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Dynamic Behaviour of Multi-phase Materials

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14. ABSTRACT
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FINAL REPORT

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Dynamic Behaviour of Multi-phase Materials

In response of

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RTB1-a: Aerospace Materials for Extreme Environments
RTA1-a: Dynamic Materials and Interactions.

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EXECUTIVE SUMMARY

This project investigated the micro-mechanisms of dynamic deformation in heterogeneous materials containing multiple (FCC, BCC) phases while subjected to extreme loading conditions. The research program was primarily conducted using our state-of-the-art testing facilities at UNSW Canberra: a convertible single/double stage gas gun able to achieve impact velocities of 4.5 km/s and a compression/tensile Hopkinson bar. Our diagnostic equipment to monitor the in-situ deformation included a 4-point Photon Doppler Velocimetry (PDV) and a variety of high speed cameras (e.g. Phantom). The deformed microstructures were analysed via SEM (EBSD), TEM and X-Ray analyses. These techniques collectively allowed us to provide a comprehensive understanding of how microstructural features affect the overall dynamic mechanical response of simple heterogenous materials.

Our results have been shared with AFRL scientists, they could be very valuable as input and validation of mesoscale simulations currently used by their models. These results can also serve as benchmark for some of their ongoing research endeavours in accurately predicting material behaviour under extreme conditions. Finally, a more measurable scientific outcome of this project is in the form of 2 journal articles and 4 conference proceedings have been published as part of this project. At least 3 more journal papers are being finalized in which AFRL personnel (e.g. Dr. Manny Gonzales) are co-authors. All published, and future, works include a proper acknowledgement to AOARD funding.

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Background

Applications in the defense and aerospace sectors are constantly pushing the current design envelope of traditional materials due to new capability and affordability requirements. These applications specifically require materials that can withstand the inherent extreme loading environments. These conditions demand that suitable materials must exhibit exceptional hardness, toughness, strength and resistance to heat and impact. This suite of properties limits the pool of suitable materials to high strength, multi-phase materials that can satisfy the entire spectrum of requirements in the demanding operating conditions found in defense, including US Air Force, applications. Thus, it was the primary objective of this project to elucidate the effects of microstructural features on the fundamental deformation mechanisms of heterogeneous materials subjected to extreme loading conditions of strain rate and pressure.

Although the dynamic mechanical behaviour of materials, in particular shock loading, has a long history with works carried out primarily by US and UK labs (e.g. LANL, LLNL, AFRL, AWE), most of these works have dealt with single phase metals. Moreover, most of these studies have always been carried out from the "materials science" perspective or the "shock physics" perspective. It is not until recently that researchers, including the PI (Escobedo), are trying to establish fundamental and comprehensive connections between microstructure and loading conditions. This information is critical for models that attempt to predict the dynamic behavior of materials at extreme conditions of particular interest to Defense organizations. From the scientific perspective, this project is aligned with AFRL labs' ongoing work on martensitic steels and with large scientific endeavours of other US government labs such as MARIE (Matter-Radiation Interactions in Extremes).

Aim and objectives

Aim: Develop an in-depth understanding of the fundamental deformation and failure mechanisms at the microscopic level of multi-phase materials subjected to extreme loading conditions.

To achieve our stated aim, the project had two key objectives:

(1) Building on the PI and co-PIs fundamental and successful experimental expertise in materials behaviour, elucidate the complex mechanical response of a heterogeneous alloy under extreme loading conditions via a novel experimental program involving pre-, *in situ* and *post-mortem* analysis methods via dynamic testing, laser interferometry diagnostics, and microstructural characterization.

(2) Develop a strong collaboration with AFRL scientists during the duration of this project. Take this project as a stepping stone into more challenging and complex scientific problems, possibly submitting joint proposals, e.g. AFOSR funding as well as Australian based (ARC- Australian Research Council).

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Materials and Methods

Materials

A 20 mm thick LDX 2101 (UNS S32101, EN 1.4162) hot-rolled plate and a 6 mm thick LDX 2404 (UNS S82441, EN 1.4662) hot-rolled coil-plate were used in this work. The manufacturing process by the supplier involved melting the raw materials using an electric arc furnace then using Argon Oxygen Decarburization (AOD) process to reduce the carbon content to the targeted amount (less than 0.04% for LDX 2101 and less than 0.03% for LDX 2404 [1]) before slab-casting. The slab was then hot rolled to the final thickness. Finally, the plate was heat-treated at ~1050°C followed by water quenching. The bulk chemical compositions of the materials are listed in Table 1.

