Decision Science Letters 5 (2016) 31–44

Contents lists available at GrowingScience

Decision Science Letters

homepage: www.GrowingScience.com/dsl

A study on the machinability of some metal alloys using grey TOPSIS method

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C H R O N I C L E

Article history:
Received June 25, 2015
Received in revised format:
September 2, 2015
Accepted September 4, 2015
Available online
September 5 2015

Keywords:
Machinability
Alloys
Aluminium
Copper
Alloy steel
Grey theory
TOPSIS

A B S T R A C T

The machinability of a material can be defined as the ease with which it can be machined. Materials with good machinability property require less power to cut, can be cut quickly, and easily obtain a good finish without wearing the tooling much. Therefore, to manufacture components economically, production engineers are challenged to discover ways to determine machinability of materials which mainly depends on their mechanical properties, as well as on other cutting conditions. In this paper, the machinability characteristics of alloys of three materials, i.e. aluminium, copper and steel are studied applying grey TOPSIS (technique for order preference by similarity to ideal solution) method. For each case, eight different alloys are considered whose machinability is evaluated based on different mechanical properties which are expressed in grey numbers. Using the adopted methodology, it now becomes easier for the manufacturers to select a particular alloy that can be easily machined. It is observed that A357RC, CuCr1Zr and AISI 5140 are the best machinable aluminium, copper and steel alloys, respectively. It is also found that the ranking performance of grey TOPSIS method remains unaffected with the variation in greyness of the considered mechanical property values.

1. Introduction

The machinability of a material can be defined as the ease with which it can be cut (machined) by a tool permitting material removal with a satisfactory finish at the lowest possible cost. Materials with good machinability require less power to cut, can be cut quickly, and easily obtain a good finish without wearing the tooling much. Practically, no two materials subject to machining can behave alike when cutting them with the same tool, at the same cutting speed and feed rate, using the same machine and working under similar conditions. Some may produce long curly chips (like mild steel), some may produce short chips (like cast iron), some may get a smooth finish, some may end up with a rough surface, some may produce chatter, and some may produce lots of heat and quickly blunt the tool. The machinability is not a specific property of a material, but a mode of its behavior during cutting, and assessments of machinability should, therefore, specify the general conditions of cutting. Machinability

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doi: 10.5267/j.dsl.2015.9.002

is related to all aspects of a manufacturing process, such as product design, quality control, and especially, process planning and machining operations. Thus, it is an important consideration for engineers in materials selection, and also is the base of selecting cutting tools and optimizing the machining parameters. The machinability aspect is of considerable interest to the production engineers to study the machinability of a work material in advance so that the processing can be planned efficiently. Machinability of a material is one of the prime metal cutting parameters that has influence in selecting several other cutting parameters.

A number of variables, like inherent properties or characteristics of work materials, tool geometry, cutting tool material, nature of tool engagement with the workpiece, cutting conditions, cutting fluid, type of cutting, and machine tool rigidity and its capacity greatly influence machinability of materials. Other dependent process variables, such as tool life, specific power consumption, cutting forces, achievable surface finish, dimensional accuracy, temperature generated, noise, vibration and chip characteristics are also directly related to machinability (Rao, 2006). Depending on the technical and economic needs of a machining process, some criteria may have primary or secondary roles in machinability evaluation. It is observed that addition of a certain proportion of an alloying material in the base metal can significantly improve its machinability characteristics. Like, in iron and steel, presence of sulphur (up to 0.35%) helps in breaking of chips while improving machinability. An alloy may be described as a metal with more than one element, the other elements are being added to enhance the base metal's properties to suit a particular application. In order to fulfill the continuous use of various alloys in diverse field of engineering, it becomes quite important to study their machinability characteristics so as to guide the production engineers in selecting the proper cutting conditions and the related parameters. Taking a typical free cutting steel (AISI B1112, a steel with a chemical composition C 0.08-0.13%, Mn 0.60-0.90%, P 0.09-0.13% and S 0.16-0.23%, and having a hardness of 160 BHN) as a reference material and allocating a machinability rating (also referred as machinability index) of 100 to it, the machinability ratings can be allocated to other materials (Mills, 1983).

