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# Effect of process parameters on material removal rate during grinding of hot work steel AISI H11 under dry, wet and compressed gas environment

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***Abstract:*** *Grinding can be described as a multi-tooth metal cutting operation in which material is generally removed by shearing and ploughing in the form of micro sized chips by the abrasive grits of the grinding wheel. This paper presents an important investigation of material removal behaviour during grinding of hot work steel AISI H11 under different working environments (dry, wet cooling and compressed gas) and process parameters ( feed rate, depth of cut and wheel speed). During the experimental investigation, Aluminimum oxide grinding wheel was used to perform cutting action. It was observed that under compressed gas, increase in depth of cut and decrease in feed rate resulted in significant increase in material removal rate.*
***Keywords:*** *Environment, Depth of cut, Feed rate, Grinding, Material removal rate.*

## I. Introduction

There are several processes of manufacturing machining operations, i.e., drilling, milling, turning and grinding processes that are important for the conversion of raw materials into finished goods. Most of these processes deal with giving a new shape and form to the raw materials either by changing their state or shape. One such important process is grinding, and it is very useful technique for metal removal at fast rates and for the high level finishing of final products. Grinding is typically a finishing process where quality is important and mistakes are costly. In order to attain high quality parts and high productivity it is necessary to properly choose the correct process parameters. These parameters are usually determined through testing and experience. Grinding is a material removal and surface generation process used to shape and finish components made of metals and other materials. Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface. The grinding wheel is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the work. As these abrasive grains wear and become dull, the added resistance leads to fracture of the grains or weakening of their bond. The dull pieces break away, revealing sharp new grains that continue cutting.

Grinding has been the object of technical research for some decades now. Walton et. al.[1] have used Physical vapor deposition (PVD) coating method on low carbon steel(51CrV4) work piece with CBN grinding wheel for accurate temperature measurements even under aggressive grinding condition and environment. The obtained result shows that high pressure grinding fluid does not influence the coating performance. The temperatures estimated by the PVD-coating technique have been used to validate thermal models based on the circular arc heat source for varying specific materials removal rates. Kwak et. al.[2] presented the experimental setup to analyze effectively the grinding power and the surface roughness of the ground workpiece in the external cylindrical grinding of hardened SCM440 steel using the response surface method. The experimental results show the mathematical model. From adding simply material removal rate to the contour plot of these mathematical models, it was seen that useful grinding conditions for industrial application could be easily determined. Monici et. al. [3] have explained the concept of optimized cutting fluid application method to improve the efficiency of the process and show that combine use of neat oil and CBN wheel give better efficiency than aluminium oxide grinding wheel. Xu et. al. [4] have investigated the experimental procedure for vitreous bond silicon carbide wheel for grinding of silicon nitride. The result shows that silicon carbide grinding wheel can be used for precision form grinding of silicon nitride to achieve good surface integrity. Badger [5] has researched on the factor affecting the grindability of high speed steel(HSS) by measuring G-ratio and power consumption in surface grinding with an aluminium oxide wheel. It was found that dominant factor affecting grindability in HSS is the size of the vanadium carbides. Guo et. al. [6] have studied the effect of both wheel wear and process parameters on the grinding performance of plated CBN wheel on a nickel alloy to obtain particular model. Liu et. al. [7] have researched the stringent requirements for grinding wheels include low damage on ground surfaces, self-dressing ability, consistent performance, long wheel lives and low prices to manufacture the silicon wafers. Anderson et. al. [8] have developed a model to predict the contact temperature with using infrared data. The infrared data showed that with increasing depth of cut numerical models were more accurate than analytical model. The obtained results suggest that use of analytical contact zone thermal model should be limited to shallow grinding while numerical models are more suited to larger depth of cut and result also showed higher Peclet number in grinding results in lower overall workpiece temperature.

