Experimental research and numerical modelling of deformation and fracture processes of metamaterials based on titanium alloys manufactured by additive methods

This research project investigates the mechanical properties of metamaterials, innovative materials created using advanced 3D printing techniques (specifically Laser Powder Bed Fusion - LPBF) from a titanium alloy powder (Ti-6Al-4V) with particle sizes ranging from a few to 40 micrometers. These materials have exciting potential for applications like bone implants, and the study aims to understand how they behave under various forces and conditions, paving the way for stronger, more reliable biomedical solutions.

The project focuses on key mechanical properties, such as the material's ability to deform before breaking (critical plastic strain), the point at which it begins to deform permanently (yield strength), its maximum strength (ultimate strength), resistance to cracking, and how long it can withstand repeated stress (fatigue life). A unique aspect of 3D-printed materials is their anisotropy—meaning their properties vary depending on the direction of printing. This study will explore this directional dependency in both elastic (reversible) and plastic (permanent) deformation, using a specialized model called the Hill yield criterion. Tests will be conducted on samples with and without heat treatment, where specimens are heated in a vacuum furnace and cooled slowly to see how this process affects their behavior.

Researchers will conduct experiments on cylindrical samples with ring-shaped notches of varying radii, made using LPBF from the titanium alloy. These samples will be subjected to simple loads like tension and torsion, as well as combined forces (tension and torsion), until they break. The team will also test non-proportional loading, where forces are applied unevenly. Using a computer modeling technique called the finite element method (via the Abaqus software), researchers will analyze stress and strain values in the specimens, especially at points where fracture initiates. This data will help develop a model for fracture initiation, considering both the material's plastic deformation and the printing direction.

The project also explores metamaterials with modified internal structures (mesostructures), specifically three well-known designs: Kelvin, Octet Truss, and Diamond. These structures will be tweaked by rounding the joints and optimizing the size of structural elements to boost strength and stiffness without significantly increasing weight. Before physical tests, computer models will simulate stress and strain in these modified structures. The study will also use computed microtomography (with a resolution of about 2 micrometers) to capture real internal structures, including manufacturing defects like small notches, and simulate how fracture form under stress.

Fatigue testing is a key focus, as defects from the 3D printing process can affect how long these materials last under repeated stress. The team will test modified structures of varying densities, analyzing how these changes improve fatigue life, strength, and the way of fracture initiation compared to unmodified designs. Two approaches will be used: one based on macroscopic stress and another examining local stress and damage within the structure using computer models.

The findings will guide the design of metamaterials with tailored properties, such as strength and stiffness, by adjusting their density and structural features like joint rounding. This is especially crucial for bone implants, where reducing stiffness compared to solid materials can lower stress at the bone-implant connection, while still maintaining strength and flexibility. The right structure also encourages bone tissue to grow into the material, improving the implant's integration and reliability. Ultimately, this research could lead to better, longer-lasting implants that work seamlessly with the human body.