With the increasing number of new materials available in the market every year, the manufacturers are facing great difficulties in selecting the most appropriate material for their products. Thus, there is always an ardent need to adopt a simple systematic methodology for efficient and effective evaluation of machinability of various work materials. In this paper, a multi-criteria decision-making (MCDM) tool in the form of grey TOPSIS (technique for order preference by similarity to ideal solution) method is applied to study the machinability characteristics of three types of alloys, i.e. aluminium alloys, copper alloys and alloy steels. Various important mechanical properties of those alloys are taken into consideration while identifying the best machinable alloys from the list of candidate alternatives. As it is often difficult to express the mechanical properties of the considered alloys using single numbers, they are expressed in terms of grey numbers. The TOPSIS method, being an easily comprehensible MCDM technique and having a strong mathematical background, is also quite suitable to this type of evaluation and selection problem. The grey TOPSIS method thus helps the engineers to evaluate the machinability charactertics of the considered metal alloys for a given machining application and selection of a proper alloy to strengthen the present work material selection procedure.

2. Literature review

Enache et al. (1995) presented a new mathematical model using some of the evaluation criteria influencing a material's machinability property with the determination of partial and global machinability indices. Kim et al. (2002) developed a cutting speed optimization program to study and enhance the machining precision and tool life in high speed machining operation using ball end mill. The machining precision and tool life were compared in free surface machining conducted by general cutting method and the technique of optimal cutting speed. Rao and Gandhi (2002) developed a methodology to determine the machinability of work materials for a specific machining operation using digraph and matrix approaches. Boubekri et al. (2003) proposed a methodology for machinability evaluation of steels while directly using the cutting force and surface roughness data, along with the subsequent development of an aggregate machinability indicator. Manna and Bhattacharayya (2003) presented the results of an experimental investigation on the machinability study of silicon carbide particulate aluminium metal matrix composite (Al/SiC-MMC) during turning using fixed rhombic tools. It was claimed that the research findings would provide useful machining solution by utilizing fixed rhombic tooling during processing of Al/SiC-MMC.

Rech et al. (2004) developed a novel approach to compare the machinability of three mold steels during rough milling. Davim and Reis (2004) studied the influences of various cutting parameters, like cutting velocity, feed rate etc. on power, specific cutting pressure, surface roughness and International dimensional precision in polyetheretherketone (PEEK) reinforced with 30% of glass fibre (PEEK GF30) material. Davim and Mata (2005) studied the machinability in turning processes of fiber reinforced plastics using polycrystalline diamond cutting tools. Orthogonal arrays and analysis of variance were employed to investigate the influence of cutting parameters on specific cutting pressure and surface roughness. Stoić et al. (2005) tested the machinability of hard materials in high speed turning process and also investigated the influence of cutting parameters on machinability rates.

Šalak et al. (2006) studied the machinability of powder metallurgy (PM) steels using different methods for various cutting processes. It was shown that face turning test method was simple and could fulfill some of the major requirements while assessing the machinability of PM steels in turning. Şeker and Hasirci (2006) presented the results of machining tests as conducted to study the effect of microstructure and mechanical properties of austempered ductile irons on cutting forces and surface roughness. Rao (2006) presented a systematical procedure to evaluate the machinability of work materials for a given machining operation. Davim and Figueira (2007) employed orthogonal array and analysis of variance to study the machinability property of cold work tool steel. Morehead et al. (2007) investigated the machinability of equal channel angular extrusion (ECAE)-processed pure copper using both tungsten carbide and polycrystalline diamond cutting tools to facilitate broader applications of ECAE-processed ultrafine-grained copper.

Hoseiny et al. (2012) compared machinability of some of the most popular grades of pre-hardened plastic mold steel in two milling and two drilling operations. Sridharan and Muthukrishnan (2013) presented a comparison of machinability of jute fiber reinforced composites prepared using untreated and alkali treated fiber. Xu et al. (2013) developed a polar diagram method for describing and evaluating the potential machinability properties of different workpiece materials. Lobato et al. (2014) applied bio-inspired optimization methods to study the machinability of stainless steel AISI 420 while considering tool life and cutting force in terms of cutting speed, feed per tooth and axial depth of cut in an end milling process. Sameer Kumar and Suman (2014) selected magnesium alloy materials for use in automotive wheel applications using MCDM methods. Wang et al. (2014) proposed a new method to evaluate the machinability of difficult-to-cut materials and then evaluated the machinability of four kinds of superalloys.

