no average moment per atom, i.e. M=0. In the presence of an external magnetic field, a partial alignment of these atomic magnetic moments occurs in the direction of the applied magnetic field. This partial alignment results in a net positive magnetization and positive susceptibility. The effect of this net positive magnetization is expected to be responsible for the enhancement of mechanical properties. In contrast to exposure to a high magnetic field, when the applied field is zero, the net magnetization also becomes zero. Thus, theory of the sub-atomic scale interactions of electrons is expected to be highly sensitive to magnetic field ensuing enhancement of mechanical properties in paramagnetic metals and alloys.

In this report, paramagnetic metals and alloys (e.g. aluminum, magnesium, Ti-6Al-4V, tantalum) were selected as the experimental materials for preliminary scientific investigation. High magnetic field is induced in the specimens by systematic increases in magnetic induced intensity (B= 0-2 Tesla). The influence of magnetic field on both the mechanical properties and microstructure evolution were investigated. This current work serves as a preliminary effort to establish and quantify new relationships of paramagnetic alloys under the influence of increased magnetic field. In conclusion, based on the MPE, the high magnetic field was applied in the plastic deformation processing, which is compression test, to investigate the influence of a magnetic field on the plasticity of paramagnetic materials alloys.

1.2 Hypothesis

The magnetic field density (B) is an important parameter to invoke changes in plasticity of paramagnetic metals and alloys. The scientific concept is that deformation response is enhanced with the increase in B, owing to the phenomenon of "depinning" of dislocations from their motion inhibiting obstacles in paramagnetic alloys [**2**]. Thus, it can be said that the magnetic field has an important effect on the plasticity of paramagnetic alloys. The main objective of the present work is to unravel the effect of magnetic field on the microstructures and properties of paramagnetic alloys. Further, examination of the potential for improving both the strength and toughness of composites via this technique is proposed to be carried out. In terms of the effect of magnetic fields on material processing, it is well known that magnetic fields can significantly modify crystallization, grain growth, crystal morphology, composition homogenization, phase transition, and texture evolution. In addition, use of conventional processing such as (1) hot rolling, (2) cold rolling, (3) friction stir processing etc. [**3**] with aid of magnetic field has also been shown to have influence owing to its affect the diffusion of atoms [**4**].

1.3 Characterization Techniques

The subsequent variations in microstructural evolution (primarily the dislocation density and grain morphology), mechanical properties (strength and elongation) and the inherent relationships between these parameters will be examined and quantified. The magnetic field effects on both deformation induced mechanical and phase transformation behavior will be evaluated by MTS magnetic system and systematic microstructural characterization. The relationship between mechanical properties and microstructure will be analyzed. The resultant improved properties will be quantitatively correlated with the field-induced transition of the electron spin state and the phenomenon of dislocation pile up by studying changes in the local dislocation density. The microstructures of specimens exposed to magnetic field will be characterized before and after deformation. Phase fraction and distributions will be quantified using FEI Nova 230 scanning electron microscope (SEM) vie electron back scatter diffraction (EBSD). In addition, fractographic behavior of the materials morphologies will be examined by FEI Quanta 650 SEM to further investigate the effect on magnetic field on fracture in the specimens. X-ray diffraction (XRD) analysis will be carried out to for phase identification and relative quantification of bulk changes in phase volume. The dislocation density, morphology and distribution as it relates to changes in magnetic field exposure will be quantified using the EBSD technique using the SEM. Following simultaneous exposure to the magnetic field and deformation, magnetizing force remaining in the material will be determined using a physical property measurement system (PPMS) to assess the dependence of the magnetization intensity on the value of B.

1.4 Mechanical Testing Techniques

The mechanical testing will be carried out on the MTS 322 test frame custom equipped with the electric current controlled GMW magnetic field electronic system, this comprises of the multi-physics materials processing (MPMP) system that has been established. The MPMP system set up broadly is composed of (1) magnetic pulse generator control system, (2) solenoid coil, (3) high resolution magnetic field senor, (4) MTS 322 test frame (MTS, Eden Prairie, MN, USA), (5) high power servo-hydraulic driven MTS Silent Flow 661 actuator system and (6) custom tensile and compression components (REL Inc., Calumet, MI, USA). The MPMP system will enable systemic correlation of the deformation response of the materials as it depends on changes in the applied magnetic field.

