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QUANTITATIVE ANALYSIS OF POROSITY AND VOIDS IN CAST FE-MN-AL STEEL ALLOY MATERIAL VIA X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

The x-ray computed tomography (XCT) technique is a widely applicable and powerful non-destructive inspection modality for evaluation and analysis of geometrical and physical characteristics of materials, especially internal structures and features. XCT is applicable to metals, ceramics, plastics, and polymer and mixed composites, as well as components and materiel. The Combat Capabilities Development Command - ARL and its partners are currently investigating the use of cast Fe-Mn-Al steel alloy material in support of weight reduction initiatives in Army development programs. Steel alloy Fe-Mn-Al has been identified as a key enabling material technology to reduce the weight in ground combat vehicle systems. A set of Fe-Mn-Al blocks each approximately 2" thick by 3" wide by 3" long, which had been sectioned from an industrially cast ingot (~12000 lbs.), were individually scanned by XCT using a conventional 450kV x-ray source and a solid state flat panel detector. Due mainly to the thickness of the blocks, as well as to minimize geometric unsharpness and the overall scan geometry (set up), the scans had a very low response at the detector through the Fe-Mn-Al blocks. The XCT scanning parameters and overall protocol used to mitigate the very low intensity throughput and achieve acceptable scan image results will be discussed. Image processing methods used to segment porosity features in the Fe-Mn-Al blocks will also be discussed. Finally, the spatial distribution and size composition of the porosity/void content and how it may relate to processing will be described.

Keywords: x-ray computed tomography, steel, Fe-Mn-Al, porosity, voids, distribution analysis

1. INTRODUCTION

The x-ray computed tomography (XCT) technique is a widely applicable and powerful non-destructive inspection modality for evaluation and analysis of geometrical and physical characteristics of materials, especially internal structures and features. XCT is applicable to metals, ceramics, plastics, and polymer and mixed composites, as well as components, assemblies, and materiel. The principal advantage of XCT is that it provides densitometric (that is, radiological density and geometry) images of thin cross sections through an object in a non-invasive manner. Because of the absence of structural superimposition, images are much easier to interpret than conventional radiological images. The Army Research Laboratory (ARL) and its partners are currently investigating the use of cast Fe-Mn-Al steel alloy material in support of weight reduction initiatives in Army development programs. Steel alloy Fe-Mn-Al has been identified as a key enabling material technology to reduce the weight in ground combat vehicle systems. A large industrial Fe-Mn-Al alloy ingot several feet long, 52 inches wide, and 12 inches thick with a nominal chemistry of Fe-30Mn-9Al-0.8Si-1C-0.5Mo was produced by electric arc furnace (EAF) melting in a 40-ton heat and subsequent casting using a bottom pour method, after which a normalization heat treatment was performed. XCT scanning of several specimens sectioned from three different solidification areas of the ingot determined the internal mesoscale structure of these areas and identified a number of significant individual features. The solidification areas included a central region in the middle (thickness) of the ingot and regions just inside the outside edges of the ingot along the 52 inch width. In this paper the locations and organization of the sectioned specimens will be given. The XCT scanning parameters and overall protocol used to mitigate the very low intensity throughput and achieve acceptable scan image results will be discussed, as well as scan results of interior structure and features of each solidification area. Image processing methods used to segment porosity features in the Fe-Mn-Al blocks will also be discussed, as well as initial analysis of the spatial distribution and size composition of the porosity/void content.

2. Fe-Mn-Al MATERIAL AND XCT METHOD

2.1 Sectioned Fe-Mn-Al Specimens

After the normalization treatment a 3" wide slice from just below the hot top of the ingot was removed for analysis. A water jet method was used to remove fourteen (14) 2"x3"x3" blocks from the ingot slice according to the schematic in Figure 1, in which the width of the ingot is left-to-right, the thickness direction is vertical, and the 3" slice direction is into the page. The solidification direction is from the outside towards the inside and the filling direction of molten material is coming out of the page. Six blocks were sectioned from the middle interior of the ingot slice, labeled C1 to C6, as shown in Figure 1. Four blocks each were sectioned from two outside regions on either side of the middle interior region to be representative of possible solidification effects in the same area, labeled A1 to A4 and B1 to B4, as shown in Figure 1.

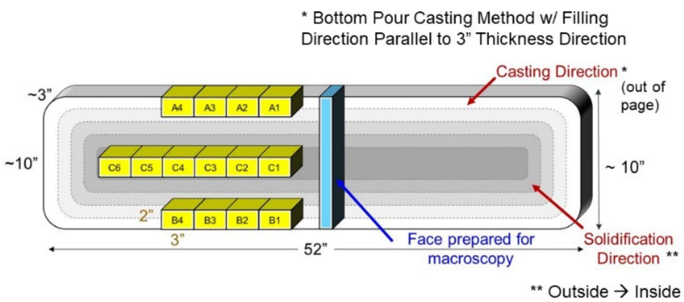

FIGURE 1: SCHEMATIC OF SPECIMEN BLOCKS SECTIONING.