3. Grey TOPSIS method

Grey number has been originated from the concept of grey theory (Deng, 1982; 1989) which can suitably consider insufficient and incomplete information. Grey theory is a popular method used to study behavior of mathematical systems having uncertain information. It is observed that information derived from real world is always uncertain or incomplete. Hence, extension of the applications of grey numbers from white numbers (crisp values) is often necessary for real world applications. The grey number is a number with uncertain/incomplete information. In grey theory, if the system information is fully known, the system is called a white system. On the other hand, if the information is not known at all, it is a black system. A system with partially known information is called a grey system. The advantage of grey theory over fuzzy theory is that it can consider condition of fuzziness, which simply states that it can deal flexibly with fuzzy situation. Thus, white number, grey number and black number are the three classifications to differentiate the level of uncertainty in information (Li et al., 2007; Lin et al., 2008; Zavadskas et al., 2009).

Let $\otimes G=[\underline{G},\overline{G}]=\{G \mid \underline{G}\le G\le \overline{G}, \underline{G} \text{ and } \overline{G}\in R\}$. Then, $\otimes G$ which contains two real numbers $\underline{G}$ (the lower limit of $\otimes G$) and $\overline{G}$ (the upper limit of $\otimes G$) is defined as below:

a) If $\underline{G}\to -\infty$ and $\overline{G}\to\infty$, then $\otimes G$ is called the black number which means without any meaningful information.
b) Else if $\underline{G}=\overline{G}$, then $\otimes G$ is called the white number which means with complete information.
c) Otherwise, $\otimes G=[\underline{G},\overline{G}]$; $\otimes G$ is called the grey number with insufficient and uncertain information.

Let there are two sets of grey numbers denoted by $\otimes G_1=[\underline{G}_1,\overline{G}_1]$ and $\otimes G_2=[\underline{G}_2,\overline{G}_2]$. The basic mathematical operations of these two sets of grey numbers can be given as follows (Turskis & Zavadskas, 2010):

$$\otimes G_1+\otimes G_2=[\underline{G}_1+\underline{G}_2,\overline{G}_1+\overline{G}_2] \tag{1}$$

$$\otimes G_1-\otimes G_2=[\underline{G}_1-\underline{G}_2,\overline{G}_1-\overline{G}_2] \tag{2}$$

$$\otimes G_1\times\otimes G_2=[\min(\underline{G}_1\underline{G}_2,\underline{G}_1\overline{G}_2,\overline{G}_1\underline{G}_2,\overline{G}_1\overline{G}_2),\max(\underline{G}_1\underline{G}_2,\underline{G}_1\overline{G}_2,\overline{G}_1\underline{G}_2,\overline{G}_1\overline{G}_2)] \tag{3}$$

$$\otimes G_1\div\otimes G_2=[\underline{G}_1,\overline{G}_1]\times\left[\frac{1}{\underline{G}_2},\frac{1}{\overline{G}_2}\right] \tag{4}$$

In this paper, TOPSIS method is applied to study the machinability characteristics of some of the alloys of three metals where different mechanical properties (criteria) of the alloys are expressed in grey numbers. This method is also quite suitable for solving group decision-making problems in an uncertain environment. The procedural steps of grey TOPSIS method are demonstrated as follows (Jadidi et al. 2008; Zolfani & Antucheviciene, 2012; Sadeghi et al. 2013):

Step 1: Develop the grey decision matrix.

$$D=\begin{bmatrix}\otimes G_{11} & \otimes G_{12} & \dots & \otimes G_{1n}\\ \otimes G_{21} & \otimes G_{22} & \dots & \otimes G_{2n}\\ \dots & \dots & \dots & \dots\\ \otimes G_{m1} & \otimes G_{m2} & \dots & \otimes G_{mn}\end{bmatrix} \tag{5}$$

where $\otimes G_{ij}$ is the performance of i^{th} alternative with respect to j^{th} criterion expressed in grey numbers.

