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Investigating different discharge energy and surface integrity characteristics in wire-EDM of inconel 718

S. Arunachalam, Rajaram Sahu, Biswaranjan Biswal, Debananda Behera
Department of Mechanical Engineering, NM Institute of Engineering and Technology,Bhubaneswar , Odisha
Department of Mechanical Engineering, Raajdhani Engineering College,Bhubaneswar,Odisha
Department of Mechanical Engineering,Aryan Institute of Engineering and Technology Bhubnaeswar , Odisha
Department of Mechanical Engineering,Capital Engineering College,Bhubaneswar,Odisha

ABSTRACT: *This study presents the characteristics of surface integrity vs. discharge energy in W-EDM of Inconel 718. The results show that the EDMed surface topography shows dominant coral reef microstructures at high discharge energy, while random micro voids are dominant at low discharge energy. Surface roughness is equivalent for parallel and perpendicular wire directions, and average roughness can be significantly reduced for low discharge energy. Superalloys such as Inconel 718 are widely used in turbomachinery industry due to their outstanding mechanical properties. Inconel alloys are very difficult to machine using conventional mechanical processes like broaching, milling or grinding. Wire electrical discharge machining (W-EDM) is an alternative competitive process to manufacture complex Inconel part geometries. However, surface integrity of W-EDMed Inconel components is poorly understood. The thick white layers are predominantly discontinuous and non-uniform at relative high discharge energy. Micro voids are confined within the thick white layers and no micro cracks were found in the subsurface. The thin white layers by trim cut at low discharge energy become more continuous, uniform, and are free of micro voids. Compared to the bulk material, white layers have dramatic reduction in microhardness due to significant thermal degradation. In addition, surface alloying from wire electrode and water dielectric are obvious in main cut at high discharge energy, but it can be minimized in trim cuts at very low discharge energy.*
Keywords*: Surface integrity; wire-EDM; Inconel alloy; discharge energy*

I. INTRODUCTION

Nickel-based superalloys such as Inconel 718 are widely used in aerospace, nuclear, and chemical industries because of their excellent mechanical and chemical properties at elevated temperatures. It is estimated that Nickel-based superalloys compose over half of the materials used in the aerospace industry, in particular for the hot section of gas turbine engines for components such as turbine disk, blades, combustors, etc. [1].

When machining Nickel-based superalloys, the significant challenges faced are that they have low thermal conductivity that increases the thermal effects during machining, they often exhibit strong work-hardening behavior, high adhesion characteristic onto the tool face altering cutting process parameters completely. In addition, they may contain hard abrasive particles and carbides that create excessive tool wear, and hence the surface integrity of the end products can be disappointing [2,3].

Compared to mechanical cutting, electrical discharge machining (EDM) is a competitive alternative process to machine Nickel-based superalloys. EDM can machine hardened steels [4], titanium alloys [5], cemented carbide [6], and conductive ceramics [7] regardless of their hardness and strength. It also allows machining of complex part geometry. Unlike mechanical cutting and grinding, the tool electrode does not rotate for material removal, holes with sharp corners and irregular contours can be conveniently machined by EDM. The low force nature in the EDM gap also allows the machining of thin and flexible parts, deep grooves and holes which otherwise are difficult to machine by milling [8]. Despite the low machining efficiency of EDM, the machining accuracy and surface finish are very high, especially at trim cutting conditions. These unique process characteristics make EDM an enabling technology in tool, aerospace, automotive, and medical device industries.

Compared with die sinking EDM, wire-EDM is widely used because it can be fully automated and flexible in making complex geometrical shapes in one setup. This process capability is particular important for aero-engine manufacture. Since EDM is a thermal dominant process, the very high temperature has significant impact on the process-induce surface integrity including surface topography, microstructure change, residual stress, microhardness, and element distributions. The heat affected zone (HAZ) with a white layer is often associated with high tensile residual stress, microcracks, porosity, grain growth, and alloying from the tool electrode or dielectric fluid [9]. A recent study claims that wire-EDM is the most detrimental to surface integrity compared to hard turning and grinding [10]. However, this is not necessarily true since the degree of thermal damage depend on not only process conditions but also EDM generators. Thermal damage in main cut can be removed or minimized by subsequent multiple trim cuts at reduced discharge energy. Relaxation pulse with low energy has been tried to improve surface quality in EDM of silicon carbide [7]. It has shown that machining sequence with trim cut and polishing technology is essential to guarantee surface integrity

[11]. With the development of low energy generators and EDM strategy, thermal damage by EDM may be minimized.

