LASER ULTRASONIC SYSTEM FOR ON-LINE STEEL TUBE GAUGING

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ABSTRACT. A laser-ultrasonic system has been installed on a seamless tubing production line of The Timken Company and is being used to measure on-line the wall thickness of tubes during processing. The seamless process consists essentially in forcing a mandrel through a hot cylindrical billet in rotation and typically results in fairly large wall thickness variations that should be minimized and controlled to respect specifications. The system includes a Q-switched Nd-YAG laser for generation of ultrasound by ablation, a long pulse very stable Nd-YAG laser for detection coupled to a confocal Fabry-Perot interferometer, a pyrometer to measure tube temperature and two laser Doppler velocimeters to measure the coordinates of the probing location at the tube surface. The laser, data acquisition and processing units are housed in a cabin off line and connected to a front coupling head located over the passing tube by optical fibers. The system has been integrated into the plant computer network and provides in real time thickness data to the plant operators. It allow much faster mill setups, has been used since its deployment for inspecting more than 100,000 tubes and has demonstrated very significant savings.

INTRODUCTION

Nowadays in the state of increased world competition, manufacturing companies have even stronger incentives to better control production and to minimize the fabrication and rejection of out-of-specifications products. This is in particular the case of the steel industry and of one segment of this industry involved in the production of seamless mechanical steel tubing. This tubing is used in demanding applications, such as hydraulic cylinders and power transmission components (gears and bearing races) where a weld seam is prohibited. Seamless tubes are also used for the same reason in other applications such oil drilling and as pipes in a variety of industrial processes. The tube making process begins with heated cylindrical billets that are formed into hollows by cross rolling over a

CP657, *Review of Quantitative Nondestructive Evaluation Vol. 22,* ed. by D. O. Thompson and D. E. Chimenti
2003 American Institute of Physics 0-7354-0117-9

piercing plug. The hollows are elongated into shells by cross rolling over a mandrel bar and formed into the final tube size in a reducing mill (see Fig. 1 for a sketch of the process). The piercing process can cause wall thickness variations, which often follow a helical pattern. The need of a thickness measurement sensor follows not only from the requirement of controlling the wall thickness to specification, but also from the desire for improved process control to increase yield and reduce scrap and rework. Particularly in the case of hollow parts that are machined from tubes, the closer the tube is to optimal dimensions, the larger the savings, derived from reduced machining time and tool wear as shown in Fig. 2.

Although penetrating radiation (γ-rays) techniques have been developed and used for thickness gauging tubes, they have various limitations and in particular, they cannot measure tubes with a mandrel inside. On the other hand, ultrasonic techniques are widely used in industry for thickness gauging, flaw detection and materials characterization [1]. Regarding thickness gauging, the time-of-flight between successive echoes is first