Step 2: Normalize the grey decision matrix.

$$D^*=\begin{bmatrix}\otimes G^*_{11} & \otimes G^*_{12} & \dots & \otimes G^*_{1n}\\ \otimes G^*_{21} & \otimes G^*_{22} & \dots & \otimes G^*_{2n}\\ \dots & \dots & \dots & \dots\\ \otimes G^*_{m1} & \otimes G^*_{m2} & \dots & \otimes G^*_{mn}\end{bmatrix} \tag{6}$$

where $\otimes G^*_{ij}=\left(\dfrac{\underline{G}_{ij}}{\frac{1}{2}\left[\sum_{i=1}^{m}\overline{G}_{ij}+\sum_{i=1}^{m}\underline{G}_{ij}\right]},\dfrac{\overline{G}_{ij}}{\frac{1}{2}\left[\sum_{i=1}^{m}\overline{G}_{ij}+\sum_{i=1}^{m}\underline{G}_{ij}\right]}\right)$

Step 3: Determine the criteria weights.

In a group decision-making environment, say, there are k persons and the weight of j^{th} criterion can be calculated using the following equation:

$$\otimes w_j = (\otimes w_{1j}^{p_1} . \otimes w_{2j}^{p_2} .... \otimes w_{lj}^{p_l})^{\frac{1}{\sum p_l}} \tag{7}$$

where $\otimes w_{lj}^{p_k}$ (j = 1,2,…,n) is the weight which the l^{th} decision maker (l = 1,2,…,k) assigns to j^{th} criterion and is described by grey number $\otimes w_{lj} = [\underline{w}_{lj}, \overline{w}_{lj}]$.

Step 4: Develop the weighted normalized grey decision matrix

$$V = \begin{bmatrix} \otimes V_{11} & \otimes V_{12} & \cdots & \otimes V_{1n} \\ \otimes V_{21} & \otimes V_{22} & \cdots & \otimes V_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \otimes V_{m1} & \otimes V_{m2} & \cdots & \otimes V_{mn} \end{bmatrix} \tag{8}$$

where $\otimes V_{ij} = \otimes G_{ij}^{*} \times \otimes w_j$.

Step 5: Determine the positive and the negative ideal solutions.

For m possible alternatives set A = $\{A_1, A_2, \ldots, A_m\}$, the positive ideal solution $A^{\max}$ = $\{\otimes G_1^{\max}, \otimes G_2^{\max}, ..., \otimes G_n^{\max}\}$ can be obtained as below:

$$A^{\max} = \left\{ \left[\max \underline{V}_{i1}, \max \overline{V}_{i1}\right], \left[\max \underline{V}_{i2}, \max \overline{V}_{i2}\right], ..., \left[\max \underline{V}_{in}, \max \overline{V}_{in}\right] \right\} \; (1 \le i \le m) \tag{9}$$

On the other hand, the negative solution $A^{\min} = \{\otimes G_1^{\min}, \otimes G_2^{\min}, ..., \otimes G_n^{\min}\}$ can be derived as follows:

$$A^{\min} = \left\{ \left[\min \underline{V}_{i1}, \min \overline{V}_{i1}\right], \left[\min \underline{V}_{i2}, \min \overline{V}_{i2}\right], ..., \left[\min \underline{V}_{in}, \min \overline{V}_{in}\right] \right\} \; (1 \le i \le m) \tag{10}$$

Step 6: Calculate the separation distances from the positive ideal and the negative ideal solutions.