Task 1: Synergistic exposure of magnetic field during deformation

During the testing of the experimental materials under magnetic field, synergistic control of the multicomponent system is exercised. The magnetic pulse is generated upon activation of the software-based interphase which governs both the switching function and magnitude of electric current to induce the desired magnetic field. The software and system are coupled by a magnetic sensor, positioned equidistant within the two poles, which enables magnetic field data acquisition and control of the magnetic field exposure. The specimen is positioned equidistant between the two poles prior to being deformed in either compression or tension under magnetic field, this is to be repeated for the selected experimental alloys under multiple levels of magnetic field. Upon activation of the magnetic pulse generator control system, a large pulse of electric current to the working coils resulting in the localized increase in magnetic field within the magnetic poles. Systematic variation of magnetic field between 0 and 2 T magnetic induction intensity (B) will be carried out in order to investigate the changes in both microstructural evolution and mechanical properties invoked by exposure to the magnetic field.

Task 2: Intermittent exposure of magnetic field during deformation: In-situ study correlating work hardening response and applied magnetic field

While running the tensile/compression test, the sample will be treated continuously between the magnetic poles within the localized influence of magnetic field. The effect of magnetic field on properties will be studied using a second strategized approach of magnetic field pulsing to intermittently expose the materials during deformation. In addition, the intermittent exposure study is to be designed to strategically apply and remove the magnetic field at various stages during deformation to understand changes in hardening response. This is expected to answer questions which clearly establish and quantify a relationship between work hardening response and magnetic field.

Task 3: Effect of holding time on strength of materials

The effect of holding time on tensile sample for certain time (e.g. 24 hours) and thereafter test under influence of magnetic field might give some idea on the strength of paramagnetic alloys.

1.5 Discussion

The physics behind this magnetic result mainly focus on the dislocation behavior in quantum scale. When paramagnetic alloys are subjected to magnetic field, the dislocation density is increased as the magnetic intensity is enhanced [**5**]. So, the concept of Lorentz force, magnetizing force and Zeeman Effect are not sufficient to explain this phenomenon but rather we need quantum scale understandings [**6**]. Based on quantum approach, the magnetic field can affect the electron spin states in radical pairs established between paramagnetic dislocation cores and obstacles. With magnetic field, the electron spin tends to transition from singlet state (high bonding energy) to triplet state (low bonding energy) which results dislocation depinning [**7**].

2. Funding from ARL for magnetic set up

The ARO-DURIP funding was directly used for the multi-physics materials processing (**MPMP**) system in the Center for Friction Stir Processing (CFSP) at UNT. This equipment will have a very broad research and educational impact in the application of magnetic field. Additionally, it will provide pathways to discover basic science linking processing to microstructural evolution and its subsequent impact on mechanical properties. The details of the system are given in the next section.

3. Details of the MTS magnetic system procured

Figure 1 shows the photograph of the MTS Magnetic set up with GMW electromagnet bought by UNT through ARO-DURIP funding. It is a series 322 load frames system developed and manufactured by MTS [**8**].