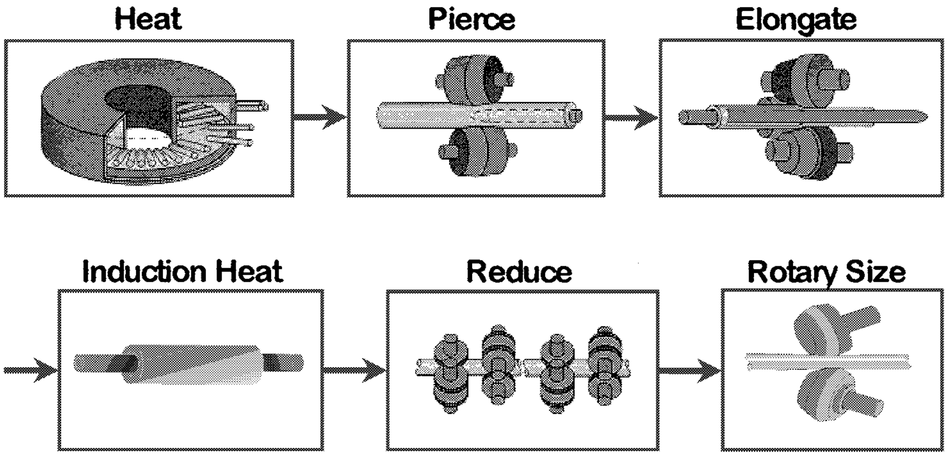


FIGURE 1. Seamless tube manufacturing process

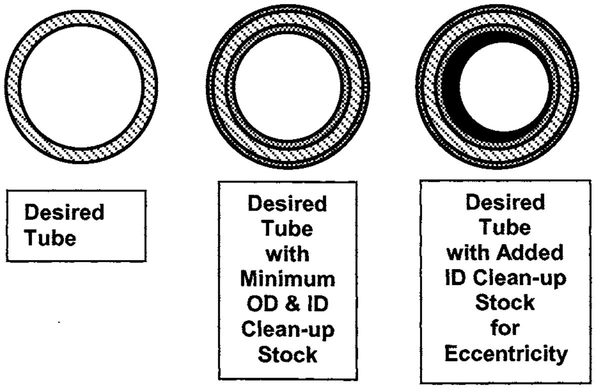


FIGURE 2. Tolerances requirement for mechanical tubing

measured and then, by using the proper value of the ultrasonic velocity obtained by calibration, the thickness is calculated. The ultrasonic waves are usually generated and detected by piezoelectric transducers and coupled to the inspected part either by direct contact or through a water bath or a water jet. In this case, these conventional ultrasonic techniques are not applicable, first because of the tube temperature (in the range of 1000 degrees C) and secondly, because it is not very precisely guided. This difficulty of achieving precise guiding has made in particular non-contact electromagnetic transduction (with EMATs transducers) unsuccessful, since in this case close proximity to the surface (typically in the millimeter range) is needed.

Laser-ultrasonics, which uses lasers for the generation and detection of ultrasound at a distance (typically several tens centimeters to one meter and even more) does not have such limitations and was the technique used to develop the mill-worthy system described here [2]. Although there has been previously in-plant demonstration of this technique for on-line tube gauging, this the first time a system is continuously used in production [3,5]. This system has been developed to perform measurements on a tube in rotation at the exit of one of the machine sketched in figure 1 and to provide full wall thickness mapping. For this purpose three technologies are used: laser-ultrasonics to provide the basic signal related to wall thickness, pyrometry to measure the temperature at the measurement location for the determination of the ultrasonic velocity and laser Doppler velocimetry for providing after integration the coordinates of the measuring location at the tube surface.

PRINCIPLES OF THE TECHNOLOGIES USED IN THE SYSTEM

Laser- ultrasonics

Generation of ultrasound is performed in the ablation regime by a sufficiently strong laser pulse. The recoil effect following material ejection off the surface (essentially surface oxide) and plasma pressure produce strong longitudinal wave emission perpendicular to the surface. The ultrasonic waves after reflection by the inner wall of the tube cause a small surface motion (typically in the nanometer range) (see Fig. 3). Detection uses a second laser with a pulse duration sufficiently long to capture all the ultrasonic echoes of interest (typically 50 μs) and very stable in frequency and intensity. The ultrasonic surface motion produces a Doppler frequency shift on the scattered light that is demodulated by an interferometer. In practice the surface being rough, the scattered light has speckle and an interferometer insensitive to speckle should be used, which could be a confocal Fabry-Perot [6,7] or a photorefractive interferometer [8,9].

Pyrometry

The surface temperature is measured by measuring the infrared emission from the tube surface. A standard two-color scheme is used by measuring the emission around two wavelengths and taking the ratio of the two signals. This scheme avoids knowing the surface emissivity, which is however assumed of being wavelength independent. This is a reasonable assumption, especially if the two selected wavelengths are relatively close.

