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Monitoring of MMCs grinding process by means of IR thermography

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Abstract

The objective of this investigation is to assess the IR thermography as a monitoring system able to detect the grinding conditions in order to test its use as an industrial tool for optimizing and control the process. To this aim an experimental investigation has been carried out in the grinding of Metal Matrix Composites (MMCs). These materials exhibit additional drawbacks with respect to conventional materials due to the abrasive nature of the reinforcement together with the softness of the matrix. The results show how the IR thermography can give a significant contribution in the definition of a strategy to control the grinding process as well as for the maintenance of the grinding machine.

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Keywords: Grinding; IR thermography; Maintenance

1. Introduction

The most concern of the grinding process is the temperature which can produce burns, structural alterations of the material and residual stresses, which can greatly affect the properties of the workpiece as well as poor dimensional accuracy [1]. The grinding process of MMCs exhibits additional difficulties with respect to conventional materials, due to the abrasive nature of the reinforcement and to the softness of the matrix which tends to obstruct the porosity

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of the wheel. This occurrence, which can appear in the very early stage of the process, produces a large increase of the temperature due to the large flat area of the wheel which slides on the workpiece. For this reason, frequent wheel dressing operations are required, which increase the time of not added value of the process.

Therefore, the optimization of wheel dressing intervals necessary to keep the best grinding conditions in order to reduce the non-productive time and avoid loss of quality is a key factor for keeping the factory competitive. Likewise, the optimization of maintenance operations of the grinding machine is also important in order to reduce the down-time.

Therefore, ideally, it would be desirable to have available a monitoring system of the process which be able to predict any imminent failure both of the process and the machine tool.

Among process parameters often monitored during the grinding process, the temperature is the most representative one, which has mainly been measured by thermocouples and pyrometers.

The first devices, still largely employed, used to measure the temperature in grinding are sacrificial thermocouples embedded inside the workpiece [2-4]. The main advantage of this method is the possibility to detect temperatures at different depths from the ground surface until the thermocouple is exposed to the surface. In particular, Li and Axinte [4] used an array of sacrificial thermocouples to validate an innovative stochastically grain-discretised temperature model (SGDTM), which predicts 3D temperature maps detailed even at the grain scale.

However, the use of thermocouples, though effective for a deeply understanding the phenomena involved in the grinding process, does not represent a practical method to keep in control the process in industrial conditions.

The first significant attempts that used thermal radiation to detect the temperature in a grinding process were made by Kops [5] and Kops and Shaw [6] using an infrared thermal camera. Such investigations permitted to evidence that the variation in sharpness and wear of the abrasive particles causes significantly change in the temperature and, in the last analysis, reduce the dimensional accuracy of the workpiece. The Authors also found that the chips propelled by the grinding wheel impinging on the ground surface provide an additional thermal input for the work piece, which can be prevented by directing opportunely the coolant at the ejection zone of the chips.

Ueda et al. [7] presented a new type of sensor, consisting of an optical fibre and an InAs cell, which permitted to measure the temperature of the single grains just after cutting. Subsequently, Ueda et al. [8] developed a two colour pyrometer with a fused fibre coupler, which allowed to measure more rapid temperature changings and found that the rate of increase of the temperature on the cutting grains coming into contact with the workpiece reaches values as high as 10^7 °C/s. Experimental tests carried out with such a sensor allowed to evidence that the temperature can reach values as high as the melting temperature of the material being machined. This result was experimentally demonstrated by Malkin [9] and, more recently, by Deahao Liu et al. [10] in the case of grinding steel.

Thermal imaging technics have not had much success as monitoring systems in grinding operations since the early thermal cameras exhibited several problems such as the need of a cooling system, non-stable output, low temperature ranges, bulky size as well as high purchase and maintenance costs.

Not to be overlooked, moreover, the operational difficulties created by the presence of the fluid which in real industrial processes shields the entire grinding zone.

In the literature, the thermography is mainly used as a means for better understanding the mechanisms of the grinding process, e.g. Anderson et al. [11] used IR thermography to validate numerical thermal models as well as model predicted thermal partition ratios. Brosse et al. [12] developed an inverse method with numerical model to predict the temperature distribution and used an IR camera to validate the results. Arrazola et al. [13] used IR thermography to measure the temperature on the rake face of the tool in orthogonal cutting and, by combining the results with numerical modelling, evidenced the different thermal behaviour of titanium alloys and steels.