The separation distance from the positive ideal solution is computed as follows:

$$S_{ij}^{\max} = (\overline{V}_{ij} - \overline{A}_{\max})^2 + (\underline{V}_{ij} - \underline{A}_{\max})^2 \tag{11}$$

The separation distance from the negative ideal solution is calculated as below:

$$S_{ij}^{\min} = (\overline{V}_{ij} - \overline{A}_{\min})^2 + (\underline{V}_{ij} - \underline{A}_{\min})^2 \tag{12}$$

Step 7: Compute $T^{\max}$ and $T^{\min}$ values.

$$T^{\max} = \sum_{j=1}^{n} S_{ij}^{\max} \tag{13}$$

$$T^{\min} = \sum_{j=1}^{n} S_{ij}^{\min} \tag{14}$$

Step 8: Calculate the separation measures (D^+ and D^-).

$$D^{+} = \sqrt{\frac{T^{\max}}{2}} \quad \text{for } 1 \le i \le m \tag{15}$$

$$D^{-} = \sqrt{\frac{T^{\min}}{2}} \quad \text{for } 1 \le i \le m \tag{16}$$

Step 9: Compute the relative closeness index for each alternative.

$$C = \frac{D^{-}}{D^{+} + D^{-}} \tag{17}$$

The alternatives are now ranked depending on their relative closeness index values. The higher the closeness index, the better is the alternative.

3. Illustrative examples

In order to demonstrate the applicability of grey TOPSIS method in identifying the best machinable alloys from a group of candidate alternatives, the following three examples are illustrated.

3.1 Aluminium alloys

Aluminium, with a density of 2700 kg/m^3, is the lightest amongst all ordinary metals, approximately three times as light as steel. Along with the other metals, aluminium alloys are widely used in many customary processes, like machining, forming, bending, vessel-making and stamping. The absolute requirement for light structures makes aluminium and its alloys to take a major share as a suitable material in sky. In aeronautical applications, precision casting of aluminum components has found considerable attention due to reduced cost of the components. While using aluminium alloys, the design of high-speed ships is modified, by reducing the weight of hulls by 40% to 50% over steel. High corrosion resistance, even in water, makes aluminium and its alloys most suitable for more durable hulls, masts and superstructures on boats and bridges. These favorable physical properties of aluminium and its alloys are also responsible for their growing use in mechanical applications. Machines having moving parts, such as robots, are being made with an increasing number of aluminium components to reduce inertia. With respect to heat exchange (liquid-to-liquid or liquid-to-gas), aluminium's thermal conductivity plays an important role in electronics, seawater desalination, HVAC exchangers and plastics industry, where aluminium alloy molds with enhanced mechanical properties are widely used to shorten fabrication cycles by up to 30%. In the near past, newer aluminum casting processes have been developed for reduced manufacturing costs and the properties of aluminum cast alloys are optimized to increase tensile ductility and fracture toughness, without any adverse effect on tensile and yield strength.

In this paper, the machinability characteristics of three series of cast aluminium alloys, i.e. A357, A224 and 7475 are studied using grey TOPSIS method. The chemical compositions of the considered aluminium alloys are as follows: for A357 series: Si 7%, Mg 0.6%, Ti 0.15%, Cu < 0.2%, Fe < 0.2%, Mn < 0.1%, Zn < 0.1%, others < 0.15%, Al rest; for A224 series: Si < 0.067%, Ti 0.35%, Cu 5%, Mn 0.35%, Zr 0.2%, others 0.1%, Al rest; and for 7475 series: Mg 2.4%, Ti 0.1%, Cu 1.8%, Zn 5.7%, others 0.1%, Al rest. The machinability characteristics of eight such aluminium alloys from these three series are evaluated with respect to five mechanical properties, i.e. yield strength (in MPa), tensile strength (in MPa), elongation at fracture (in %), strain energy density (MJ/m^3) and quality evaluation index (in MPa). Among these, yield strength, tensile strength and quality evaluation index require higher values (beneficial criteria). On the other hand, minimum values are required for elongation at fracture and strain energy density (non-beneficial criteria). The corresponding decision matrix for the machinability study of aluminium alloys is developed in Table 1. In this table, the acronyms F and R associated with the alloy designations stand for flat and round respectively. On the other hand, the acronyms S and C denote Sophia and conventional casting processes respectively.