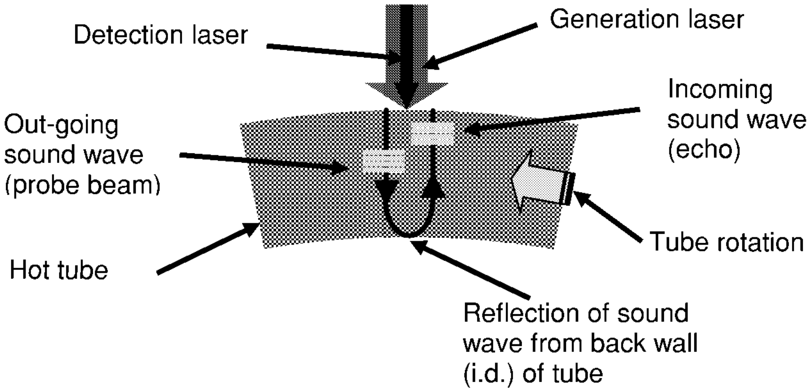


FIGURE 3. Principle of laser ultrasonic wall thickness gauging of a tube

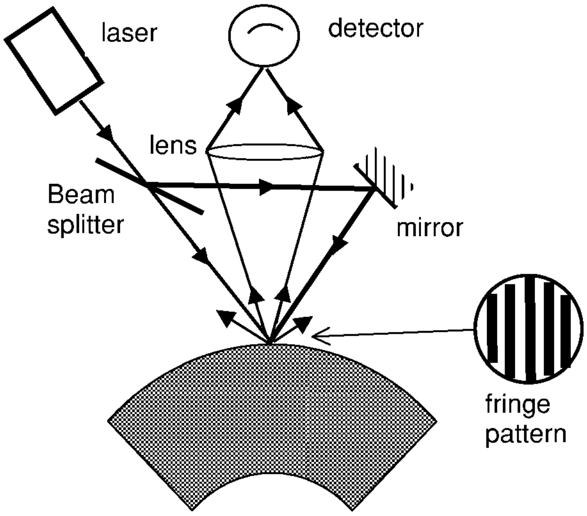


FIGURE 4. Principle of laser Doppler velocimetry

Coordinate Determination

For this purpose two laser Doppler velocimeters are used. These systems produce a fringe grating at the surface of the tube by the intersection of two laser beams derived from the same laser (see figure 4). The velocity V is simply related to the Doppler frequency f : $f= 2V \sin\theta / \lambda$ where θ is the half angle between the intersecting beams. One velocimer projects fringes along the tube axis to measure the tube translation velocity whereas the other one projects fringes in the perpendicular direction to measure the rotational velocity. These velocities are then integrated to give the displacement from a starting point. Knowing the tube diameter, this allows the determination of the generation/detection location all along the tube.

DESCRIPTION OF THE SYSTEM

Lasers are delicate instruments that will not reliably operate in the harsh environment near a steel processing line, in presence of high temperature, dust, fumes and water splashes. Although adequate protective enclosures could be developed, it should be noted that lasers require servicing from time to time (at least for changing flashlamps) and opening of such enclosures, so they could be contaminated by the environment. Therefore, it is very beneficial to locate them away from a production line, so in the developed system, they are housed with other delicate sub-systems in the clean air-conditioned environment of an off-line cabin. The light beams for the three functions (laser-ultrasonics, pyrometry and velocimetry) are transmitted by optical fibers that link them to a front coupling head located right on the line. The general configuration of the system is shown in figure 5. For additional mobility of the system this cabin is mobile and is made from a truck trailer. The lasers include the generation Q-switched Nd-YAG laser operating at 1.064 µm and the detection laser, which is long pulse (50µs) and high stability and also operates at the same wavelength. The repetition rate is 100 Hz, which gives depending upon the processing conditions and the tube diameter 5 to 15 data points around the tube circumference. The demodulator used is a confocal Fabry-Perot and its unit is also located inside the cabin. The demodulator unit also includes the pyrometer and its electronics and the velocimeters detector and electronics. The velocimeters use a fraction of the power of the cw Nd-YAG laser used to seed the detection laser. The umbilical cord that includes fibers for transmitting the generation beam, the detection beam, the scattered light beam phase modulated by ultrasound, the illumination beams for the velocimeters, the scattered light from the velocimeters beams and the infrared emission from the tube for the pyrometer is about 25m long. The cabin also houses data acquisition electronics, several computers for processing the various signals and calculating time-of-flight between echoes, thickness, eccentricity, measurement location and temperature. The cabin also includes a monitor from which all the informations provided by the system could be displayed as numerical values, chart or maps. Information the most useful to the production line operators, i.e. thickness profile along the tube and temperature is also available on a remote consol near the line and at various locations in the plant through additional monitors (not represented in Fig. 5), the system being integrated in the plant computer network.