Atzeni [9] et. al. have developed experimental setup to test the influence of cutting speed and feed per gain on surface roughness after grinding cycle. The observed data have been statistically processed to obtain relationship between among roughness and kinematic parameters. The obtained model shows that the roughness is mainly influenced by the feed per grain and to a lesser degree by the cutting speed. Aurich [10] et. al. have found experimental investigation of dry grinding operations of hardened heat preheated steel and then obtain data compared with wet grinding operation which is taken as reference prototype. Tawakoli et.al. [11] have investigated the effect of ultrasonic vibration on dry grinding and obtained result show that the application of ultrasonic vibration can eliminate the thermal damage on workpiece, increase the G-ratio and decrease the grinding force considerably. Nguyen [12] have investigated the performance of new segmented grinding wheel system and observed that segmented grinding wheel gives better surface integrity with minimum use of coolant as compared to standard wheel.

Brinksmeier [13] et. al. have investigated elastic bonded wheels for a grind-strengthening and super finished surface in a single step. Further, to achieve a high mechanical impact and to minimize the thermal effect of grinding process require a low cutting speed and showed that if chip thickness is constant, the chip formation mechanism shifts towards micro-ploughing and thus additionally increases the specific grinding energy. Fathallah [14] et. al. have investigated for better surface integrity of AISI D2 steel by using sol-gel grinding wheel and cooling by liquid nitrogen comparatively with conditions using aluminium oxide and cooling with oil-based. Ronald [15] et. al. have studied on the influence of grinding wheel bond material on the grindability of metal matrix composites. The obtained result showed that resin bonded wheel performed better than electroplated wheel. Herman [16] et. al. have researched radial wear of super hard grinding wheels in the process of internal grinding of bearing rings. The new developed grinding wheel is designed for bonding the abrasive grains of sub microcrystalline boron nitride using a glass-ceramic bond. This grinding wheel is compared to CBN grinding wheels composed from ceramic bonding system for roughness profile on the wheel working surface and the wear resistance. Vijayender singh [17] et. al. have developed experimental setup for grinding the composite ceramic material with cryogenic coolant. The observed result showed that cryogenic coolant (ecofriendly) in grinding gives better surface quality of material.

Ramdatti [18] et. al. have applied the Taguchi techniques to obtain an optimal setting of grinding process parameters resulting in an optimal value of material removal rate and surface roughness when machining EN-8, EN-39 and cast iron. Demirci [19] et. al. have investigated the influence of nature of bond on surface edge finishing. Experimental results showed that the grinding forces vary sensitively with bond type and wheel velocity. Using diamond grain's wheel, it was found that roughness level obtained with metallic bond is lower than that obtained with resin bond. Using a resin-bonded wheel, two mechanisms of material removal were revealed according to grain's type. (i) A partial ductile regime, i.e., ductile streaks and brittle fracture, obtained with diamond grains, and (ii) a fully ductile regime obtained with SiC grains. It was found that ground surface obtained using SiC grains' wheel has a better roughness than that obtained using diamond grains wheel. Besides, SiC grains seem to lead to more marked streaks and form defects. Demir [20] et. al. investigated influences of grain size and grinding parameters on surface roughness and grinding forces. The results showed that grain size significantly affected the grinding forces and surface roughness values.

Increasing grain size and depth of cut increased the grinding forces and surface roughness values. Pil-Ho [21] et. al. have researched grinding process for surface roughness, grinding force and tool wear. It was observed that at low air temperature decrease the magnitude of grinding force and tool wear significantly, which could result in loner tool life. Mane [22] et. al. have developed experimental setup to study for surface finish enhancement of grinding process using compressed air. From developed experimental study it is observed that, the use of air helps to improve the surface finish of machined surface. Kadirgama [23] et.al. have discussed the optimization of cylindrical grinding when grinding carbon steel (AISI 1042) and effect of three variables (work speed, diameter of workpiece and depth of cut) towards surface roughness with aluminium oxide as grinding wheel. It was found that work speed is the most dominant factors on the Ra, followed by the diameter of workpiece and depth of cut respectively. Ondrej Jusko[24] has investigated that least appropriate material for grinding wheels for cutting 14109.6 bearing steel is CBN with Aluminium oxide grains; Abral and SG grinding wheels are more suitable. A comparison of the two innovative abrasive materials shows that the performance of abral is slightly superior. Deepak pal [25] et. al. applied Taguchi parametric optimization technique to study the optimization of grinding parameters for minimum surface roughness. It was observed that surface roughness decreases as material hardness increases. It also decreases with increase in speed and changing grain size from G46 to G60, but increases changed to G80. Manimaran [26] et. al. have researched the experiment on the grinding of AISI 316 stainless steel under dry, wet and cryogenic cooling with Alumina(SG) grinding wheel. It has been concluded that with increasing depth of cut under cryogenic cooling, the surface roughness was decreasing as compared to dry and wet cooling. Grinding force and grinding zone heat temperature also obtained less under cryogenic cooling mode.