2.2 XCT Scanning Procedures

Given that the approximately 3"x3" steel alloy Fe-Mn-Al blocks were 2" thick, the attenuation of 450keV maximum energy polychromatic Bremsstralung x-rays was high. A general rule of thumb sometimes used in XCT practice is to set up the scan procedure such that approximately 50% of the initial x-ray intensity from the x-ray source is attenuated by the object of interest. The purpose of this approach is to have a balance between image contrast and intensity, or signal, at the detector, and hence signal-to-noise ratio (S/N), in the XCT scans. XCT scans can still be performed with attenuation factors significantly below or above 50% with resultant effects of loss of contrast or loss of detector signal and possibly decrease in S/N. However, XCT images generated from these types of scans can still show pertinent physical information and features and provide acceptable physical data about a specimen.

Figure 2 shows a two-dimensional x-ray projection image through the 2" thickness of one of the Fe-Mn-Al blocks using the x-ray technique (tube energy and current) of the XCT scan method, the parameters of which are given in Table I. The detector field-of-view (FOV) around the relatively dark block is unsaturated and has an intensity level of about 85% of maximum, or saturation level. The intensity level through the thickness of the block is only about 6%, well below the general 50% transmission rule of thumb. It is extremely difficult to distinguish any individual features or significant density variations in the single projection image, which has been frame averaged. The XCT scan method used four times (4X) frame averaging and projection image "oversampling" to maximize the detection of density variations within the Fe-Mn-Al blocks. In Nyquist-Shannon sampling theory [1], given a polychromatic (i.e., multiple frequency) temporal (or spatial) continuous function, f(x), with known maximum spatial frequency X_{max}, it is completely determined by giving its sampled ordinates at a series of points spaced less than or equal to a distance of $1/(2X_{max})$ apart. The threshold $2X_{max}$ is called the Nyquist rate and is an attribute of the continuous spatial input f(x) being sampled. The sample rate, R, must exceed the Nyquist rate for the samples to suffice to represent f(x). The threshold R/2 is called the Nyquist frequency and is an attribute of the sampling equipment. The scans of the blocks purposely collected twice as many projections as normal based on the pixel width of the specimen field-of-view to oversample the scan space.

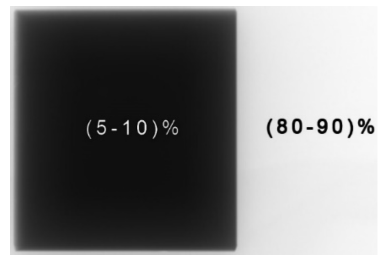

FIGURE 2: OFFSET AND GAIN CORRECTED PROJECTION IMAGE THROUGH Fe-Mn-Al BLOCK (DARK).

X-ray Voltage (Peak)	450kV
X-ray Energy (Peak)	450keV
X-ray Current	1550uA
Detector Sample Rate	1fps
X-ray Focal Spot Size	400um
Source-to-Image-Distance	875mm
Source-to-Object-Distance	575mm
Magnification	1.52
Detector Element Pitch	200um
Effective Pixel Pitch	131um
Unsharpness	1.04 pixels
Frame Average	4
# Projections (Views)	2200
Source Filter (Cu)	15.9mm (.625")

TABLE I: XCT SCANNING PARAMETERS

3. RESULTS AND DISCUSSION

3.1 XCT Image Results

Figure 3 shows images of blocks A2, B4, and C4 on the left, middle, and right, respectively, in which the spatial views are in the two inch thickness direction. Block A2 has one small porosity indication circled in black while block B4 has no porosity or void indications. This was typical of the A and B blocks scanned, all located at the perimeter of the slab cut from the cast ingot. In contrast, block C4 has a large void feature about 6.5 millimeters in diameter on the right side, which is approximately in the middle of the two inch thickness. Figure 4 shows images of block C4, with the image on the left relatively close to an outer face and the other images clearly showing not one, but two, large void features at approximately the middle thickness of the block. The nature of the porosity and voids in block C4, which were representative of all of the C blocks, clearly changed from extended and asymmetric, or more crack like, features nearer to the outside of the block to significantly more symmetric, rounded, voids in the center region of the block. It is readily apparent from the images in Figures 3 and 4 that the gray levels are not uniform across the specimens and generally vary from one local area to another, which was essentially due to the very high x-ray attenuation by the Fe-Mn-Al steel and resulting beam hardening. Thus, a simple global gray level threshold was insufficient to segment porosity and void features from nominal material.