The inspection head that includes appropriate focusing optics for laser ultrasonic probing and Doppler velocimetry is shown in Fig. 6. The head rests upon a mechanical part, the laser light shield, through which passes the tube, whose function is to hold the inspection head above the tube and to provide laser light shielding. The section encircling the tube is sufficiently long for blocking scattered light, so the amount of light that can escape in the worst case is negligible, thus ensuring eye safe operation. The inspection head is moved on top of the laser shield by an overhead crane as shown in Fig. 5. The head has its own cooling unit and its temperature is monitored. The head has an output window that is protected from water splash and fumes deposits by a strong airflow. It was found convenient to have an eye-safe enclosure near the line for calibration purposes. This enclosure, the calibration box, is a cubic metal box, rests on the plant floor and can hold the inspection head. Pieces of tubes and a black body source can be located in it for verification and calibration purposes.

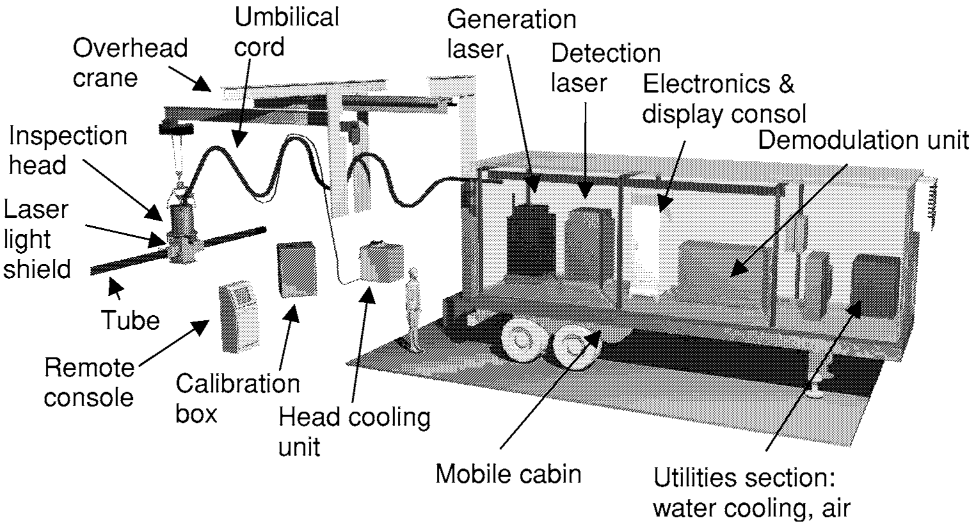


FIGURE 5. General configuration of the system

The system software developed under Labview provides a variety of displays, ranging from the basic display for the line operators shown in Fig. 7 to more advanced displays. One of such displays is shown in Fig. 8. It shows a color-coded thickness map using flat projection of the tube surface. Thickness profiles along a generatrice and though a cross section are selected by cursors and are displayed. The cross section plot shows departure from perfect concentricity.

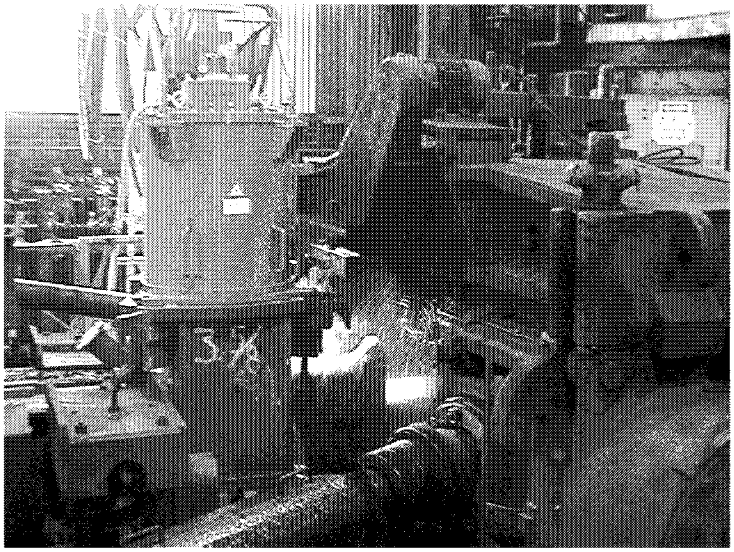
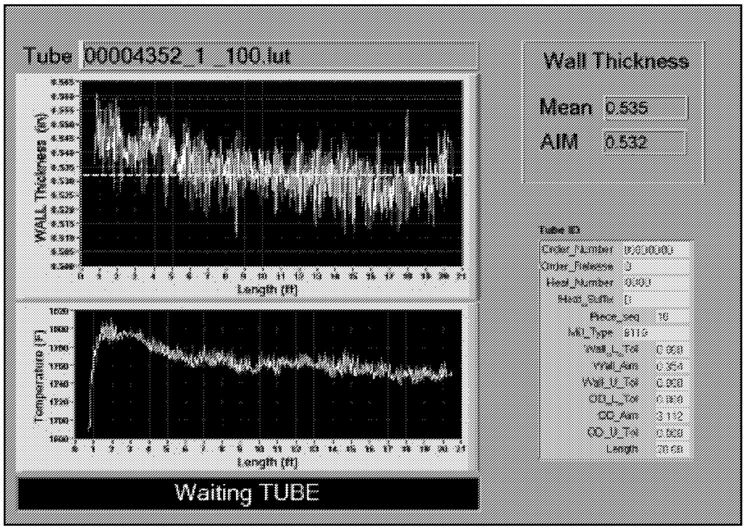