On the other hand, today, thermal imaging technology is increasingly used in many industrial environments for predictive maintenance inspections, because it is fast as well as directly faced towards what is going to be wrong. Thermal images contain plenty of information regarding the process and the machinery that realizes the process itself, which is worthwhile to investigate in order to exploit fully its potentialities.

In this paper, an experimental investigation in the grinding of Metal Matrix Composites (MMCs) has been carried out in which a thermal camera has been employed to monitor the process together with a novel methodology developed to elaborate the acquired data is presented.

2. Temperature measurement with IR camera

According to the radiation laws, each body emits radiation with a wavelength which depends on its temperature.

The measurement of temperature with a thermal camera is based on the detecting of the radiance of a body, which can be calculated by the Planck's law, Eq. 1 [5]:

$$L_0 = c_1/\{\pi\lambda^5[exp(c_2/\lambda T) - 1]\} \quad (\mathrm{W\ m^{-3}\ Sr^{-1}}) \qquad (1)$$

where c_1 = 3.7418x10^{-16}(Wm^2) and c_2 = 1.4388x10^{-2}(m·K) are the first and the second radiation constants, respectively, λ(m) the radiation wavelength and T(K) the absolute temperature. Eq. 1 refers to a black body emission and therefore, for real bodies, it has to be multiplied by ε, the coefficient of emissivity, which depends on the material, the surface roughness and the temperature. Real bodies reflect part of the incident energy according to the coefficient of reflection r, so that the following relationship subsists: $\varepsilon + r = 1$. Since the radiation measured by a thermal camera includes also the reflection coming from the surrounding ambient, particular attention is required to exclude such radiation from the acquired signal. Therefore, one of the main concerns in thermography is the lacking of knowledge of the emissivity of the bodies under the observing frame, which can be different from one body to another and, in addition, it changes according to the changes of the environmental conditions.

The necessity to see physically some parts involved in the process, i.e. the workpiece and the tools, the use of an expensive equipment as well as rather cumbersome, constitute further reasons for impeding the employment of such a technique, first, for optimizing the process conditions, and later for the monitoring of the process itself.

IR thermography is particularly suited for both the above mentioned purposes since the temperature is an effect which is directly related to the intrinsic functioning of the process, i.e. the interaction between the tool and the workpiece in any manufacturing process. In particular, it could be of great help in assessing the integrity of the surface system which include the external surface of the workpiece and the subsurface layer of the material.

However, the IR thermography should not necessarily be addressed to measure the real temperature distribution of the process, rather its variation with respect to certain optimum conditions previously defined in the setup stage the process itself.

The real problem is to extract from the thermal images the proper features which could allow to evidence the characteristic functioning of the particular process under investigation. Therefore, up to now, many users have used the thermography limiting the analysis to simple and qualitative observations of the acquired thermal maps.

In order to extract the right features, the knowledge of the process is particularly important, while the subsequent task is how to elaborate such data to extract the significant features. This is not an easy task because the thermal images are invariably complex and affected by various kind of noises, without forgetting the big data volume to analyse often in short time.

3. Grinding of MMCs

Due to their high specific strength and stiffness as well as their relatively resistance to high temperatures, Metal Matrix Composites find application in several mechanical components.

Grinding process can play an important role in machining such materials for both heavy-duty machining and for finishing. However, the soft matrix is not well suited to be removed by an abrasive process, therefore when grinding such materials, the pores of the wheel rapidly undergo clogging, while the wear of the grains increases more slowly although their hardness can be of the same order of the wheel abrasive. Therefore they must be considered as difficult-to-grind materials.

The clogging of the wheel causes a high increases of friction forces which implies, as a consequence, a temperature increase on both the workpiece and the wheel. Therefore, frequent wheel dressing is required in order to maintain unchanged the grinding capability of the wheel.

Some empirical relationships for the prediction how the grinding parameters affect the forces, the specific grinding energy and surface roughness of the workpiece are reported in [14].