## II. Experimental Procedures

The H-11 hot work steel plate blank has been heated to a temperature of $1025^0$C with half an hour soak time followed by quenching in a $500^0$C hot salt bath. It was then tempered in two cycles with maximum temperature of $450^0$C and 2 hours of soak time to obtain a final hardness of 45 HRC. Hot work AISI H11 steel have been chosen because of high hardness, excellent wear resistance, hot toughness and good thermal shock resistance properties and have wide application in die and hot-work forging, extrusion, helicopter rotor blades and shafts. The chemical composition of H11 is given in Table I.

**Table I: Chemical composition of AISI H11 steel (wt %)**

| Constituent | C | Si | Mn | P | S | Cr | Mo | V |
|---|---|---|---|---|---|---|---|---|
| Composition (In % ) | 0.35 | 0.92 | 0.4 | 0.011 | 0.026 | 5.10 | 1.30 | 0.6 |

The same Aluminimum oxide grinding wheel was used throughout the work. Its specification was "AA46/54 K5 V8" and it was manufactured by Carborundum universal limited company. The wheel dimensions were 200 x 13.31 x 75mm. The grinding experiments were conducted on AISI H11 hot work tool steel under the three different environments of dry, wet and compressed gas. In gas environment, the compressed Nitrogen gas supplied at the grinding zone at an appropriate distance of 45 mm approximately from the cutting zone. The pressure of the compressed gas delivered to the cutting zone is maintained to fix at 3 bar in all gases environmental experiments. And, in wet grinding cooling consists of 20% coolant oil in water, applied directly at the inter-face of grinding wheel–work material at 6.5l/min. For dry grinding there is no coolant is used. The work piece material, H-11 hot die steel with 304 mm × 110 mm × 24 mm size was used and the cuts were made widthwise. During the experiments, cuts were made of 110mm length.

The schematic diagram for experimental setup is shown below in figure I. A digital weighing machine was used to measure the weight of work piece before and after each cut of grinding. To investigate the parameters of grinding, In this experimental procedure 27 Nos. of experiments by combining most robust set of different four parameters each having three levels. The different sets of combinations are obtained by as per Taguchi's L27 orthogonal array from Minitab software. The combinations of parameters with different levels are given below in table II.

**Figure I: Schematic arrangement for experimental setup**

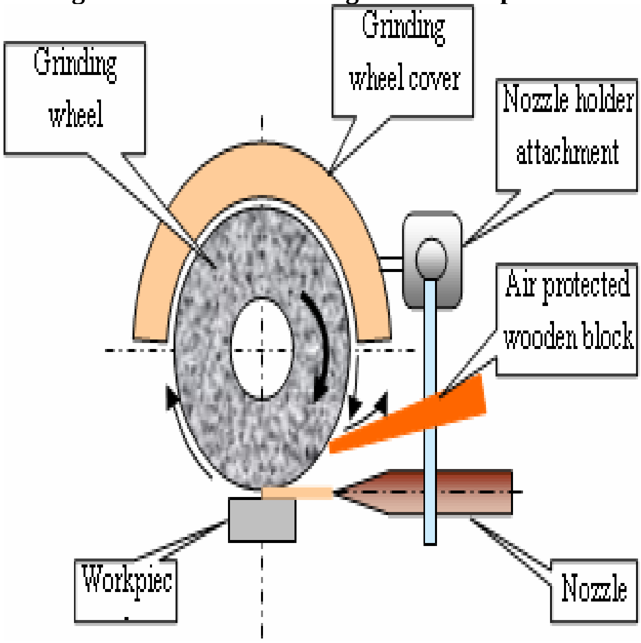


**Table II: Process parameters with their values at 3 levels.**

| Parameters designations | Process parameters | Level-1 | Level-2 | Level-3 |
|---|---|---|---|---|
| A | Environment | Dry | Wet | Gas |
| B | Wheel speed (rpm) | 1000 | 1500 | 2000 |
| C | Feed Rate (mm/min) | 5 | 10 | 15 |
| D | Depth of cut (mm) | 0.1 | 0.2 | 0.3 |

As mentioned in table III, in this experimental setup total 27 Nos. of experiments have been performed on surface grinding machine. During each experiment the various parameters and its level combination are obtained as per Taguchi's L27 orthogonal array. The various levels of parameters are combined during every experiment are shown below table III.