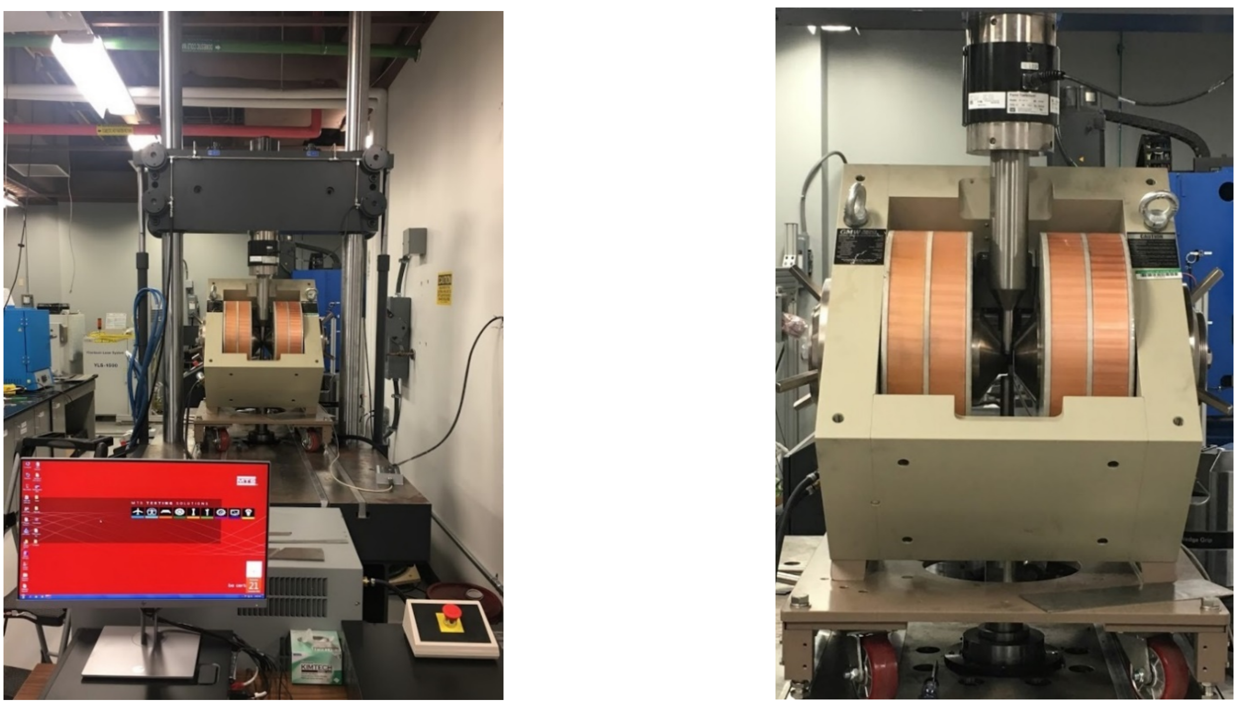

Figure 1. MTS Magnetic set up with GMW electromagnet at UNT through the funding provided by ARO-DURIP.

The specifications of this MTS system are as follows:

1. Load frame unit
2. Crosshead lifts and locks
3. Manifold (Actuators, Servo valves and Accumulators)
4. Transducers
5. Grip Controls

The basic specifications of MTS in terms of fatigue ratings, dimensions and weights are given in this table below.

MTS Model 322.41	
Load unit fatigue rating	500 KN (110 kip)
Maximum specimen/grip clearance	2057 mm (81.0 in)
Width between columns	762 mm (30.0 in)
Height -with standard columns	3677 mm (144.75 in)
Table height	984 mm (38.7 in)
Table width -side-to-side, without lifts	1067 mm (42.0 in)
Width -side-to-side, with lifts	1219 mm (48.0 in)
Depth -front-to-back	1500 mm (60.0 in)
Weight	3870 kg (8500 lb.)

The force transducer used with this system is a series 661 force transducer. The following are the specifications:

Model	**Load Capacity**	**Thread Size**	**Weight**
661.23-01	500 KN (5.5 kip)	M52 x 2.0 mm x 48.3 mm(2.0 - 12 UN-2B x 1.9 in)	16 kg (35.3 lb.)

Additionally, dipole electromagnet was introduced in the system. This electromagnet accepts 20 mm pole gap with face diameters up of 50 mm. This model GMW 3473-70 is fitted with a 70 Amp coil pair with enhanced cooling, and has a coil gap of 96 mm. **Figure 2** shows the electromagnet excitation plot at 50 mm pole face diameter. This system is recommended when high fields are required at large pole gaps or to achieve maximum field stability for spectroscopic or similar applications.

