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A fuzzy model for predicting burns in surface grinding of steel

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Abstract

Existing analytical thermal models for predicting surface burns due to grinding have limited use because of their reliance on parameters that are not readily obtainable in practice. This paper presents a practical and consistent fuzzy rule-based model for estimating the grinding conditions at which ‘‘burn limits’’ occur. The model consists of 37 absolute and eight relative rules. It has a wide range of applications over many types of steels, Alundum wheels, and grinding conditions. It is also simple to implement, from a rule-chart mode to an intelligent on-line adaptive control mode.

Keywords: Grinding; Machining; Thermal damage; Coolant; Steel

1. Introduction

Many practicing engineers seem to be less satisfied with some of the analytical models in the literature [1]. Their concern is that these models may not be practically usable, or not in agreement with their daily experience. This situation is interesting, given the number of grinding models that cover every aspect of the process [2]; but the difference in views is understandable, because the objective of many models is to explain grinding fundamentals rather than to become a workshop user guide. Nevertheless, these models can become more practical, if the achieved understanding of the grinding mechanisms can be repackaged in a simpler form.

Take the thermal models of grinding as an example of employing a moving heat source theory [3] with various boundary conditions to estimate the temperature distribution inside the grinding zone. This distribution is then used to predict the generation of residual stresses, thin film boiling, onset of surface burns, or other surface integrity features [2,4–6]. While these models have contributed towards better understanding of the fundamentals of grinding, they require knowledge of parameters, such as energy partition, actual machine power consumption, real contact length, inter-granular spacing, or wear flat area. Many of this information are not readily known in a production environment. Moreover, thermal properties of many work-materials, coolants, or grit materials are not precisely known for the conditions prevailing in grinding [7,8]. Consequently, practicing engineers continue to rely on the experience and skills of their machine operators.

A production operation does not require an ‘‘absolute’’ model that can deliver high accuracy, because such accuracy is not reproducible in practice. What is needed, as pointed out by Shaw [9], is a ‘‘relative’’ model that can guide the user generally as to what to do and how to do. This is because there will always be a certain degree of on-shop trial-and-error, but a relative model will make a good starting point.

This paper aims to address some of these practical concerns, focusing on the prediction of work-piece surface burns, by introducing a simple fuzzy model. The main objective of the model is its practical applicability, such that a machine operator can refer to it from time to time. It should be possible for practicing engineers to use it in process planning, or as part of an intelligent model-reference adaptive controller, without the need for additional information. Moreover, the model should be easy to modify by appending further practical experience.

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2. Basis of the model design

This fuzzy model is based on the following aspects:

a. In practice, a mild degree of surface burns can be tolerated during the roughing stage, at which surface burns can be viewed as cosmetic inconvenience that will be removed later during finishing or spark-out. As long as the depth of the damage and burn layer is shallow enough to be removed during finishing, it can be tolerated for the sake of higher material removal rate.
b. There is a sharp discontinuity for all grinding variables in the presence of surface burns, e.g. the sharp increase in tool wear, forces, temperatures, and surface roughness when surface burns appear. These discontinuities can have adverse effects on the total economics of the process.
c. As noted by Malkin and Cook [10], the energy levels at which a grinding burn occurs seems to be independent of the type of steel, when ground under the same conditions. Moreover, the minimum specific grinding energy is also independent of the type of steel [11]. Surface burning seems to be a property of iron not steel. From an iron–carbon phase diagram, it can be seen that the only constant independent of alloying is the eutectoid temperature (725 °C). Therefore, surface burns can be considered to occur when the grinding temperature is higher than the eutectoid temperature, and when the duration is long enough for austenite formation to occur. This applies to annealed steels where no metallurgical changes can occur below 725 °C. As for hardened steels, tempering and partial loss of hardness can occur at temperatures as low as 150 °C, depending on the alloying elements [12]. Therefore, some degree of surface softening of pre-hardened steel seems inevitable under any grinding condition. Consequently, the definition of "controllable" damage in hardened steels is restricted to the formation of a "white layer" at the surface due to martensite reformation. This brittle layer is bound to crack under external surface loading due to lack of support by the softer layer beneath it. Accordingly, 725 °C can be considered as the principle criterion for the onset of surface damage in steels.
d. Localised melting will usually happen at the grit–work interface. The rule of thumb used by Rabinowicz [13] is that flash temperature in friction (in °C) is half the sliding speed (in cm/s). Applied to a grinding wheel (30+ m/s), this would give a flash temperature above 1500 °C, which is sufficient for melting many steels. Therefore, except for extremely slow wheel speeds (cool cut mode of grinding [14]), temperature at the rubbing zone of the grit–work interface will always be well above 725 °C. However, if such surface temperature cannot be maintained long enough, the reformed martensite layer will be so thin that it will be completely removed by subsequent grits.
e. Grinding fluids, or coolants, are often applied in grinding mainly for the following purposes:[1]