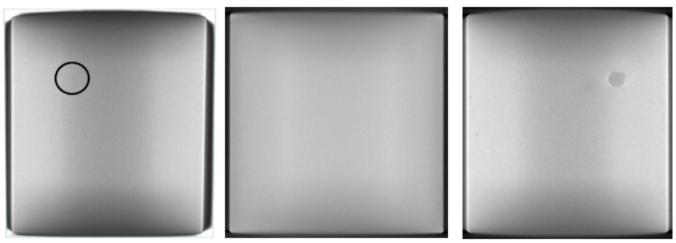

FIGURE 3: IMAGES OF BLOCKS A2, B4, AND C4

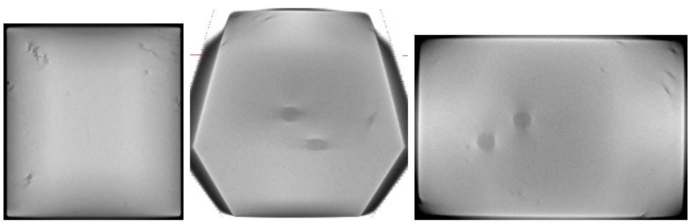

FIGURE 4: IMAGES OF BLOCK C4

3.2 Image Processing Methodology

A stack of approximately two inch by three inch cross-sectional images of block C4 was exported from the reconstructed XCT data. A series of image processing steps was applied to each image in the stack to segment, or binarize, porosity and void features from nominal material, including non-local means (NLM) filtering for noise reduction, adaptive mean-based thresholding, dilation, despeckling, and location dependent selective masking. Figure 5 shows an image from the stack, the NLM filtered (three times) image, and the image after standard global thresholding on the left, middle, and right, respectively. Standard global thresholding does not segment any porosity or voids from nominal material. Figure 6 shows the same image (w/o global thresholding) after adaptive mean-based thresholding, dilation, despeckling, and selective masking from left to right. This series of image processing steps resulted in a fairly good segmented representation of porosity and void content in the material. The segmented image stack provides the necessary binary data to perform analysis of the spatial distribution and size composition of the porosity/void content. As previously stated, it is apparent how the nature of the porosity and void features change from near the outside of the block to the center of the block. This is likely due to the ingot slice cooling from the outside first to the inside last, producing more dendritic grain structure towards the outside as opposed to more equiaxed grain structure on the inside.

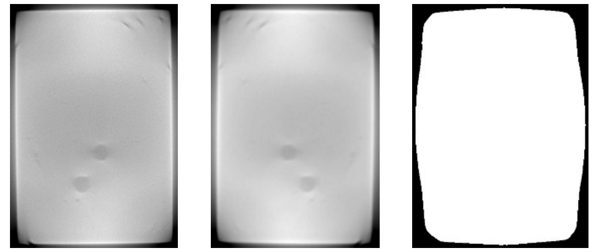

FIGURE 5: IMAGE PROCESSING OF BLOCK C4 USING GLOBAL THRESHOLDING

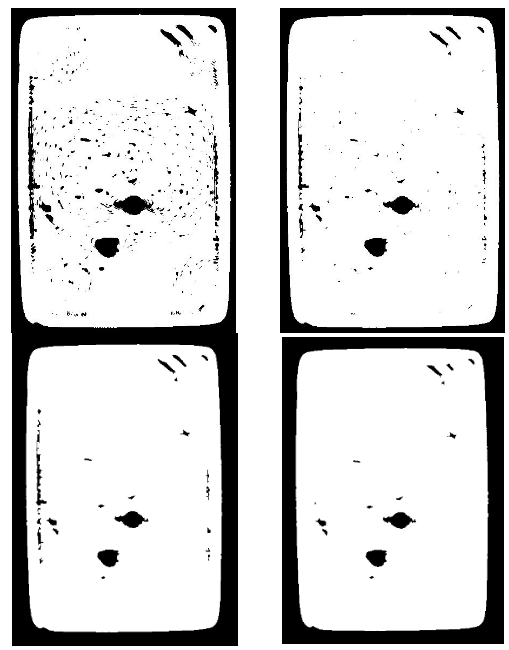

FIGURE 6: MULTI-STEP IMAGE PROCESSING OF BLOCK C4

4. CONCLUSION

Several sectioned Fe-Mn-Al steel alloy blocks were XCT scanned using frame averaging and oversampling with a 450 kV conventional source in the 400 micron FSS mode. Results showed that the A and B blocks sectioned from the perimeter of the cast billet contained relatively very low levels of porosity with no particularly large features, while C blocks sectioned from the center of the cast billet contained high levels of porosity with relatively large voids near their centers. The nature of the changes in the porosity and voids in the C blocks were likely due to the outside to inside cooling of the material. A series of image processing techniques were applied to a set of cross-sectional axial slices (images) generated from the reconstructed volume of block C4 to isolate porosity and void features.

REFERENCES

[1] Shannon, Claude E., "Communication in the presence of noise", *Proceedings of the Institute of Radio Engineers.* **37** (1): 10–21, 1949.