**Table III: No. of experiments (Taguchi $L_{27}$ ($3^4$) orthogonal array)**

| Exp. No. | A:Environment | B: Wheel speed (rpm) | C: Feed Rate (mm/min) | D: Depth of cut (mm) | MRR (gm/min) |
|---|---|---|---|---|---|
| 1 | Dry | 1000 | 5 | 0.1 | 0.059 |
| 2 | Dry | 1000 | 10 | 0.2 | 0.363 |
| 3 | Dry | 1000 | 15 | 0.3 | 0.285 |
| 4 | Dry | 1500 | 5 | 0.2 | 0.571 |
| 5 | Dry | 1500 | 10 | 0.3 | 0.273 |
| 6 | Dry | 1500 | 15 | 0.1 | 0.095 |
| 7 | Dry | 2000 | 5 | 0.3 | 0.428 |
| 8 | Dry | 2000 | 10 | 0.1 | 0.090 |
| 9 | Dry | 2000 | 15 | 0.2 | 0.143 |
| 10 | Wet | 1000 | 5 | 0.1 | 0.095 |
| 11 | Wet | 1000 | 10 | 0.2 | 0.454 |
| 12 | Wet | 1000 | 15 | 0.3 | 0.143 |
| 13 | Wet | 1500 | 5 | 0.2 | 0.182 |
| 14 | Wet | 1500 | 10 | 0.3 | 0.571 |
| 15 | Wet | 1500 | 15 | 0.1 | 0.047 |
| 16 | Wet | 2000 | 5 | 0.3 | 0.909 |
| 17 | Wet | 2000 | 10 | 0.1 | 0.238 |
| 18 | Wet | 2000 | 15 | 0.2 | 0.285 |
| 19 | Gas | 1000 | 5 | 0.1 | 0.095 |
| 20 | Gas | 1000 | 10 | 0.2 | 0.600 |
| 21 | Gas | 1000 | 15 | 0.3 | 0.272 |
| 22 | Gas | 1500 | 5 | 0.2 | 0.800 |
| 23 | Gas | 1500 | 10 | 0.3 | 0.272 |
| 24 | Gas | 1500 | 15 | 0.1 | 0.095 |
| 25 | Gas | 2000 | 5 | 0.3 | 0.800 |
| 26 | Gas | 2000 | 10 | 0.1 | 0.091 |
| 27 | Gas | 2000 | 15 | 0.2 | 0.238 |