The bulk work on EDM-induced surface integrity is limited to tool steels, very little research has been conducted regarding surface integrity for Nickel-based superalloys. Aspinwall et al. [12] have shown that wire-EDM of IN 718 produced an average Ra of 2.93 µm in main cutting and 0.21 µm in finish trim cut. The average thickness of a white layer is about 6 µm by main cut while it cannot be observed in finish trim cut. In addition, no significant change of microhardness was measured in the subsurface.

It is well known that discharge energy has a significant influence on surface integrity. However, the evolution of surface integrity from high to low discharge energy levels has not been thoroughly understood. This study aims to address this issue in wire-EDM of IN 718 by comprehensively characterizing surface integrity in main cut and multiple trim cuts with the reduced discharge energy.

II. EXPERIMENTAL PROCEDURE AND OPERATING PARAMETERS

with deionized water dielectric. Uncoated brass wire electrode of 200 µm diameter was employed. Since the work is a fundamental research instead of making an actual part, workpiece material blocks of 10 mm × 10 mm × 10 mm were selected and wire machined using an appropriate sequence of cuts including a main/roughing cut and subsequent three trim cuts each at reduced discharge energy via relaxation type waveforms. Since commercial EDM machines and associated process conditions are designed to meet specific materials, thickness, surface roughness, and productivity, operators may only choose suitable process parameters from the built-in database. Unlike the capability of using a variety of process parameters in CNC cutting and grinding, one have very limited process space to program specific voltage, current, and discharge duration. In addition, the process parameters on the controller screen have an implicit relationship with the actual used voltage, current, and discharge duration. Furthermore, the commercial Sodick EDM machines have 20 process parameters to influence machining performance. Therefore, EDM process is more like a black box for users to produce the desired surface integrity.

The most influential process parameters pulse on time and current were selected for main cut and three trim cuts corresponding for four levels of discharge energy. Table 2 shows the EDM conditions for the main cut and three trim cuts due to the absence of recommended parameter values for IN 718 in the built-in process database of the machine. The measurement of energy consumption in EDM is very challenging, so energy consumed only for main cut and trim cuts was not measured in this study. However, the discharge energy at main cut and trim cuts are on the very different levels.

Table 1. Typical compositions of Inconel 718

Element	(wt. %)	Element	(wt. %)
Ni	53.40	C	0.067
Cr	18.95	Si	0.06
Fe	17.01	Co	0.05
Nb	5.48	P	0.009
Mo	3.20	B	0.006
Ti	1.08	S	0.005
Al	1.00	Mg	<0.01
Cu	0.07	Mn	0

Table 2. EDM energy level in main cut and trim cuts

Cut type	Discharge energy level	Depth (mm)	Speed (mm/min)
Main cut (MC)	highest	10	9.5
Trim cut 1 (TC1)	high	8	12.2
Trim cut 2 (TC2)	low	6	14.1
Trim cut 3 (TC3)	lowest	4	20.5

Wire-EDM of IN 718 alloy, Table 1, was carried out on a Sodick Mark Ex EDM A280L (w.o. servo control)

