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Effect of feed on sub-surface deformation and yield strength of oxygen-free pitch copper in machining

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Abstract

The article deals with the influence of the machining induced surface integrity on tensile properties of 99.99% purity Oxygen-Free Pitch copper (OFC), used in nuclear and research facilities. The increase in the feed in machining was found to lead to an increase, up to 55%, in yield strength of the OFC specimens. Intensive sub-surface deformation and a high degree of work-hardening in the near-surface layer are attributed to this effect. Increase of feed resulted in an increase of deformation depth ε_{III} and work-hardening ΔH detected via SEM and nanoindentation. The correlation coefficient between the tensile properties and sub-surface deformation was found to equal R = 0.983.

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Keywords: Sub-surface deformation; yield strength; machining; copper

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1. Introduction

The issue of final storage of spent nuclear fuel in a safe environmental way is a problem to be solved. In Sweden, the Svensk Kärnbränslehantering (SKB) authority approved a strategy to store spent nuclear fuel in canisters manufactured of 99.99 % pure copper – (OFC) which is to be stored underground [1].

KBS-3 canister design [2] has been found as the most suitable for storage among several tested. During the development of manufacturing protocol for KBS-3, tensile tests have been found a valuable tool for quality assurance of produced OFC components. Yield strength was identified as one of the important parameters to achieve specified design of the canisters [2]. Tensile test rods produced by turning operation with varying machining conditions from the same OFC blank identical to KBS-3 canister material have shown a variation in yield strength which could be linked to surface damage and surface integrity of machined rods.

The surface integrity is the term used to evaluate the quality of the surface and/or sub-surface of a component, generated by the machining process. Topography, plastic deformation, hardness, variations in microstructure, residual stress, micro cracking and phase transformation, are among the conventional parameters related to surface integrity [3, 4]. Material hardness and strength (yield and tensile) define the degree to which sub-surface plastic deformation during machining can occur. OFC is known to be a soft and ductile material [5] which aggravates the effects of sub-surface deformation and work-hardening as a result of machining. The provided energy in the cutting process is consumed through plastic deformation in three deformation zones (Fig. 1) – primary (I), secondary (II) and tertiary (III). The width of the tertiary deformation zone ε_{III} as illustrated in Fig. 1 is one of

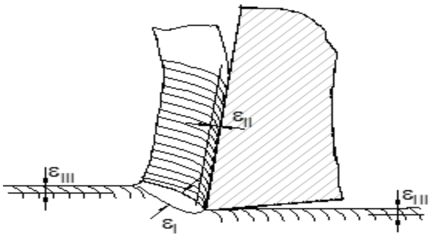

Fig 1 Illustration of deformation zone widths ε_I, ε_{II} and ε_{III} [6].

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the criteria for sub-surface deformation and work-hardening propagation. Several previous studies regarding sub-surface deformation in longitudinal turning have shown the influence of cutting data parameters, tool geometry, and tool wear on various surface integrity parameters [7-13]. Micro- or nanoindentation has been found to be valuable tools for evaluation of sub-surface deformation and analysis of alteration to the microstructure due to the machining [3-4, 7-12].

An increase in the feed when machining NiCr20TiAl [7] and Inconel 718 [8] nickel-based alloys resulted in an increase of the depth of sub-surface layer subjected to work-hardening, of cutting forces and of surface plucking. Similarly [9], machining of AISI 4340 steel has also resulted in a deeper work-hardened layer when the size of the tool wear land increased. The impact from tool wear on the sub-surface deformation has also been found more dominant than the impact of cutting speed and application of coolant when machining Inconel 718 with whisker reinforced alumina tools [10, 11]. High level of tool wear results in rise of thermal/mechanical load acting on the machined surface, and this was attributed to the variation of sub-surface deformation and microstructure [10].

Tool rake angle was found to have impact on both surface strain levels and sub-surface deformations during machining of OFC. Sub-surface strain distribution increases with decreasing rake angle and with increasing undeformed chip thickness h_0 or feed. Opportunities for controlling material microstructure in the sub-surface via strain and strain rate in machining have been observed [13, 14].