Table 1: Chemical composition (wt. %) of the investigated materials.

Element	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	N	Fe
LDX 2101	0.030	4.080	0.590	0.010	0.030	1.550	21.500	0.340	0.240	0.230	Bal.
LDX 2404	0.020	2.930	0.420	0.001	0.025	3.660	24.120	1.610	0.340	0.273	Bal.

Electron Backscatter Diffraction (EBSD) measurements of as-received materials (Fig. 2) show equal area fractions of the FCC austenite (γ) and the BCC ferrite (α) phases in both cases. Both materials have a pancake structure, the austenite islands appear thinner in the TD and RD planes.

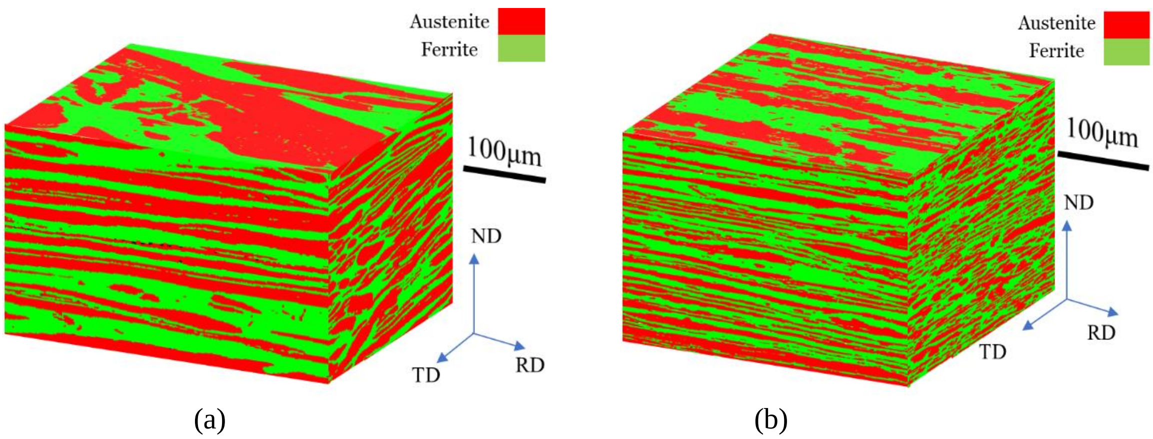

Fig. 2 EBSD phase maps of the reference planes in as-received condition (a) LDX 2101, and (b) LDX 2404

These two materials allowed us to systematically investigate the effect of crystal structure, FCC vs BCC, as well as grain size effects on dynamic damage mechanisms. We published our initial characterization work in Ref. [1].

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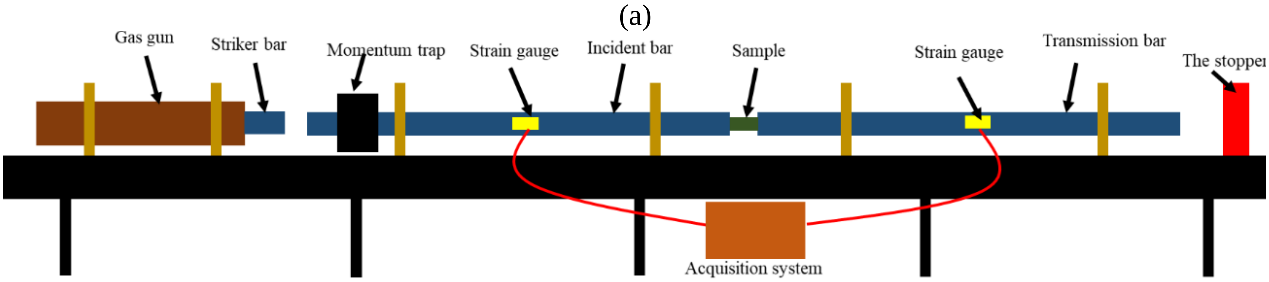
Experimental Methods