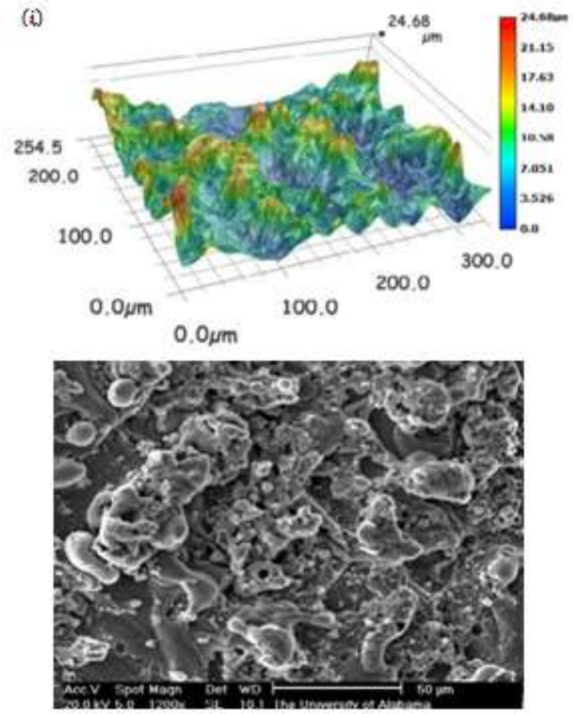
III. RESULTS AND ANALYSIS

3.1 3D topographic map

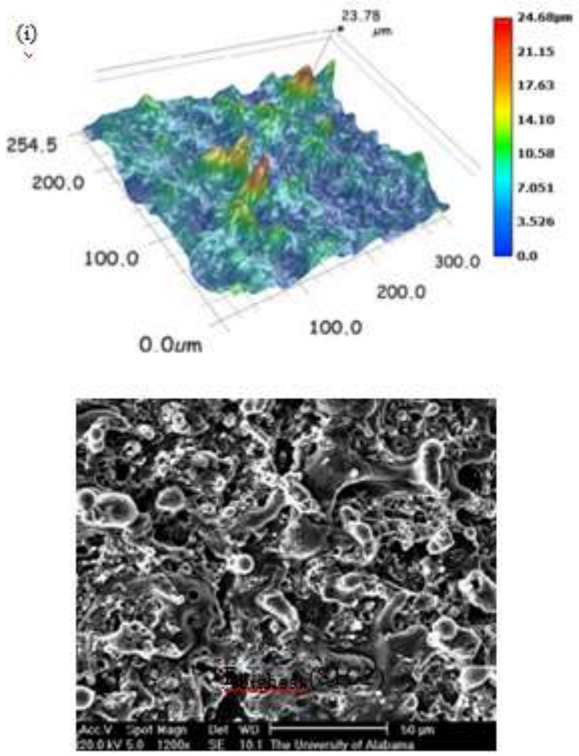
3D surface topographic maps of the EDMed surfaces were measured using Keyence VHX1000 with Lense Keyence VHZ-100R. JEOL-7000 scanning electron microscope (SEM) was also used to examine surface micro topography. Figs. 1a-1d show the 3D surface topographic maps and SEM images of the EDMed surfaces. The peaks and valleys on the topographic maps were formed by the overlaps of the stochastic/random (ii) distributed craters. It is clear that surface morphology of the EDMed surfaces depends on the applied discharge energy. During the EDM process, the very high temperature in every discharge causes material micro melt and evaporation, and then leaves a crater on the machined surfaces. The size of the crater is influenced by discharge energy. With the decrease of discharge energy from main cut (MC at $E_{highest}$) to trim cuts (TCs at reduced discharge energy), the peak-to-valley reduces significantly from 24.68 µm to 9.41 µm.

The EDMed surfaces (Figs. 1a-1b) show coral reef microstructures in MC ($E_{highest}$) and TC1 (E_{high}). The spherical debris may be re-solidified from the vaporized material or splashed molten material by rapid water

(a) Topographic map by MC @ Ehighest quenching. The formation mechanism of spherical wouldbesimilartoproduction of powders via atomization of molten metal in water. This phenomenon was also reported by Klink et al. [4] in W -EDM die steel in water dielectric in finish trim cut of ASP2023 tool steel. Unlike EDMed steel surfaces in literature, microcracks cannot be seen on the surface. Compared to the EDMed surface in MC ($E_{highest}$) and TC1 (E_{high}), random micro void (Figs. 1c-1d) is a distinctive characteristic for the EDMed surfaces at TC2 (E_{low}) and TC3 (E_{lowest}). During discharge, the presence of large volume of gases in the channel will lead to a high super saturation of gas in the molten pool. The discharge (ii) energy in the plasma channel melts the material, but is not sufficient to produce a high exploding pressure which can spray all the molten metal away from the EDMed surface. When the remaining molten material solidifies on the surface, the gas bubbles would expel from the molten material, and result in micro voids. As the discharge energy decreases, more molten material would not be swept away but solidifies on the surface, which results in more random micro voids.