    1. To provide a hydrodynamic lubrication layer between the grit and the work-piece, thus reducing the amount of heat generated due to rubbing and friction.
    2. To provide a medium for convective heat removal from the work-piece.
    3. To provide a wheel sharpening mechanism, by removing ground debris adhering to the wheel surface. Surface burns will eventually occur under any dry grinding condition due to wheel loading.
    4. To provide a quenching medium for the newly formed surface. This is particularly important for pre-hardened steel, which cannot recover all its surface hardness under dry grinding conditions.
    5. To improve surface finish. The fluid trapped between grit and the work-piece dampens grit vibration under dynamic loads, and reduces surface roughness.
    6. To provide favourable ambient conditions, e.g. reducing surface oxidation by purging air away from the surface, or providing an erosive environment that facilitates material removal.

f. Zadeh's principle of incompatibility [15] states that "As the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics". In other words, the closer one looks at a real-world problem, the fuzzier its solution becomes. Grinding is truly a complex system, and fuzzy logic techniques may offer a good solution.

Points (a) and (b) above indicate that the optimum conditions for grinding are those near to having burns, because they yield greater removal rate without process deterioration. However, due to process variability, burn limits are often not sharp, but are fuzzy ranges. If a process is maintained within such fuzzy ranges, an optimum removal-rate can be secured without burns, or with slight burns that can be removed by spark-out. Points (c) and (d) above indicate that although we are going to

[1] It is important to note that analytical thermal models of grinding focus only on the second function, i.e. the convective heat removal, mainly due to mathematical difficulties in treating the other functions.

focus on a model for annealed carbon and alloy steels, it can be extended it to hardened steels as well.

Point (e) above emphasises the inadequacy of current analytical models due to the inherent difficulty in describing the very complex behaviour of the grinding fluid. This behaviour remains, mostly, qualitative and subjective in nature. Point (f) above raises questions about the possibility of ever achieving a precise, yet relevant, closed-form mathematical model of a very complex system like grinding.

3. Fuzzy modelling

3.1. Approach

A fuzzy model can be viewed as a rule-based expert system with the added benefits from fuzzy sets theory. This theory facilitates the interpolation between, and extrapolation beyond the existing rules. Thus, it overcomes "rule drought" which is one of the drawbacks of conventional expert systems. For example, when input values do not match exactly any of the input conditions (premises) of the existing rules, a conventional expert system may not fire any rule and may fail to provide any (consequence) output.

To overcome this drawback, we will develop a fuzzy model that will fire at least one rule for any set of input values, regardless of the completeness or precision of the values, and will work even in the absence of some of the input values, e.g. with unknown wheel grade or not fully defined coolant composition. This can be realized by disposing of numeric input values altogether and dealing primarily with linguistic values such as "very large", "large", "small", "extremely small", etc. [16]. All these features are achieved via simple mechanisms, i.e. membership functions, which are fuzzy sets.

Another drawback with classical expert systems is that they require soliciting knowledge (heuristic rules) from a human expert. In many cases, such an expert may not be available at reasonable cost, or it may be that the knowledge obtainable is of questionable quality due to personal bias or misinformation. The present grinding model is developed without resorting to a human expert.

3.2. Experiment

An extensive set of grinding tests were conducted over a wide range of conditions, and the results were fed into a system that is capable of extracting valid rules from the data.[2] All the surface grinding tests were conducted on annealed AISI 4140 steel. The reason for choosing this steel is that it contains medium (0.4%) carbon and some alloying elements such as chromium and molybdenum that enhance hardenability. Therefore, it is representative of the typical behaviour of many carbon and alloy steels so that the rules developed can be reasonably applied to many steels.