FIGURE 6. View of the inspection head located on line measuring a tube being processed



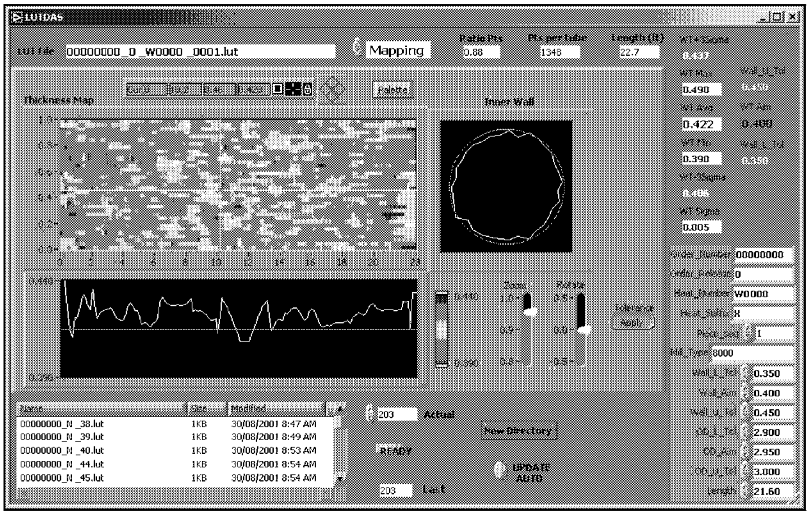
Tube 00004352_1 _100.lut

Mean 0.535

AIM 0.532

Waiting TUBE

FIGURE 7. Basic display showing the wall thickness along the tube with its calculated mean value. The horizontal lines indicate the aimed value and the tolerance. The plot below indicates the temperature along the tube.



LUT file 00000000_0 _W0000 _0001.lut

Mapping

Ratio Pts 0.88

Pts per tube 1348

Length (ft) 22.7

WT Max 0.490

WT Avg 0.422

WT Min 0.390

WT Sigma 0.005

Order_Number 00000000

Order_Release 0

Heat_Number W0000

Heat_Suffix X

Piece_Seq 1

Mill_Type 8000

Wall_L_Tol 0.350

Wall_Aim 0.400

Wall_U_Tol 0.450

OD_L_Tol 2.900

OD_Aim 2.950

OD_U_Tol 3.000

Length 21.60

Name	Size	Modified
00000000_N _38.lut	1KB	30/08/2001 8:47 AM
00000000_N _39.lut	1KB	30/08/2001 8:49 AM
00000000_N _40.lut	1KB	30/08/2001 8:53 AM
00000000_N _44.lut	1KB	30/08/2001 8:54 AM
00000000_N _45.lut	1KB	30/08/2001 8:54 AM

203 Actual

READY

203 Last

FIGURE 8. The map indicates with a color code the thickness over the whole tube surface (the surface is projected flat). The cursors select one generatrice and a cross section. The thickness plot along this generatrice is shown below and the departure from perfect concentricity through the cross section is shown on the right.

RESULTS AND PERFORMANCE OF THE SYSTEM

Accuracy of the system to gauge properly hot tubes was verified by selecting several tubes and measuring them after cooling with a conventional ultrasonic gauging system. The results obtained while hot and after tube cooling were found in very close agreement (within +/- 0.5%).