(a) Topographic map by MC

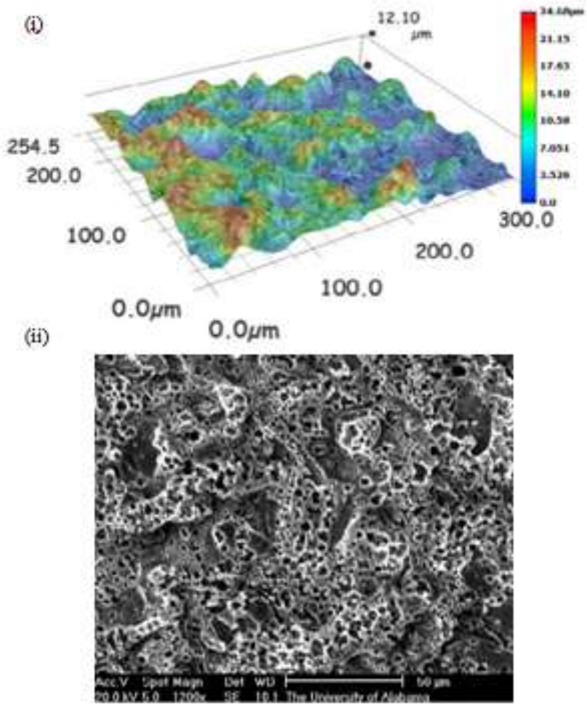


b) Topographic map by TC1 @ E_{high}

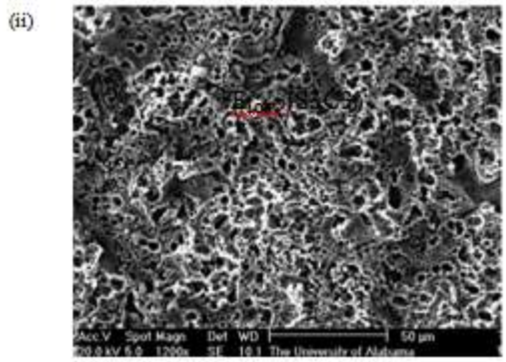
Fig. 1. 3D topographic map at different dischargeenergy: (i) Optical map; (ii) SEM image

3.2 Surface roughness

Roughness of the EDMed surfaces in Fig. 2a was measured using a Mahr stylus (PGK 120 with 90º and 2 µm radius tip) along the directions parallel and perpendicular to the wire. Two important findings can be found. The first one is that surface roughness in both directions at both MC and TCs conditions shows that surface directionality is negligible for the EDMed surfaces. Therefore, the direction of cutting speed has little effect on surface roughness. The very slight difference may be due to wire deflection and vibration in the EDM process [12]. Secondly, compared to the MC($E_{highest}$), average roughness is significantly reduced from 3.75 µm ($E_{highest}$) to 1.25 µm in TC3 (E_{lowest}). This can be explained by the fact that as the discharge energy decreases, a shallower and smaller erosion crater on the surface will be produced. Furthermore, as the discharge energy decreases, the amount of thermal energy transferred to the sample decreases, and so less material will be melt. A large fraction of molten material would be swept away from the surface by the dielectric, while the remaining molten material will be rapidly re-solidified. Surface roughness can be further improved by using more trim cuts, but the trend of discharge energy on roughness would be similar.



(c) Topographic map by TC2 @ E_{low}



(d) Topographic map by TC3 @ E_{lowest}

Fig. 2a. 3D topographic map at different discharge energy: (i) Optical map; (ii) SEM image