While this steel is usually supplied in hardened conditions, tests were performed on annealed samples only, for three reasons:

1. To ensure that the test results are not biased by any accumulated damage from earlier processing of the material.
2. To allow for testing over the widest possible range of grinding conditions without being obstructed by work-piece hardness.
3. To ensure that work-piece burns are indeed associated with martensite formation at temperatures above 725 °C.

For hardened steels, one may argue that burn marks are due to tempering which can occur at relatively low temperatures. In annealed steels, the only metallurgical change due to grinding is martensite formation. Thus, it leaves no doubt about the level of temperature reached for burns to occur. Further, if a temperature above 725 °C is reached with annealed steels, there is no reason why similar, if not higher, temperatures cannot be reached with hardened steels.

In the experiments, vitrified Alundum (38A) grinding wheels, supplied by Norton Company with "controlled structure," were used. Various wheel hardness grades, ranging from soft (H grade) to hard (R grade), and a wide range of grit sizes, ranging from coarse (#36) to fine (#120), were tested. This covers many of the possible combinations of wheel grades and grit sizes used in practice.

Grinding tests were performed over a range of cutting depths and work speeds. Cutting depths covered four orders of magnitude from 1 μm to 10 mm. Work speed also ranged over four orders of magnitude from 1 mm/min to 10 m/min. This wide range includes all grinding conditions from form-finish-grinding (FFG) to creep-feed-grinding (CFG). However, grinding wheels were always maintained at the maximum surface speed recommended by the manufacturer (30 m/s). Methods for extending results to lower speeds will be discussed later.

Two modes of wheel dressing were employed, both using a single-point diamond tool perpendicular to the wheel surface and cutting two passes. For coarse dressing, each pass was performed at 25 μm in-feed and 300 mm/min cross feed. For fine dressing, each pass was 5 μm in-feed and 75 mm/min cross feed. Moreover, three levels of coolant application were used: dry,

[2] A complete description of the modelling process, including membership functions, rule extraction, and the inference algorithm can be found in [16].

medium, and high. The coolant used was Castrol Syntilo 3 synthetic oil mixed with water at a nominal ratio of 1:80 by volume. The medium level coolant had a flow rate of 11 l/min, while the high rate was 33 l/min. All coolant specifications are not controllable and are time variables, e.g. due to gradual evaporation of water from the mixture.

Many variables were measured and monitored during and after the grinding tests. Only surface burns are needed for the current model. The test samples were visually inspected and any change in colour was recorded as burn. The thickness of the burn layer was sometimes very thin. In other cases, it was more than 10 mm deep. Initially, any of these colour changes was considered a burn, and indicated accordingly in a "burn-limits" chart. In the next step, the degree of severity of the burn was used to estimate a possible location of the burn limit (transition from no-burn to burns boundary). For example, with the same wheel, coolant, and dressing specifications and at a given work speed, burns may not occur at one depth of cut but occur at a higher depth of cut. The degree of severity of burns at the higher depth is used to estimate the burn limit location between those two depths.

Finally, all the points were coordinated together to establish smoother profiles over the full range of conditions. Consequently, for each combination of wheel grade, grit size, and dressing conditions, a burn-limits chart was established. A typical example of these charts is shown in Fig. 1. Each chart shows the no-burn to burn transition at various depths of cut and table speeds. The upper left corner of the chart is typical of FFG, while the lower right corner is typical of CFG. The diagonal lines are those of constant material removal rate (MRR).

Each chart is divided into four different zones. Zone (A) is an area where surface burns will not occur even in dry grinding conditions. Zone (D) is an area where surface burns will occur irrespective of the amount of coolant applied. Zone (C) is a narrow strip within which only high follow rate of coolant will prevent burns. Finally, zone (B) is an area where medium flow rate of coolant is sufficient to prevent burns. It is important to note that the sharp transition from one zone to the next is for graphic convenience only. In practice, there exists a fuzzy zone around each burn limit, in which burns may or may not occur in an unpredictable manner. This chart is typical of all the burn-limits chart obtained. The main difference among various charts is the location of the boundaries, which tend to shift to the right (less burns or higher removal rates) with coarser dressing, softer wheel grade, and finer grit size.