4. Experimental tests

The experimental tests have been carried out on a horizontal grinding machine using as a workpiece a Metal Matrix Composite (MMCs) constituted by a matrix of aluminium-silicon casting alloy reinforced with boron carbide particles. The details of the material and the grinding parameters adopted in the tests are reported in Table 1. An up-grinding condition was adopted in which the table supporting the workpiece has an intermittent traverse feed at the beginning of each working stroke.

Table 1. Material and grinding parameters.

Material
Aluminium-Silicon Alloy A360 reinforced with B_4C 5%wt, grain size F280, as cast Workpiece: rectangular plate 110 x 60 x 6 mm
Grinding parameters
Grinding wheel: 39C 60-KVS (Abrasive SiC, Grit 60, Vitrified) Wheel diameter: d_s = 200 mm Wheel peripheral speed: V_s = 22 m/s Depth of cut: a = 0,008 mm Workpiece speed : Vw = 300 mm/s Traverse feed: f_t = 3 mm/double stroke Grinding conditions: wet and dry

During tests, the temperature was monitored using a thermal camera model ThermaCAM S65 HS S65 by Flir Systems. The instrument was placed in different positions with respect to the grinding wheel in order to find the better arrangement that could permit to individuate the most significant features of the process.
In Fig. 1, two configurations of the experimental setup in which the thermal camera was placed at the right side and at the front side of the grinding machine are shown.

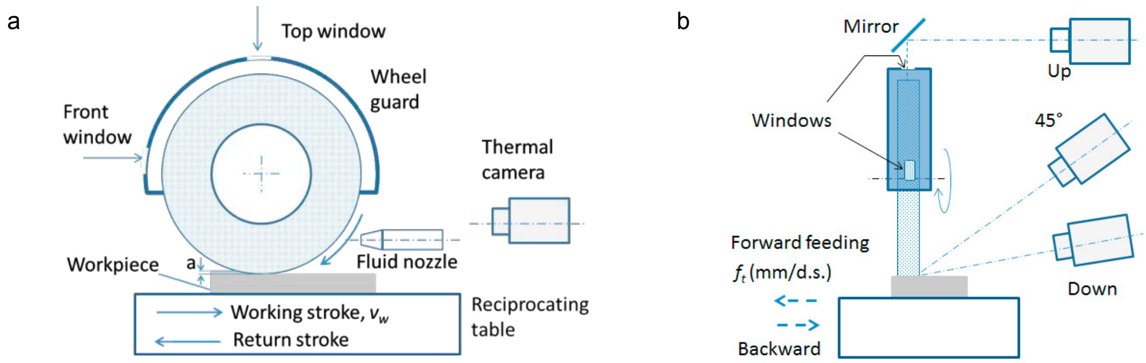

Fig. 1. Experimental setup: (a) thermal camera in right side position, (b) front position.

In the down position, the thermal camera directly looks at the grinding zone and, in particular, at the surface of the wheel approaching the workpiece, while in the up position it looks at the top surface of the grinding wheel, with respect to the grinding zone, through a mirror made of a polished aluminium sheet. In the front setup, Fig. 1b, the thermal camera can see the upper surface of the material approaching the wheel and the external side interface of the contact zone.

Further arrangements of the thermal camera, not reported in figure for the sake of space, allowed to detect the temperature of the cylindrical surface of the wheel as soon as it leaves the contact zone with the workpiece.

Both wet (water based emulsion) and dry grinding operations were carried out in order to characterize the effect of the coolant.

5. Results and discussion

Firstly, it must be pointed out that the values of temperature detected cannot be considered in absolute sense, but only comparatively, since they are affected by the error due to the emissivity, which is very different for the bodies under observation. In particular, the aluminium alloy, which constitutes the workpiece material, exhibits a low emissivity value, while the grinding wheel, which is a ceramic material having a high surface roughness, exhibits a rather high emissivity value. Therefore, in the present investigation it was decided to point the attention to characterize the behaviour of the tool. Therefore, a constant coefficient of emissivity equal to 0.9 was assumed for all tests. The results refer to an almost steady state condition of the grinding operation reached after a congruous number of passes after the beginning.

Fig. 2 shows snapshots taken at about the middle of the working stroke, when the thermal camera was in the front position.