The above literature review shows that the link between machining conditions and surface integrity is well studied, however the connection between cutting data, surface integrity and properties of the machined component, e.g. yield strength, is not yet investigated. This paper reports on the impact of the feed and related sub-surface deformation on the yield strength of test rods machined in oxygen-free pitch copper.

2. Experimental studies

The oxygen-free pitch copper (OFC) used in the tests was supplied by SKB with specification on the material according to the TX214 lid [1]. The material was supplied as rods with the length 180 mm and diameter 30 mm. The OFC material has been annealed for one hour at 500 °C prior to the machining tests. A Torshälla S 160 CNC lathe was used to machine the test rods to the dimensions according to Fig. 3. The cutting speed was kept constant at 150 m/min, which was based on previous studies. Cutting depth a_p was 1 mm for rough machining and 0.3 mm for finish machining.

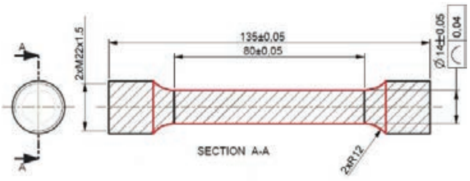

Fig 2. Tensile test rod specimen.

Machining was performed with Cimstar 501-02 cutting fluid. The machining of the test rods was done at three different feed levels: 0.15, 0.25 and 0.35 mm/rev in the middle part of the test rods marked in red (see Fig. 2). The tool used was CNMG120408-MF1 uncoated cemented carbide with 0.5 wt. % Co specifically designed by SECO Tools AB for machining OFC. Each test rod was checked for the compliance of the dimensions to the requirement (Fig. 2) after machining. A mechanical Instron testing machine with a 100 kN load cell was used to perform load to fracture test of the test rods. Two different extensometers were used to register the elongation of the test rods. Extensometer 1 (Instron 2630-102) with short range of -5 to +5 mm was used for accurate measurement of the yield strength, while Extensometer 2 (Instron 2630-113) with wider range of -5 to +50 mm was used to measure the ultimate tensile strength and total elongation. The cross-head separation rate was kept at 5 mm/min, which equals a strain rate of 0.00104 s^{-1} that meets the allowed limit according to the ISO 6892-1:2009(E) standard. Three rods for each feed were manufactured and tested. One test rod for feed $f = 0.25$ mm/rev failed during the test.

Separate rods machined with identical conditions to the test rods were sectioned, polished and etched with 10% ammonium persulfate etchant prior to the microscopy. Depth of sub-surface deformation was measured on SEM images taken at several locations along the sample surface. Nanoindentation on the non-etched samples was performed on NanoTest Vantage system with the loading range of 1 to 200 mN when using Berkovich diamond indenter with the tip radius of 120 nm. Nanoindentation for identification of the sub-surface deformation was done on the axial cross section. The first indent was placed 5 µm from the machined surface followed by the indentation every 10 µm. For the 50 mN load the spacing was increased to 20 µm apart due to interference between indents.

3. Results and discussion

3.1. Yield strength

Examples from the results from the tensile tests for different feeds are presented on Fig. 3. Yield strength R_{p02}, was determined by fitting a line with the same slope as in the elasticity region at a strain of 0.2 % (see Fig. 4). Yield strength results for each test rod at different feeds and

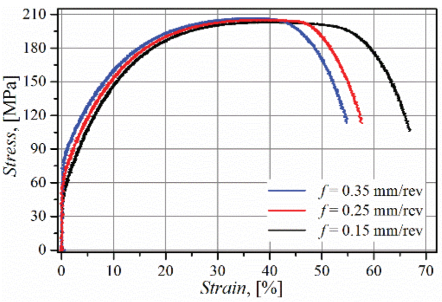

Fig 3. Stress-strain curves for OFC samples machined with various feeds.