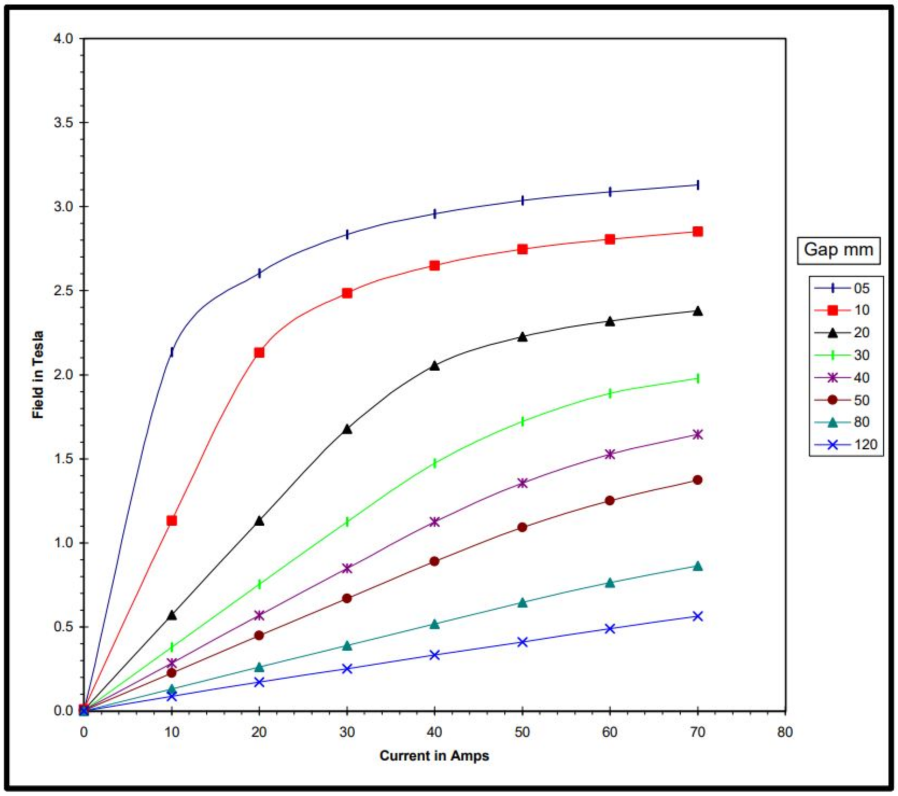

Figure 2. GMW electromagnet excitation plot at 50 mm pole face

Plus, custom tensile and compression components (REL Inc., Calumet, MI, USA) were successfully installed in MTS 322 test frame and MTS 661 actuator system [**9**]. Components are manufactured using high strength titanium (Ti-6Al-4V) designed to adapt to both the load cell and actuator to enable both tension and compression. Specimen type capabilities available with this system are as follows:

1. Compression (with/without magnetic field)
2. Tensile – rectangular geometry (with/without magnetic field)-still in development
3. Tensile – cylindrical geometry (with/without magnetic field)-still in development
4. Tensile Fatigue (with/without magnetic field)-still in development

4. Preliminary experimental setup and results

The preliminary compression test results on AA1100 (wrought), Ti-6Al-4V (wrought), pure tantalum and WE43 (wrought) are detailed in the present section. The response of the as-received condition for each of these materials was investigated in the preliminary study effort. Various magnetic fields (0T, 1T, and 2T) were applied continuously throughout the duration of the compression test. Quasi-static compression tests were performed using a servo-hydraulic material testing system (MTS) at standard strain rate of 0.001 s^{-1}. Cylindrical samples with diameter and length ratio of 1:1 were machined out from the as-received material and processed by electrical discharge machining (EDM). Super lube lubricant was used between the samples and the compression plates in order to reduce friction effects during the test. Load data was recorded during the test by a load cell with 500 KN capacity. Engineering stress and strain curves were calculated considering homogeneous deformation of the sample. **Figure 3** shows the magnetic sensor position shown by red arrow and sample position between electromagnets.

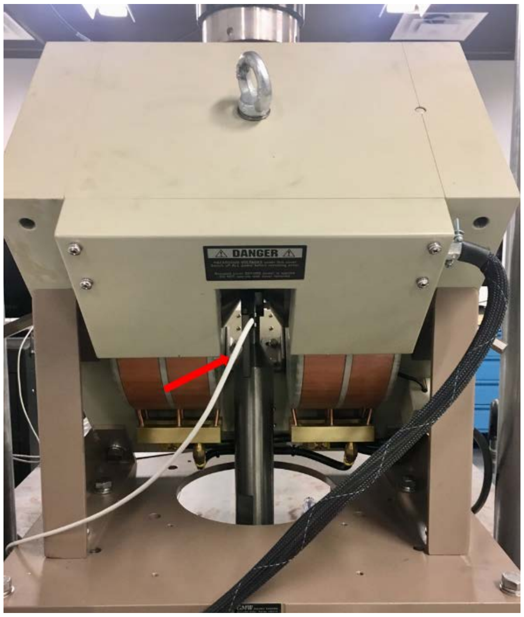

Figure 3. Images of sensor (red arrow) between the gaps of GMW electromagnet (left) and sample position (right).

The following observations were made in the presence of magnetic field: (i) as the magnetic field increases, yield strength were enhanced in all four sample materials AA1100, WE43, Ti-6Al-4V and pure tantalum, and (ii) the effect of the magnetic field on the compression test results the curves increase as the compressive strain increased. It demonstrates that the magnetic field has had a positive effect on the compression properties. In conclusion, all the strength of the magnetic field treated is improved in comparison to that of the untreated sample. In the whole procedure, the magnetic field is beneficial to the synchronous increase of mechanical properties of alloys. From the above results we can conclude that the setup will allow evaluation of magnetic field effects on metallic materials.