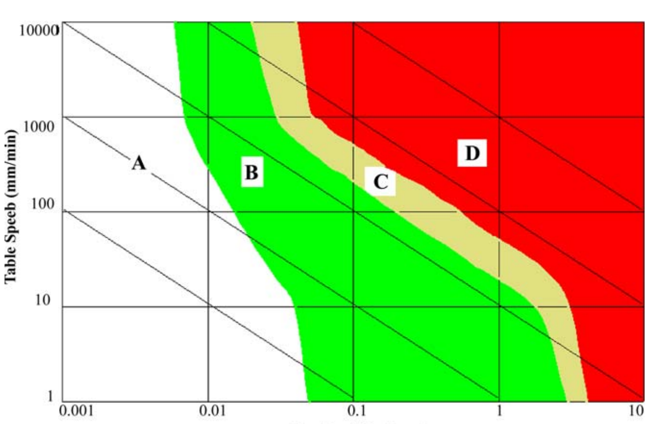

Fig. 1. Burn-limits chart for grinding with M-grade, #60 grit, vitrified Alundum wheel, and coarse dressing.

It is interesting to note that at sufficiently high MRR, burn limits become parallel to the constant MRR lines, except at the extremely high and low work speeds. Moreover, at a constant MRR, it is better to use higher work speeds (FFG) instead of larger depths of cut (CFG). This explains why CFG is not a successful proposition for grinding with Alundum wheels.[3] Finally, it can be seen that a medium level of coolant is more effective at lower work speeds than at higher speeds. This has to do with the fact that at lower speeds, the length of chip segments is longer, which makes the lubricating action of the coolant more significant.

3.3. Establishment of the fuzzy knowledge base

The burn-limits charts obtained above were fed into the fuzzy model where relevant rules were extracted. For fuzzy modelling, all numeric values are replaced with linguistic values. Dressing is already linguistic (either "fine" or "coarse"), as well as coolant application ("dry," "medium," or "high"). The other four numeric variables are fuzzified in a similar manner, by means of membership functions, Fig. 2. These membership functions help in converting numeric variables into linguistic terms. For example, a grit size #40 can be replaced with (coarse/0.5, medium/0.5). With reference to Fig. 2, this means that: while #20 grit is considered 100% coarse, and #60 grit is 100% medium, #40 grit is considered 50% coarse and 50% medium. Similarly, a 500 mm/min table speed is called (fast/0.7, medium/0.3) (note the logarithmic scale).

This transformation is very helpful in interpolating between the rules. For example, no grinding tests were actually conducted using either #40 grit or 500 mm/min table speed. A conventional expert system may not be able to match this input to any of its rules, but the fuzzy model above will respond to this input by firing

[3] The situation may be different with CBN wheels.