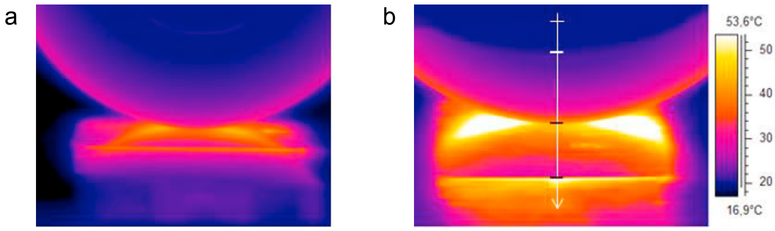

Fig. 2. Thermal images obtained with the thermal camera in front position (dry grinding): (a) down, (b) at 45°. The arrow indicates the direction of the axis taken to plot the diagram reported in Fig. 3.

As can be seen, in both cases the surface of the workpiece reflects the thermal image of the grinding wheel, much markedly in the second case, and therefore the signals coming up from the workpiece do not represent the temperature of the workpiece, but, mainly, that of the surrounding objects, in particular the grinding wheel.

A plot of the temperature signal taken along the line passing thorough the wheel axis (the arrow shown in Fig. 2b) is reported in Fig. 3, which shows what occurs as the number of grinding passes increases. In such diagram, three points are clearly evident, the first two mark the boundary of the abrasive band of the wheel, which terminates at the first peak of temperature, this latter being coincident with the interface between the tool and the workpiece.

The third peak refers to the border of the workpiece, which, however, is not representative of the temperature of the material for the aforesaid reasons concerning the emissivity.

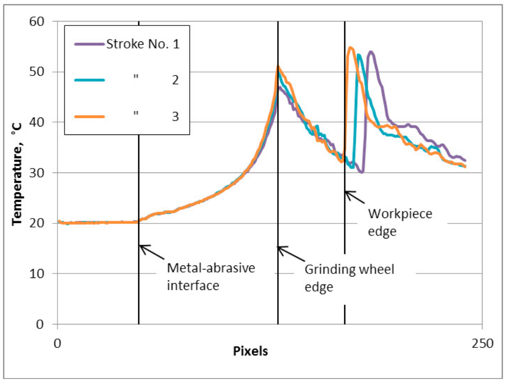

Fig. 3. Temperature trends along the direction shown in Fig. 2b, thermal camera in 45° position.

It can also be seen that the temperature at the interface increases with the number of passes, though rather slightly, due to the heat produced at each pass, which contributes to enhance the overall temperature of the wheel. The different distances of the three peaks on the right in Fig. 3, which correspond to the border of the workpiece, with respect to the peak on the left, is the result of the transverse feeding, f_t, given to the workpiece at each double stroke of the table.

An interesting trend is represented by the temperature history at the interface (peak on the left) as a function of the working stroke length (Fig. 4) which occurs when the workpiece moves from left to right, with reference to the thermal images shown in Fig. 2. In Fig. 4, the arrows evidence the increase in temperature from the beginning to the end of each stroke. By observing the diagram from left to right, the first curve in Fig. 4 refers to the down-grinding stroke, which occurs without infeed. The increase of the temperature in this case is uniquely due to the sliding of the wheel against the workpiece caused from the high springback of the material (this latter being mainly aluminium).

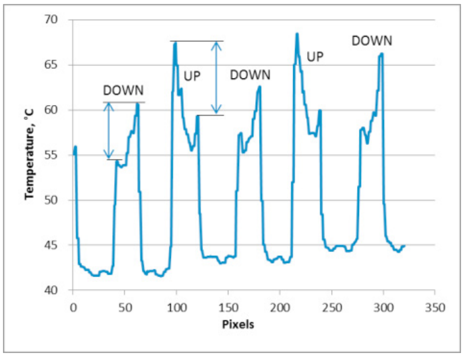

Fig. 4. Temperature trends at the interface tool - workpiece (dry conditions).

The subsequent curve which relates to the working run (up-grinding condition) is in the overall higher than the previous one. The small difference between the two curves can be justified by the fact that, after many working strokes, the wheel is quite obstructed by the soft matrix of the composite and, in addition, the low infeed value adopted (nominal value a = 0.008 mm) causes a high tool refusal, with a consequent high springback. These reasons make not much different the temperature levels between the idle run from the one in which the material removal occurs. Such trends invariably show two peaks, i.e. in the up-grinding condition the highest one occurs at the beginning of the stroke while for the down-grinding condition the highest peak occurs at the end. The presence of such peaks can be attributed to the smaller quantity of work material which is available for the heat flow both at the leading edge and at the trailing edge.