The system providing in real time wall thickness information over the whole tube length allows adjusting the mill machinery to get a product within specifications. It allows also detecting worn or defective mechanical parts elements of this machinery. We present below two examples of corrections that were made possible by the system and had avoided the production of large quantities of out-of-specifications products. The first one shows a case where high eccentricity was observed and the second one the case of a tube that was out-of-specifications except at its very ends. Without the system, using the conventional method of cutting from time-to-time tubes endings and measuring them, such defective tubes would have been unnoticed.

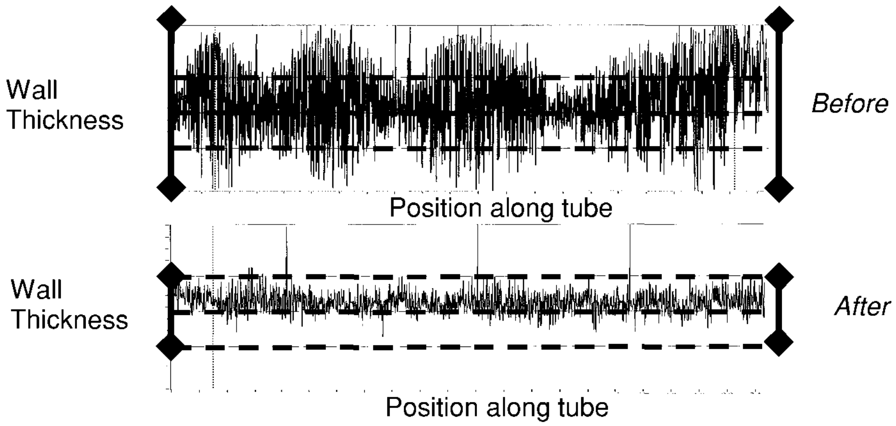


FIGURE 9. Example of a tube detected to be with high eccentricity and out-of-specifications and then, after corrective measures brought to the line, tubes are produced within specifications

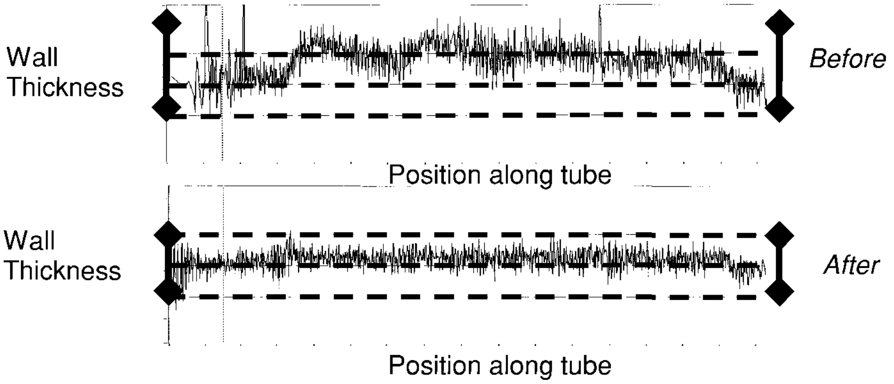


FIGURE 10. Example of a tube detected to be within specifications only at its very ends and then after corrective measures, tubes are produced within specifications all along their lengths.

CONCLUSION

We have developed and implemented a laser ultrasonic system to gauge on-line seamless tubes. This system also includes a pyrometer to measure tube temperature and a coordinate measuring system to determine the measuring locations. This system provides thickness information all along the tube length unlike the conventional technique of cutting and measuring end sections. It eliminates such a practice and contributes to increased productivity by the time saved. It allows very quickly and reliably better mill setups, thus reducing out-of-tolerance products (less scrap and rework) and troubleshooting time. With more than 100,000 tubes inspected since its March 2002 deployment, the system has demonstrated its reliability and usefulness and is leading to significant productivity increase. It will be licensed and made commercially available. Such a system, although specially designed for hot tubes thickness gauging could also be used elsewhere in the steel and metals industry, and eventually in other industries, for other testing tasks or material characterization. Depending upon the application, this may require some modifications but those will be essentially limited to the inspection head.

ACKNOWLEDGMENTS

This work was partially supported by the Department of Energy under Award No. DE-FC07-99ID 13651.

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