The maximum stress a metal alloy can withstand before failing is its ultimate tensile strength. A yield strength or yield point of a metal alloy is defined as the stress at which it begins to deform plastically. Elongation at fracture is defined as the percentage increase in length to initial length before fracture. The strain energy density of a metal alloy is defined as its strain energy per unit volume. It is equal to the area under the stress-strain diagram of a metal alloy. Quality index (QI) is a measure of machinability which can be expressed as $QI = TS + \log_{10}EF$ where TS is the tensile strength and EF is the elongation at fracture (Alexopoulos & Pantelakis, 2004; Alexopoulos, 2007). These mechanical properties of aluminium alloys are first converted into their corresponding grey numbers considering 1% greyness in calculation. This grey decision matrix with 1% greyness is exhibited in Table 2 which is subsequently normalized using Eq. (6). In order to develop the weighted normalized grey decision matrix, the grey weights of the considered mechanical properties (criteria) of aluminium alloys need to be calculated based on Eq. (7). The grey scale for the criteria weights is shown in Table 3 and the grey weights for five criteria of aluminium alloys considering a group decision-making environment involving four decision makers are given in Table 4. Now, using the grey data of Table 2 and grey weights of Table 4, the related weighted normalized grey decision matrix is developed in Table 5. Employing Eqs. (9)-(17), the relative closeness value for each candidate aluminium alloy is then computed, as shown in Table 6.

It is observed from Table 6 that aluminium alloy A357RC ranks first from the machinability point of view. Although it has moderate yield strength and tensile strength, but its minimum elongation at fracture and strain energy density drive it to attain the top position in the entire ranking list. Aluminium alloy 7475FS is the most difficult to machine due to its higher yield strength and tensile strength. In Table 7, the effects of greyness in the mechanical properties of aluminium alloys on the ranking performance of the employed grey TOPSIS method are exhibited. It becomes clear from this table that the rankings of the candidate aluminium alloys remain unaltered with the changing greyness values.

Table 1

Mechanical properties of aluminium alloys

Aluminium alloy	Yield strength (YS)	Tensile strength (TS)	Elongation at fracture (EF)	Strain energy density (SED)	Quality index (QI)
A357FS	303	372	12.19	46.04	535.0
A357RS	305	362	7.92	29.36	497.0
A357FC	305	340	2.16	8.08	389.9
A357RC	289	319	1.37	4.87	339.5
A224FS	257	387	7.85	30.71	521.1
A224RS	236	369	8.96	33.41	511.6
7475FS	479	506	4.92	27.99	609.8
7475RS	465	491	2.61	14.43	553.7

Table 2

Grey decision matrix for aluminium alloys

Aluminium alloy	YS	TS	EF	SED	QI
A357FS	(299.97,306.03)	(368.28,357.72)	(12.09,12.31)	(45.58,46.50)	(529.65,540.35)
A357RS	(301.95,308.05)	(358.38,365.62)	(7.84,8.00)	(29.07,29.65)	(492.03,501.97)
A357FC	(301.95,308.05)	(336.6,343.4)	(2.14,2.18)	(8.00,8.16)	(386.00, 393.80)
A357RC	(286.11,291.89)	(315.81,322.19)	(1.36,1.38)	(4.82,4.92)	(336.10,342.90)
A224FS	(254.43,259.57)	(383.13,390.87)	(7.77,7.93)	(30.40,31.02)	(515.90, 526.31)
A224RS	(233.64,238.36)	(365.31,372.69)	(8.87,9.05)	(33.07,33.74)	(506.48,516.72)
7475FS	(474.21,483.79)	(500.94,511.06)	(4.87,4.97)	(27.71,28.27)	(603.70,615.90)
7475RS	(460.35,469.65)	(486.09,495.91)	(2.58,2.64)	(14.28,14.57)	(548.16, 559.24)

Table 3

Scale for criteria weights

Scale	$\otimes w$
Very low	(0.1,0.2)
Low	(0.2,0.3)
Medium low	(0.3,0.4)
Medium	(0.4,0.5)
Medium high	(0.5,0.6)
High	(0.6,0.7)
Very high	(0.7,0.8)

Table 4

Grey weights for mechanical properties of aluminium alloys

Criteria	YS	TS	EF	SED	QI
Grey weight	(0.648,0.748)	(0.573,0.674)	(0.245,0.346)	(0.346,0.447)	(0.141,0.245)