The different behaviour shown by the up and down-grinding conditions can be explained, as pointed out by Malkin and Guo [15], in terms of different energy partition to the workpiece, which deviates from a constant trend more significantly for up-grinding than for down–grinding condition. In their work, the aforesaid authors, developed a model of partition energy which predicts, in the case of down grinding, a slightly decrease at the leading edge and an increase at the trailing edge, while in the case of up-grinding the same model predicts an increase at the leading edge and a strong decrease at the trailing edge.

The trends of the curves obtained in the present investigation are coherent with such a model, though in down condition the infeed is substituted by the springback effect.

In order to characterize the effect of the fluid, the temperature at the rear side of the wheel detected in a series of passes is reported in Fig. 5. The forward feeding represents the case in which the workpiece moves, at each double stroke, towards the spindle nose, the backward feeding being the opposite. The trends plotted in Fig. 5a represent four maximum temperatures taken along the measure lines showed in Fig. 5b. Firstly, it must be underlined that all the four trends are almost perfectly superimposed. This means that the temperature of the wheel surface does not undergo appreciable reduction when it rotates for an arc of about 45°. As can be noted, the wheel exhibits higher temperatures in the forward run than in the backward one.

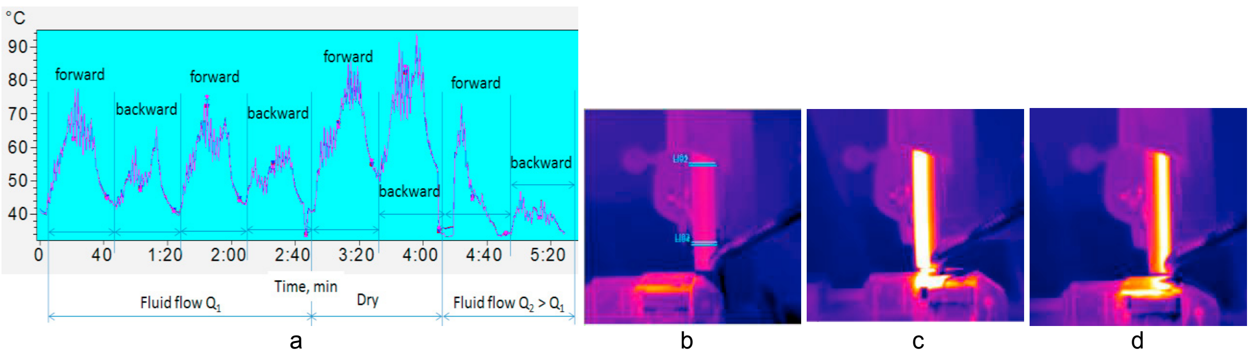

Fig. 5. Wet and dry grinding, thermal camera placed on the right side as shown in Fig. 1(a): (a) maximum temperatures along the measurement lines shown in (b); (c) and (d) snapshots taken during forward and backward passes, respectively.

This fact can be attributed to the position of the nozzle of the fluid, which determined different cooling conditions during the test and, definitely, a less efficient cooling condition during the forward pass. In fact, by observing two snapshots taken from the thermal movie, Figs. 5c, d, it is easy to understand that the fluid does not act in the same manner during the two aforesaid stages.

In Fig. 6, the trends of the maximum temperature in different positions of the wheel surface are reported in a test carried out in wet conditions. The maximum temperature is intended as the maximum value taken automatically along each line L01, L02, L03, respectively.