Dynamic experiments in a Split Hopkinson Pressure Bar (SHBP)

Uniaxial stress testing at high strain rates (> 500 s^{-1}) under compressive and tensile conditions was performed using a Split Hopkinson Pressure Bar (SHPB). n the conventional SHPB testing (Fig.3.), sample sandwiched between the incident and transmission bars is subjected to a rectangular compression pulse resulting from the striker bar impacting the incident bar. Due to the difference in areal acoustic impedance ($\rho c_l A$), where A is the cross-sectional area, between the sample and bars, a tensile pulse is reflected back at the incident bar/sample interface and a compression pulse passes through the sample into the transmission bar.

(a)



(b)

Fig.3. (a) Photo of our SHPB equipment (b) schematic of a classical SHPB apparatus.

In this study, a SHPB apparatus with 19.05 mm diameter Maraging steel C350 bars was used, the length of the incident and transmission bars were 1900 mm and 1827 mm, respectively. Sample dimensions were selected to reduce the effects of inertia and friction, it has been recommended to use samples that have length to diameter ratio (L/D) of $0.5 \leq L/D \leq 1.0$. For both tested materials, L/D was selected to be 0.6.

Aa part of this project, we developed a cost-effective (both in resources and time) framework based on Finite Element (FE) simulations to systematically design dynamic experiments. This procedure may be used for any material that has suitable properties as a pulse shaper for testing materials with high strain-hardening rate. We published our work in Ref. [2-3].

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Shock (spall) via plate-impact experiments.

Uniaxial strain testing was performed via plate-impact experiments using our 70 mm diameter bore single-stage light gas gun. A 60 mm disk named flyer plate is attached to a sabot loaded inside the gun's reservoir that is filled with either nitrogen or helium gas before the test. When a solenoid valve inside the reservoir is triggered, compressed gas is released between the sabot and a gun piston accelerating the flyer plate assembly inside the gun bore. Upon exiting the muzzle, the flyer plate speed is measured using a laser velocimetry system prior to impacting target assembly that is connected to the muzzle using plastic bolts. The impact occurs with less than three mrad misalignment because the target assembly is aligned with the gun bore center using a laser alignment system before performing the test.

After the impact, the target assembly is separated from the muzzle and deaccelerated inside a soft recovery chamber. Free surface velocity is measured from the back surface of the target using Photon Doppler Velocimetry (PDV) with 2.0 W laser power. The PDV signal is recorded using a digital phosphor oscilloscopes Tektronix®-DPO7354C with 3.5 GHz bandwidth and 40 GS/s sample rate. A MATLAB® code was used to process the signal. All details are shown in Fig. 4.