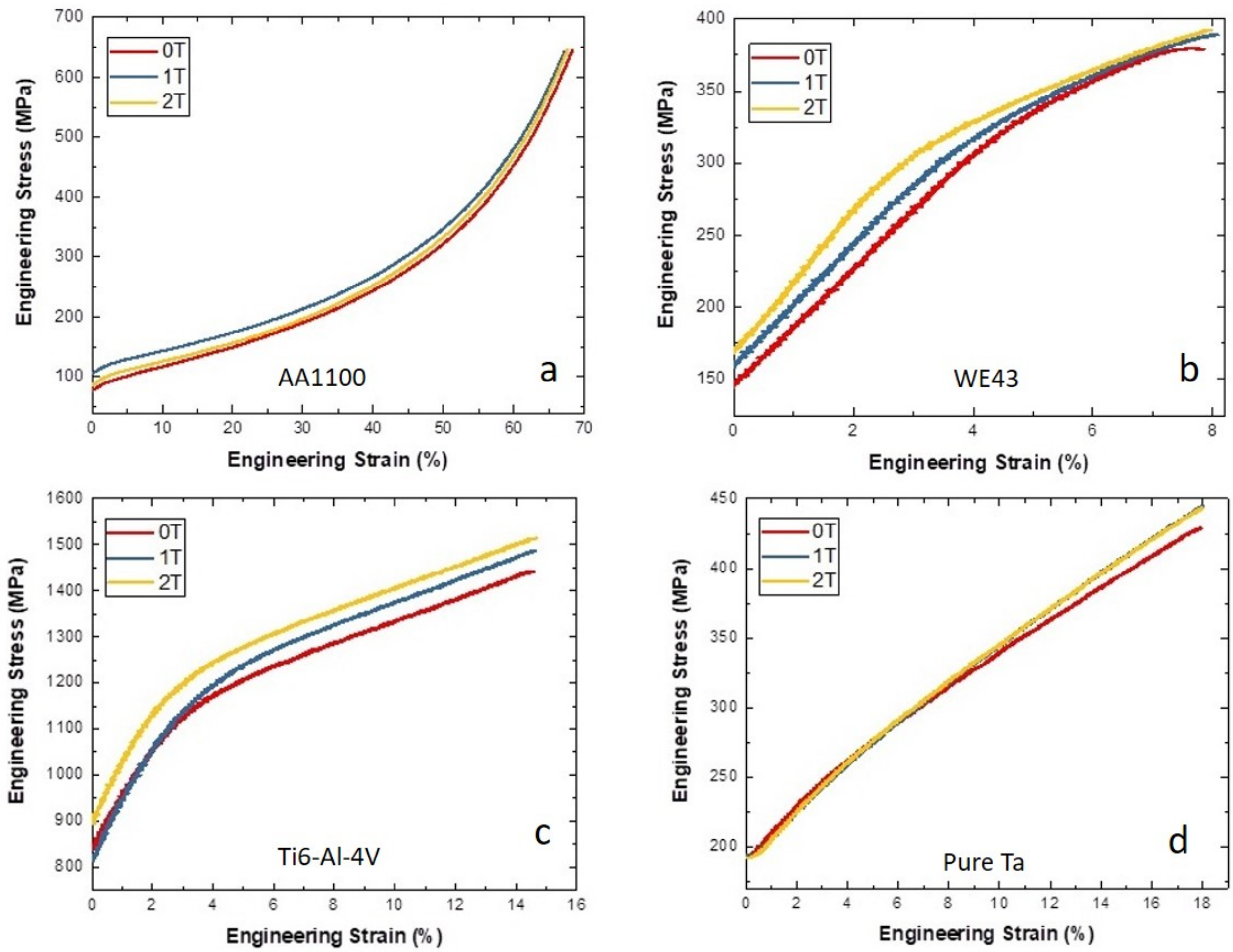

Figure 4. Engineering stress-strain curves for **(a)** AA1100, **(b)** WE43, **(c)** Ti-6Al-4V and **(d)** Pure Tantalum at various magnetic fields

5. Summary

In summary, when the magnetic induced intensity was modified as B = 0, 1 T and 2 T, this high magnetic field has an apparent effect on the compression test properties of paramagnetic materials in the presences of both magnetic field and external stress. The effective mechanism of the magnetic field does not lie in the Lorentz force, nor magnetization force nor Zeeman Effect, but the magneto plasticity effect (MPE). Based on quantum theory, a magnetic field can affect the electron spin states in radical pairs generated between the paramagnetic dislocation cores and obstacles. ***The DURIP funding has allowed UNT to establish a discovery tool to quantify the quantum effects during metal deformation and processing.***

6. References

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