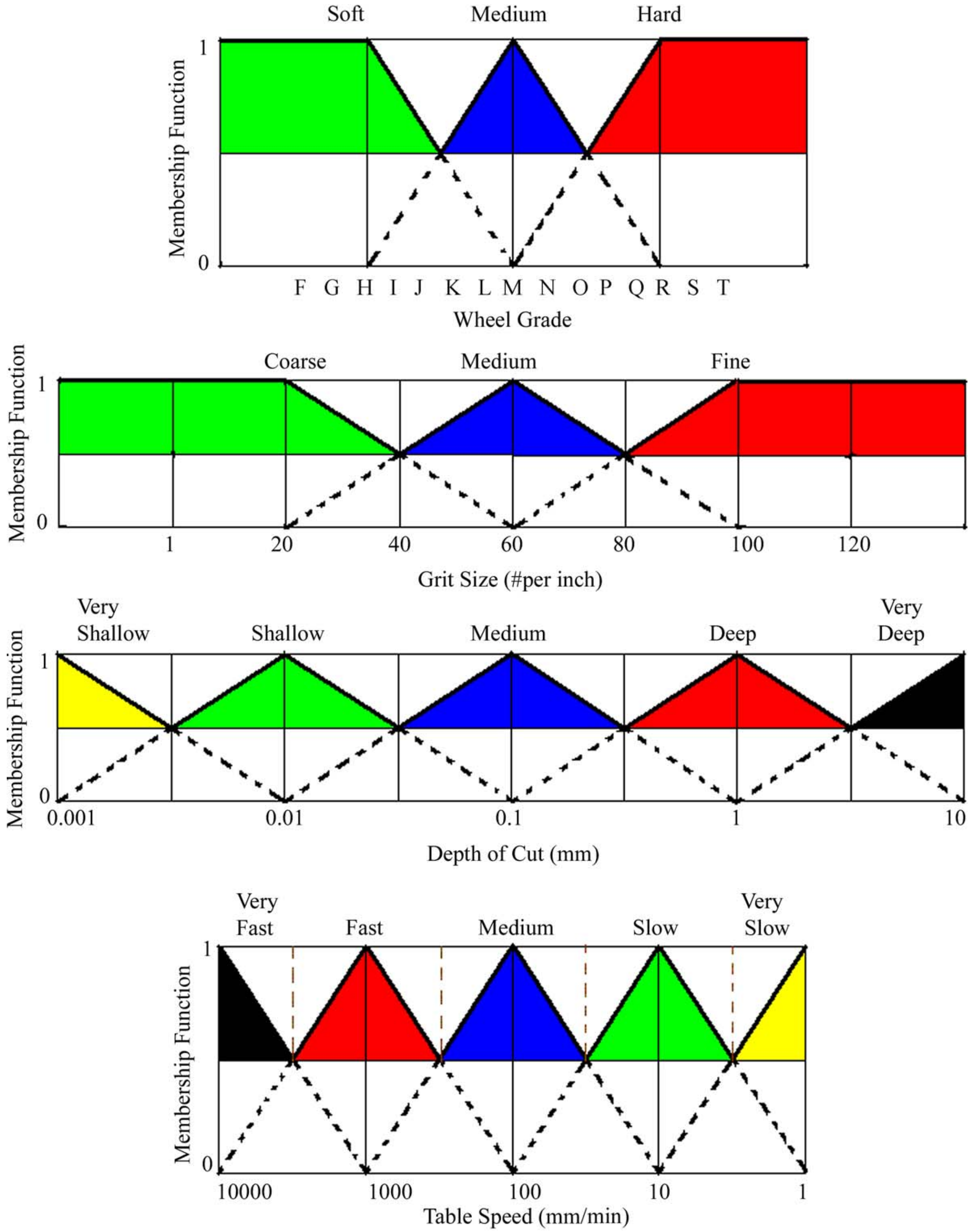

Fig. 2. Membership functions for various grinding variables.

all rules having coarse or medium grit size and fast or medium table speed. Many rules may fire, with the weight of each rule being the minimum value of all membership values of its premises.

After converting the burn-limits charts into the corresponding fuzzy rules, they resulted in 750 rules in total, of which 345 predicted no surface burns, and the rest predicted burns. Out of the 345 fuzzy rules, 196 were with coarse dressing and 149 with fine dressing, indicating that coarse dressing is better to avoid surface burns. In particular, 78 rules were with soft wheels, while hard wheels contributed only 66 rules, indicating that softer wheels are better in this respect. Fine grit wheels contributed 79 rules, while coarse grits produced only 57, implying that finer grit wheels are slightly better. Very shallow cut depth contributed 148 rules, while very deep contributed only three rules. Very slow table speed gave 89 rules, while very fast gave 46 rules. High coolant application was good, giving 147 rules, as opposed to 73 rules with dry grinding. These trends are consistent with the general perception about grinding.

The general relative fuzzy rules for avoiding surface burns in grinding are therefore as follows:

Rules (1–6). To avoid surface burns, try to use

1. coarser dressing,
2. softer wheel grade,
3. finer grit size,
4. shallower depth of cut,
5. slower table speed, or
6. as much coolant as available.

To improve the comprehensibility of the knowledge base and reduce the total number of rules, one can use the process of fuzzy rules compaction, by introducing modifiers that generalize the rules. For example, by introducing the fuzzy modifier "or more" to the fuzzy values of "coolant", the number of rules was reduced to 147. The modifier "or slower" with "table speed" reduced the number of rules to 54, which was further reduced to 52 by using "or less" for "cut depth". The "grit size" modifier "or finer" reduced the rules to 43, while "or softer" with "wheel grade" brought the total number of rules to only 37 rules, as listed in Table 1. It