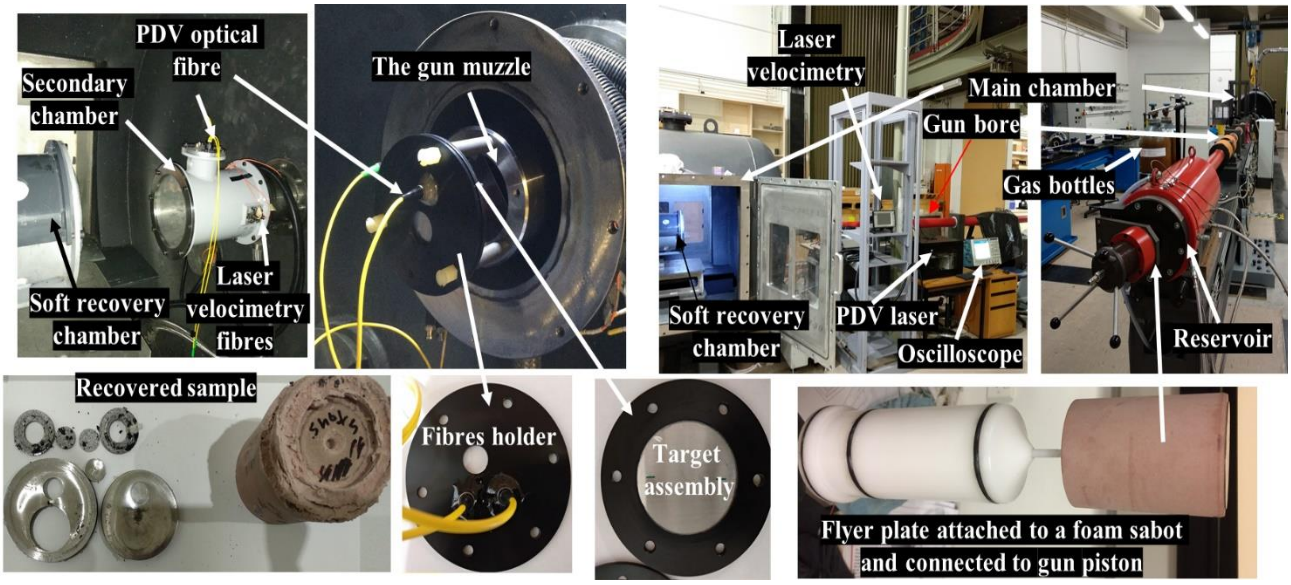

Fig.4 Single-stage light gas gun and the related parts for plate-impact experiments.

The microstructure of the deformed specimens, both using SHPB and plate impact experiments, were carefully and thoroughly examined using EBSD, TEM and XRD. The combination of these techniques allowed us to determine the dominant damage mechanisms in these complex materials. Furthermore, as part of this project, we improved these tests. Our work on this area has been published in Refs [4-6].

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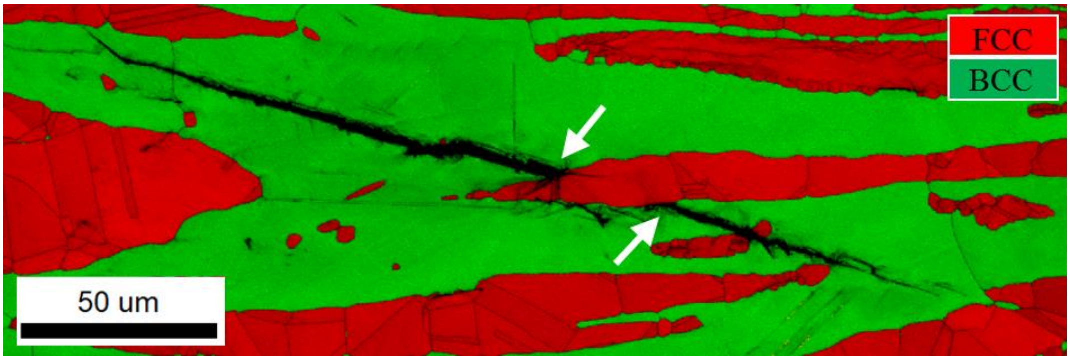
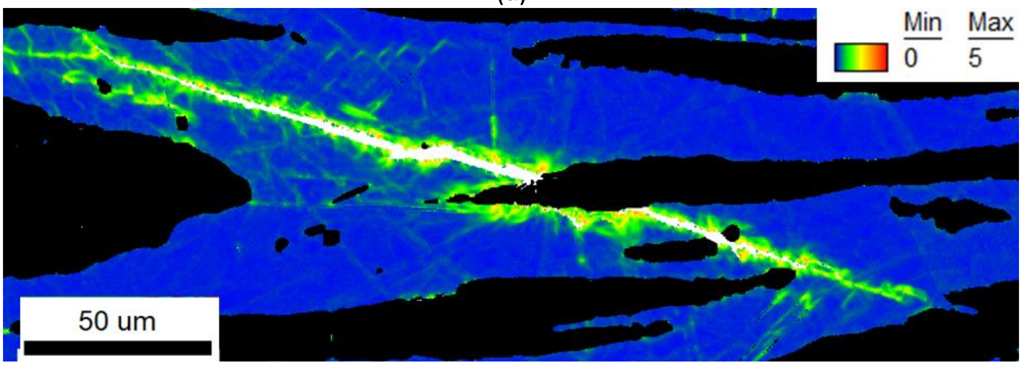
Project Outcomes

- Scientific discoveries/ advancement

The primarily outcome of this project was the elucidation of fundamental dynamic deformation and failure mechanisms of heterogeneous materials subjected to a wide range of extreme loading conditions. The emphasis was on the microstructural level (e.g. grain, phase boundaries). To date we have published 1 journal paper and a few conference proceedings. We have, however, produced enough data for at least 3-4 more journal publications, which involve Dr. Gonzales from AFRL W-P. For the sake of brevity, if we were to summarize our work in a single image, we would select Figure 5 below. It shows a phase map (Fig. 5.a) and a misorientation map (Fig 5.b). The latter is in essence a map of the plastic deformation in which the degree of crystal misorientation correlates with dislocation activity taken place inside the specimen, just underneath the surface.