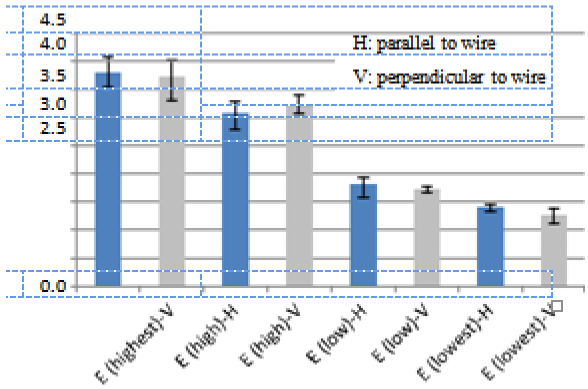


Fig. 2b. Surface roughness at different discharge energy

3.3 Subsurface microstructure

The EDMed samples were cross-sectioned, polished, cleaned, dried, and then air dried for microstructure observation in the subsurface. The etchant used consists of 100ml HCl, 100ml HNO_3 and 5g CuCl. Microstructural analysis was carried on a JEOL-7000 scanning electron microscope (SEM). Fig. 3 shows the cross-sectional view of the EDMed samples at different discharge energy. It can be seen that the thickness of white layer increases with the discharge energy. Larger pulse duration allows the high temperature penetrates deeper into the subsurface, which produces more molten material and ultimately results in a thicker white layer. On the other hand, increasing the pulse current also produces similarly phenomenon Microstructure appeared consistent or unchanged below the white layer White layers were predominantly discontinuous and non uniform at MC ($E_{highest}$) and TC1 (E_{high}). Unlike the reported microcracks in white layer of EDMed steel 13], microcracks into the subsurface were not observed. However, microcracks in terms of voids and bubble channels were confined within the white layer whose average thickness was 13.3 µm and 8.3 µm, respectively.

As the discharge energy reduces in TC2 (E_{low}) and TC3 (E_{lowest}), white layer becomes more continuous and uniform. They also become much thinner, i.e., 5.1 µm and 3.3 µm in the two trim cuts. Microcracks confined within the white layer in TC2 (E_{low}) are still visible, but the white layer in TC3 (E_{lowest}) is free of microcracks. Therefore, discharge energy is the critical factor to minimize the thickness of white layer, i.e., thermal damage into the subsurface. It is expected that white layer would be invisible in finish trim cut with minimal discharge energy. Indeed, Klink et al. [4] reported that a very thin white layer of 0.2 µm was produced in finish trim cut of ASP23 tool steel.

2.5 times compared to the bulk. The dramatic reduction in hardness suggests that significant thermal degradation occurs on EDMed surfaces regardless of discharge energy. This finding is in contrast to a previous study that little or no change in either the main or trim cutting of IN 718 12]. It was not clear where the indentations were made since indent locations on white layer were not shown in the previous study [12] In comparison, white layer of EDMed carbon steels have higher hardness than the bulk due to the rich C element [10]. However, the very low C content (wt. 0.067%) in IN 718 would not make the white layer harder after quenching in dielectric. In addition to the discontinuous and non uniform white layer, the dent size and white layer thickness is on the same order even for the lowest load (10g) in the study. These factors could slightly affect the accuracy of hardness measurement

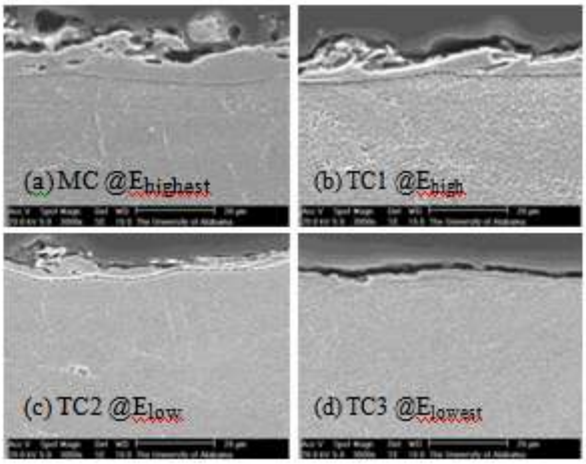


Fig. 3 White layer characteristics in main and trim cuts

3.4 Microhardness

Fig. 4 show the average microhardness and variations for the samples at different discharge energy corresponding to the main cut and three trim cuts. Three measurements were made at same depth on the subsurf ce. Knoop indentations on the white layer are visible in Fig. 4 Compared to the bulk material, the white layer has significantly reduced microhardness at each case. However, the white layer by MC ($E_{highest}$) is harder than those produced at low discharge energy ases. The hardness of white layers almost reduces by