## III. Results And Discussions

**Figure II: Main Effect Plot of S/N ratios for MRR**

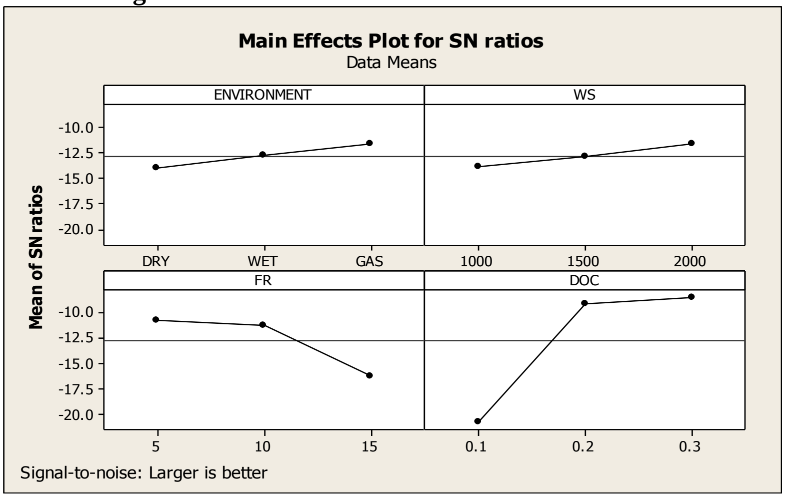
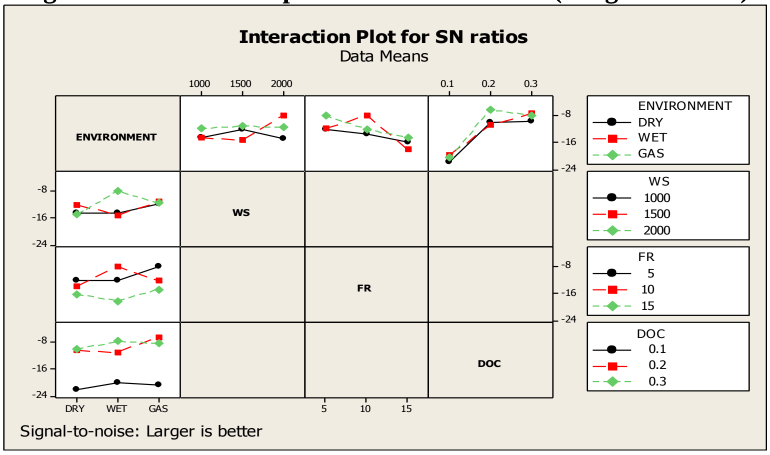


**Figure III: Interaction plot of means for MRR (Larger is better)**




The input parameters like feed rate (FR), depth of cut (DOC), wheel speed (WS) and environment of work interface zone have considerable effect on material removal rate. Table IV and Figure II demonstrate the factor effect on material removal rate. The higher signal to noise ratio, the more favorable is the effect of the input variable on the output. The graph shows that, the optimum value levels for higher material removal rate are at a feed rate 5 mm/min, depth of cut 0.3 mm and grinding wheel speed of 2000 rpm in case of compressed gas environment. From response table V for signal to noise, it can be seen that the most influencing parameter to material removal rate for AISI H11 is depth of cut (DOC) then workpiece feed rate then followed by compressed gas environment and grinding wheel speed (WS). The fig. IV(a) shows that with increase in feed rate there is decrease in MRR, fig. IV(b) shows that compressed gas environment is more significant for MRR than wet and dry environment. Fig. IV(c) and fig. IV(d) also shows that increase in wheel speed and depth of cut result in increase in material removal rate.

**Figure IV: Variations in the material removal rate with (a) Feed rate (b) Environment i.e. dry, wet cooling and compressed gas (c) Wheel speed (d) Depth of cut**