a b c d

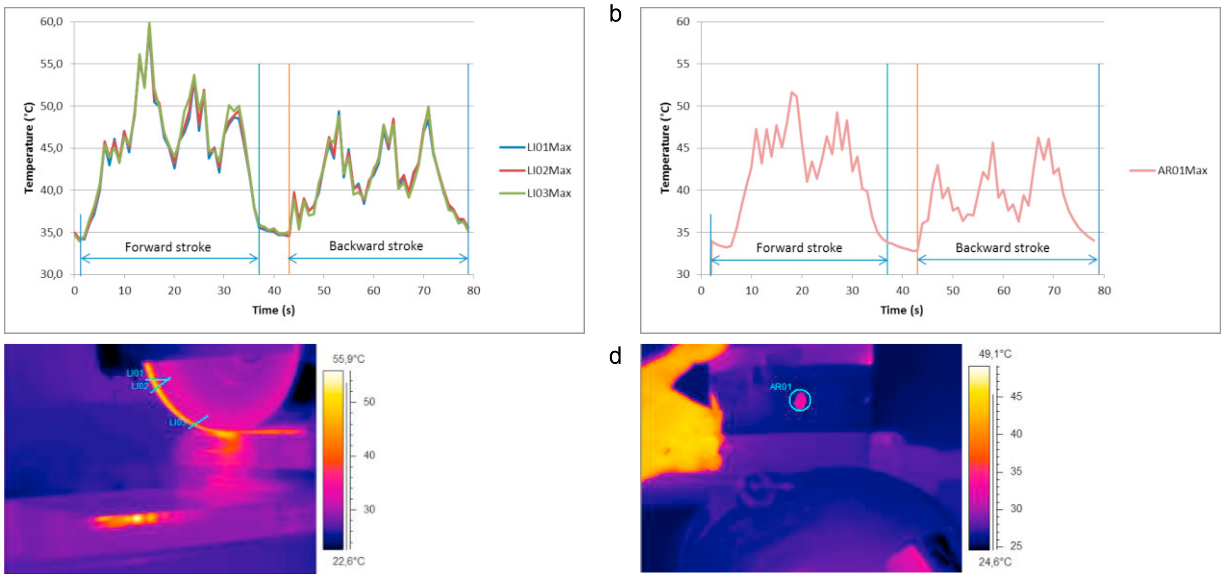

Fig. 6. Trends of the maximum surface temperature of the wheel: (a) at the exit side, along the lines L01, L02, L03, L04 shown in (c) and (b) at the top surface, i.e. half revolution after the grinding zone shown in (d), detected using a mirror as depicted in Figs. 1a,b.

The diagram on the left refers to a thermal recording taken directly at the exit side of the grinding zone, while the one on the right refers to data recorded at the top of the wheel using to this purpose a mirror of aluminium.

Also in this case, the backward stage exhibits lower temperatures for the same reasons aforesaid.

It is worth to note that the maximum values on the three different measurement lines follow closely the same trend, which means that the temperature do not vary significantly during the rotation angle (approximately in the range 30° - 40°) visible in the thermal image (c) shown below. In addition, it is possible to see that the temperature detected through the top window of the safety case of the grinding machine follows a very similar trend, though with values significantly lower. In this case, it is possible to hypothesize that this result is largely due to the losses occurred when using a not optimized mirror system.

All the previous results evidence the possibility to justify the trends of the temperature signals as well as their strict correlation with the particular situation under which they have been detected. In addition, they show a high reproducibility in spite of the measurements have been taken using standard equipment, without assuming any particular contrivance for positioning the thermal camera. In other words, to control the process using the proposed methodology in this work, it is not necessary to build in the grinding machine an expensive monitoring system of the temperature during the process.

This last point could be important in real industrial situations where the thermal camera could be used occasionally also by hands during inspections for purpose maintenance.

4. Conclusions

A monitoring system based on IR thermography has been used to characterize the grinding process, aimed to the definition of some objective criteria for keeping control of the process. The results obtained in the present investigation highlight that a proper experimental data processing can allow to recognize some characteristic features of the process when grinding MMCs. However, it is foreseeable that some results could be transferred also to anyone other ground material as well as to other machining operations.

The results of the analysis carried out on the thermal images detected during grinding, also allow to validate some theoretical hypotheses concerning the energy partition coefficient to the workpiece and the temperatures trends at the edges of the workpiece. However, for these purposes, a quantitative analysis would be advisable to perform.

The approach employed in this investigation can be used as a starting basis for the development of a system automatic process control.

It should be remarked, in addition, that a monitoring system based on the processing of thermal images taken during the grinding operation could also allow to keep control of the grinding machine, which could be very useful in view of implementation of predictive maintenance strategy.

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