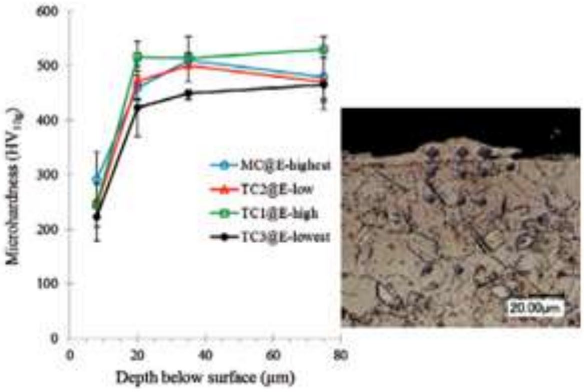


Fig. 4 Microhardness profile in the subsurface

3.5 Elemental analysis

The very high temperatures (up to 40,000 K) by plasma heat flux instantly melt and vaporize surface work material during the discharge process. Complex chemical reactions between the work material, wire material, and the dielectric are the basic characteristics of an EDM process. EDS analysis was used to measur the element composition of white layer . Fig. 5 compares the EDS spectra of the white layers by MC ($E_{highest}$) and TC3 (E_{lowest}) and the bul k for assessing alloying effect. The elements present in the white layer are clearly indicated by the peaks corresponding to their energy levels. The presence of copper was detected in the white layer at MC ($E_{highest}$), this is due to the diff usion of material between the brass wire electrode to the work material. However, Cu alloying on the EDMed surface in TC3 (E_{lowest}) is negligible due to the significantly reduced discharge energy The O presence can be attributed to the presence of water in t he discharge gap and it was observed that the percentage of element in the white layer formed in MC ($E_{highest}$) is larger than that in TC3 (E_{lowest}) . This is due to the high energy which results in more decomposition of water in the gap.

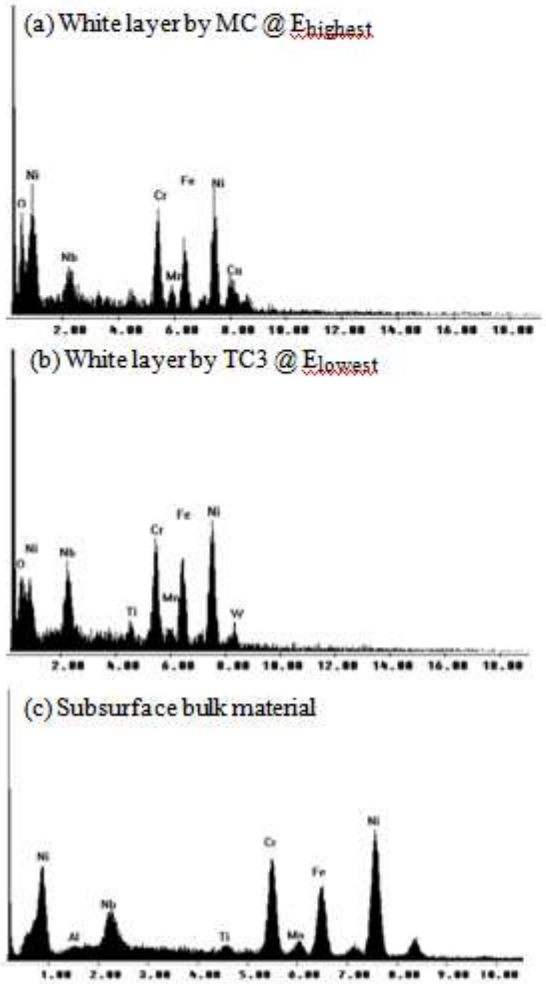


Fig. 5. Effect of discharge energy on the EDS spectra

IV. CONCLUSIONS

This study focused on the effect of discharge energy on surface integrity from main cut and trim cuts of IN 718. Key findings can be summarized as follow.

- Surface topography by main cut and rough trim cut at high discharge energy show coral reef microstructures with few voids, while random micro voids are dominant characteristics on the EDMed surfaces by trim cuts at low discharge energy.
- The EDMed surface is isotropic in terms of surface roughness. Roughness was significantly reduced from 3.75 μm to 1.25 μm at low discharge energy.
- Thick (8.3 μm-13.3 μm) white layers are predominantly discontinuous and non-uniform at relative high discharge energy. Micro voids are confined within the thick white layers. Thin (3.3 μm) white layer at low discharge energy is continuous, uniform, and free of micro voids.
- The white layers have dramatic reduction (2.5 times) in microhardness compared to the bulk material, which indicates that significant thermal degradation occurs on EDMed surfaces regardless of discharge energy. Unlike carbon steels, the very low C content of IN 718 would not make the white layer hard after quenching in dielectric.
- Surface alloying can be minimized by reducing the discharge energy in finish trim cuts.

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