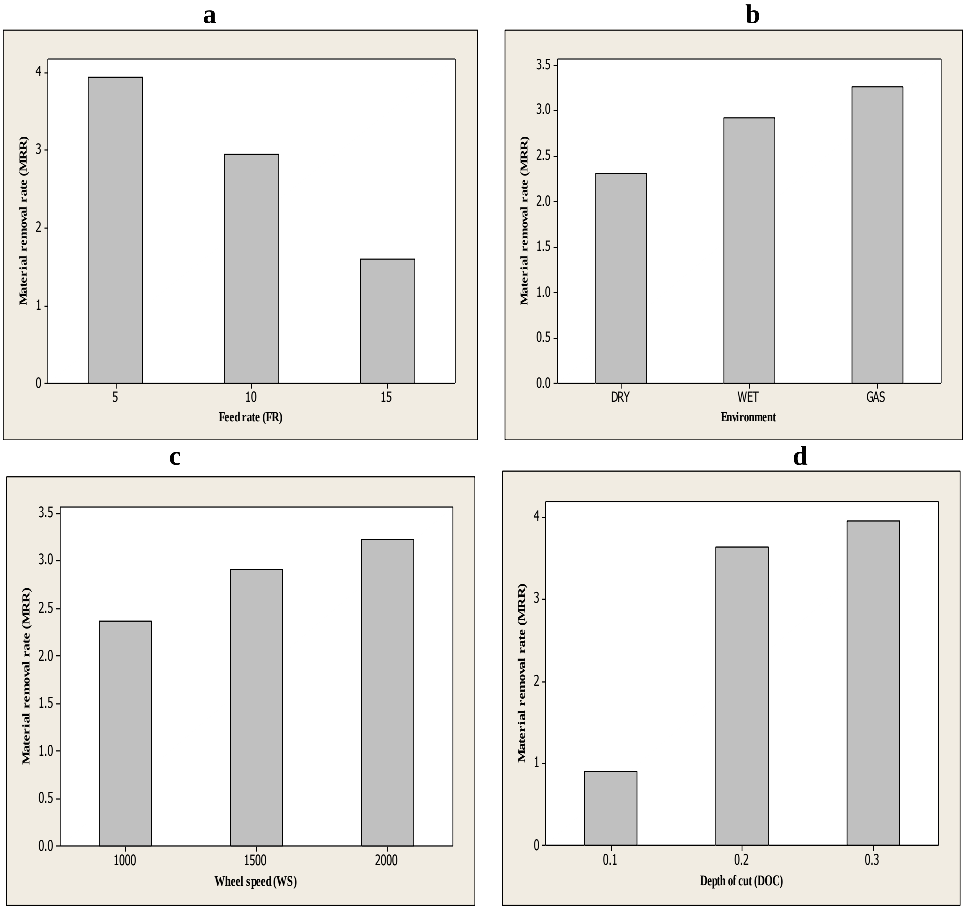


**Table IV: Analysis of variance for S/N ratios (MRR)**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P | %C |
|---|---|---|---|---|---|---|---|
| ENVIRONMENT | 2 | 24.45 | 24.45 | 12.223 | 0.58 | 0.590 | 1.75 |
| WWHEEL SPEED (WS) | 2 | 22.64 | 22.64 | 11.319 | 0.54 | 0.611 | 1.62 |
| FEED RATE (FR) | 2 | 167.11 | 167.11 | 83.555 | 3.95 | 0.080 | 11.94 |
| DEPTH OF CUT (DOC) | 2 | 862.26 | 862.26 | 431.131 | 20.38 | 0.002 | 61.60 |
| ENVIRONMENT *WS | 4 | 92.07 | 92.07 | 23.019 | 1.09 | 0.440 | 6.58 |
| ENVIRONMENT *FR | 4 | 76.21 | 76.21 | 19.052 | 0.90 | 0.518 | 5.45 |
| ENVIRONMENT *DOC | 4 | 27.95 | 27.95 | 6.988 | 0.33 | 0.848 | 1.99 |
| Residual Error | 6 | 126.92 | 126.92 | 21.153 | | | 9.07 |
| Total | 26 | 1399.61 | | | | | |

**Table V: Response Table for Signal to Noise Ratios - Larger is better (MRR)**

| Level | Environment | WS | FR | DOC |
|---|---|---|---|---|
| 1 | -14.006 | -13.853 | -10.802 | -20.792 |
| 2 | -12.736 | -12.945 | -11.306 | -9.107 |
| 3 | -11.679 | -11.623 | -16.313 | -8.522 |
| Delta | 2.338 | 2.230 | 5.511 | 12.270 |
| Rank | 3 | 4 | 2 | 1 |

Table IV presents ANOVA results for MRR. It can be seen that the depth of cut is the most important factor affecting material removal rate. Its contribution is 61.60%. The second factor influencing material removal rate (MRR) is workpiece feed rate. Its contribution is 11.94%. For the wheel conditioning i.e., environment in which wheel was used, its contribution is 1.75%. The interaction *ENVIRONMENT×WS* is most significant. Its contribution is 6.58%. The interactions *ENVIRONMENT ×FR* and *ENVIRONMENT ×DOC* are not much significant compared to interaction *ENVIRONMENT ×FR* and their contributions are 5.45% and 1.99% respectively.

## IV. Conclusion

In this paper the effect of grinding work zone environment i.e., dry, wet cooling and compressed gas and different process parameters on AISI H11 hot work steel were investigated. Experiments were carried out on the grinding of AISI H11 hot work steel with the Aluminimum oxide grinding wheel. The major conclusions from the investigation are as follows:

1. It was observed that higher material removal rate obtained under compressed gas environment than wet and dry environment, when grinding AISI H11 hot work steel under the same working parameters.
2. It was observed that depth of cut and feed rate were the most dominant factor to obtain higher MRR as compared to work zone environment condition and grinding wheel speed.

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