Table 1
Fuzzy rules for the onset of surface burns in grinding

There will be surface burns except when:						
Dressing or coarser	Wheel grade or softer	Grit size or finer	Cut depth or less	Table speed or slower	Coolant or more	
F	S	M	S	M	D	134343
F	S	M	S	VF	M	134364
F	S	M	M	M	M	134444
F	S	M	D	S	H	134535
F	M	C	VS	M	D	143243
F	M	C	VS	VF	M	143264
F	M	C	S	F	M	143354
F	M	C	M	S	H	143435
F	M	M	S	VF	H	144365
F	M	M	M	VS	M	144424
F	M	F	S	VF	D	145363
F	M	F	M	S	M	145434
F	M	F	M	M	H	145445
F	M	F	D	S	H	145535
F	H	M	VS	VF	D	154263
F	H	M	S	F	M	154354
F	H	M	M	M	H	154445
C	S	M	VS	VF	D	634263
C	S	M	S	F	D	634353
C	S	M	S	VF	M	634364
C	S	M	M	F	H	634455
C	S	M	D	M	H	634545
C	M	C	VS	VF	D	643263
C	M	C	S	VS	D	643323
C	M	C	S	VF	M	643364
C	M	C	M	M	M	643444
C	M	C	D	S	H	643535
C	M	M	S	M	D	644343
C	M	M	D	S	M	644534
C	M	F	S	F	D	645353
C	M	F	M	F	H	645455
C	M	F	D	M	H	645545
C	M	F	VD	VS	H	645625
C	H	M	S	VF	D	654363
C	H	M	M	M	M	654444
C	H	M	D	VS	M	654524
C	H	M	D	S	H	654535

is important to note that these 37 rules contain all the knowledge; meaning that all of the 750 rules (hence, all the burn-limits charts and the experimental work behind them) can be reconstructed from these 37 rules.

For programming reasons, each rule is also assigned a six digits number so that they can be sorted numerically to simplify referencing. For example, consider rule number 154445 which reads as: “If dressing is fine or coarser and wheel grade is hard or softer and grit size is medium or finer and cut depth is medium or less and table speed is medium or slower and coolant is high or more, then there will be no surface burns”.

4. Application and discussion

The best way to demonstrate the practical utility of the fuzzy model developed above is by means of worked examples. Two examples will be presented below. The first is straightforward, aiming at explaining how to use the model. The second is more complex, demonstrating the interpolating abilities of the model.

4.1. Example 1

Consider a grinding wheel with grade R and grit size #100. The wheel depth of cut is 0.1 mm and table speed is 100 mm/min. A good surface finish is required, so some kind of fine dressing will be employed. What is the minimum amount of coolant that needs to be applied to avoid burning the surface?

To answer this question, the model developed above converts the inputs into fuzzy language. In this particular case, this is (dressing: fine/1.0; wheel grade: hard/1.0; grit size: fine/1.0; cut depth: medium/1.0; table speed: medium/1.0). In a compact form, this situation can be written as (F-H-F-M-M-?). Based on dressing (F), all of the top 17 rules, in Table 1, apply. Based on wheel grade (H), only three rules out of these 17 still hold (Rules 154263, 154354, and 154445). Based on depth of cut (M), the first two rules do not hold and rule 154445 (F-H-M-M-M-H) is the only one in the knowledge base that includes (F-H-F-M-M-?) as a special case. It states that using at least high coolant and medium grit size (or finer) can avoid burns. Since the given situation uses *finer* grit, it will be safe to perform this process using high volume of coolant flow.

4.2. Example 2

A wheel of grade J with grit size #36 is coarse dressed and used to grind a 10 μm depth of cut at 1 m/min table speed, without using coolant. Will these conditions burn the work-piece?

To answer this question, the model first turns the inputs into fuzzy language. This would be: (dressing: coarse/1.0; wheel grade: medium/0.25, soft/0.75; grit size: medium/0.4, coarse/0.6; cut depth: shallow/1.0; table speed: fast/1.0; coolant: dry/1.0). This is then decomposed into four cases, with the weight of every case equalling the minimum of the weights of its premises:

1. (C-M-M-S-F-D) with weight 0.25
2. (C-M-C-S-F-D) with weight 0.25
3. (C-S-M-S-F-D) with weight 0.4
4. (C-S-C-S-F-D) with weight 0.6

With reference to the rules in Table 1, it can be seen that cases 2 and 4 do not match any of the rules, and therefore have zero weight. Case 1 is included in rule 654363 and predicts no burns with 25% confidence. Case 3 is included in two rules, 634353 and 654363, and predicts no burns with 40% confidence. However, the credibility of this case is enhanced by the fact that it matched two rules not just one. Therefore, the weighted average of all these cases becomes $(0.25 + 0.0 + 2 \times 0.40 + 0.0)/5 = 0.21$. Hence, based on the fuzzy rules, when grinding at the above conditions, there is only a 21% chance that burns will not occur. This means that it is more likely that work-piece burns will occur, if ground at these conditions.