(a)



(b)

Fig.5 (a) Phase and IQ maps for a transgranular ductile crack in a tested specimen (b) Plastic deformation map the BCC phase in (a).

The images above show a crack, black line, due to the applied shock loading. In Fig 5.(a) is observed that crack exists only within ferrite, the BCC phase. It grows through the BCC (green) grain, until is stops at the boundary with an FCC grain (red). The crack then circumvents this FCC grain and it then continues the original path, as signalled by the second white arrow. This is quite an exciting result and agrees with observations in single phase materials. For instance, previous work by CI Escobedo showed that dynamic damage in FCC copper occurs primarily along grain boundaries whereas is through the grain in BCC materials, like tantalum. This information is invaluable to have to verify any simulation of damage in multiphase materials.

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- Establishment of collaborative ties with AFRL scientists

Dr. Escobedo has worked closely with Dr. Manny Gonzales (RX) and other scientists at AFRL WP throughout this project. A visit by the CI was made in Feb 2019 to share and discuss our findings that might help their ongoing efforts with steel alloys. In addition to meetings and discussions, we also conducted some technical work that will be incorporated into publications currently being prepared. We envisioned that this project is the beginning of future, larger joint research endeavours.

- Benefits to USAF/AFRL

Our work addressed the objective of the program RTB1-a: Aerospace Materials for Extreme Environments. As aforementioned, we (PI Escobedo and AFLR collaborators), consider our work a first step towards developing a joint research effort on multi-phase (specifically tailored to extreme dynamic environments) materials aligned with the program RTA1-a: Dynamic Materials and Interactions. Furthermore, the type of loading profiles employed in our project,correspond to very common scenarios found in USAF environments and applications. For instance, a fan blade impacting an aircraft's containment casing or when a projectile strikes the fuselage.

Publication list

Three more conference proceedings are currently under review (TMS and SCCM) as well as 3 journal publications being prepared. All of them present our work funded in part by this AOARD project.

Journal

1. A. Ameri, Z. Quadir, M. Ashraf, C. Logos, J. Escobedo-Diaz (2019) "Effects of load partitioning and texture on the plastic anisotropy of duplex stainless steel alloys under quasi-static loading conditions", Materials Science and Engineering: A. Elsevier B.V., 752, 24–35.
2. A.A.H. Ameri, A.D. Brown, M. Ashraf, P.J. Hazell, M.Z. Quadir, J.P. Escobedo-Diaz (2019) "An Effective Pulse-Shaping Technique for Testing Stainless Steel Alloys in a Split-Hopkinson Pressure Bar", Journal of Dynamic Behavior of Materials. Springer International Publishing, 5(1), 39–50.

Conference Proceedings

3. AAH Ameri, JP Escobedo-Diaz, MZ Quadir, M Ashraf, W. Hutchinson (2018) 'Strain Rate Effects on the Mechanical Response of Duplex Stainless Steel', AIP Conference Proceedings 1979, 070001.
4. AAH Ameri, A Brown, Z Quadir, P Hazell, C. Logos and JP Escobedo-Diaz, (2018) "Investigating the Dynamic Tensile Response of Lean Duplex Stainless Steel and the Effects of Radial Waves Using the Recovered Plate-Impact Experiment", EPJ Web of Conferences 183, 03012
5. AAH Ameri, JP Escobedo-Diaz, MZ Quadir, A Brown, M Ashraf, P Hazell (2018) 'The effect of loading direction on the dynamic damage in lean duplex stainless steel 2101', AIP Conference Proceedings 1979, 070002.
6. TM Nankivell, A.A.H. Ameri, J.P. Escobedo-Diaz, MZ Quadir, C Logos (2019) "Investigating the Mechanical Response under Quasistatic compression of cold rolled Lean duplex Stainless Steels 2101", Characterization of Minerals, Metals and Materials 2019, 553-560

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