4.3. Discussion

Note that a fuzzy model gives a conclusion within degrees of possibility or confidence. While the model predicted, in the previous example, that surface burns are the more likely outcome, it left the door open for a less likely situation where no burns occur. Some users may perform grinding tests at these nominal conditions and realize no burns, while others may realize burns. When many diverse groups, however, perform the same test, groups that realize burns are likely to be more than those who do not. This apparent discrepancy has to do with the fact that the numerical values for grinding conditions, given in the above examples, are only nominal values. For example, wheels having the same grade and same grit size, but supplied by different manufacturers, may behave slightly different. Similarly, coolant behaviour is not reproducible among various laboratories. Further, the effect of other variables, such as different machine manufacturers, can also have an effect on the actual outcome of a grinding experiment.

4.4. Model extension and limitation

From the above discussion, it can be seen that some grinding experiments may yield results in contradictions with the rules proposed by the model. This mainly suggests that the grinding environment is different from the grinding workshop at which these rules were obtained. Therefore, to be able to use these rules effectively, the model needs calibration for each particular grinding workshop. This calibration can be done by performing a small number of experiments in the new grinding environment. The rules in Table 1 are held constant, while adjusting the membership functions, Fig. 2, to yield better predictions. In other words, the rules of the model are absolute, while membership function definitions will vary from one grinding workshop to another. Given the general improvements in quality control, differences among various grinding environments will continue to decline. Therefore, membership function fine-tuning should be easy. To help in the fine-tuning process, the relative fuzzy rules (1–6) can be used, thus providing a relative sense of direction, and helping in identifying ways to adjust the membership functions (e.g. shift them left or right). Calibrating the model to match a given grinding environment may require only a handful of short experiments.

A limitation of the model developed in this study is that it does not consider the effect of wheel speed. From the point of view of surface finish, the higher the wheel speed the better the finish. Therefore, all tests were performed at the highest wheel speed allowable by the wheel manufacturer. However, when the wheel speed varies, one may expect to have the following effects:

1. At a lower wheel speed, there are less centrifugal forces acting on the grits. Therefore, a wheel appears to be softer than the specification of its grade. Softer wheels cause less burns, and slower wheels cause less burns. Therefore, if grinding at wheel speeds less than 30 m/s, it is often satisfactory to substitute in the model a wheel grade that is one or two grades less than the *actual* wheel grade, as given by the wheel manufacturer.

   Rule 7. If wheel speed is lower than 30 m/s, then pretend that wheel grade is one or two grades less than it actually is.

2. The other way of handling the effect of wheel speed is to realize that all grinding quantities are dependent on the speed ratio. That is, the ratio of wheel speed to work speed is as important as the absolute value of each. This helps extending the present model to any wheel speed, as long as speed ratio is kept the same. For example, grinding with table speed 1 m/min and wheel speed 20 m/s will have the same speed ratio as that with table speed 1.5 m/min and wheel speed 30 m/s. Therefore, the later condition should yield similar results to the earlier, and can by used to predict surface burn.

   Rule 8. If wheel speed is not 30 m/s, then use equivalent table speed such as to maintain the same speed ratio.

   These two relative fuzzy rules, (7) and (8), seem to resolve the issues relating to the wheel speed, without conducting further experiments at various wheel speeds.

5. Conclusions

This paper developed a fuzzy model consisting of 37 absolute rules and eight relative rules for the prediction of the onset of grinding burns over a wide range of surface grinding conditions. The method to calibrate and extend the model was also discussed. The model appeals to the practicing engineer who would like to get quick answers for on-line intelligent control and/or optimisation. In its current state, the model is limited to annealed steels.

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