Table 5

Weighted normalized grey decision matrix for aluminium alloys

Aluminium alloy	YS	TS	EF	SED	QI
A357FS	(0.0737,0.0867)	(0.0671,0.0805)	(0.0616,0.0888)	(0.0809,0.1066)	(0.0189,0.0334)
A357RS	(0.0741,0.0873)	(0.0653,0.0783)	(0.0400,0.0577)	(0.0516,0.0680)	(0.0175,0.0311)
A357FC	(0.0741,0.0873)	(0.0613,0.0735)	(0.0109,0.0157)	(0.0142,0.0187)	(0.0137,0.0244)
A357RC	(0.0702,0.0827)	(0.0575,0.0690)	(0.0069,0.0010)	(0.0086,0.0113)	(0.0120,0.0212)
A224FS	(0.0625,0.7357)	(0.0698,0.0837)	(0.0397,0.0572)	(0.0540,0.0711)	(0.0184,0.0326)
A224RS	(0.0574,0.0676)	(0.0665,0.0798)	(0.0453,0.0653)	(0.0587,0.0774)	(0.0180,0.0320)
7475FS	(0.1164,0.1371)	(0.0912,0.1095)	(0.0249,0.0358)	(0.0492,0.0648)	(0.0215,0.0381)
7475RS	(0.1130,0.1331)	(0.0885,0.1062)	(0.0132,0.0190)	(0.0254,0.0334)	(0.0195,0.0346)

Table 6

Ranking of aluminium alloys

Aluminium alloy	T^{max}	T^{min}	D^{+}	D^{-}	C	Rank
A357FS	0.0152	0.0152	0.087226	0.087158	0.499805	6
A357RS	0.0074	0.0118	0.060779	0.076708	0.557926	5
A357FC	0.0090	0.0187	0.066897	0.096702	0.591092	2
A357RC	0.0100	0.0222	0.070623	0.105352	0.598677	1
A224FS	0.0076	0.0135	0.061628	0.082257	0.571688	4
A224RS	0.0080	0.0158	0.063069	0.089015	0.585302	3
7475FS	0.0198	0.0041	0.099441	0.045398	0.313437	8
7475RS	0.0177	0.0089	0.094198	0.066526	0.413915	7

Table 7
Effect of change in greyness on ranking of aluminium alloys

Aluminium alloy	1%	2%	3%	5%	10%	Rank
A357FS	0.499805	0.499850	0.499894	0.499981	0.500189	6
A357RS	0.557926	0.557848	0.557771	0.557618	0.557254	5
A357FC	0.591092	0.590842	0.590594	0.590109	0.588952	2
A357RC	0.598677	0.598402	0.59813	0.597597	0.596326	1
A224FS	0.571688	0.571562	0.571438	0.571193	0.570608	4
A224RS	0.585302	0.585189	0.585076	0.584855	0.584327	3
7475FS	0.313437	0.313614	0.313789	0.314134	0.314957	8
7475RS	0.413915	0.413989	0.414062	0.414206	0.414551	7

3.2 Copper alloys

Copper and its alloys have the most versatile applications as engineering materials. Some of its favorable properties, like toughness, ductility and malleability make it extremely suitable for tube forming, wire drawing, spinning and deep drawing operations. Other important properties exhibited by copper and its alloys are presented as below:

a) It has high thermal and electrical conductivity, even greater than any other metal except silver.
b) It has good corrosion resistance, which favors durability and long term cost effectiveness.
c) It shows good bio-fouling resistance, as it resists marine organism growth.
d) It has good machinability property, and can be easily machined at the optimal feeds and speeds with proper tools and fixtures.
e) It possesses some favorable mechanical properties, which are often better than those of quenched and tempered steel.
f) It can retain its mechanical and electrical properties at cryogenic temperatures.
g) It has low friction and wear rates. High-leaded tin-bronzes, which are cast into sleeve bearings often have smaller wear rates than steel.
h) All copper alloys can be sand cast and many can be centrifugal, continuous, permanent mold and diecast due to their good castability property.
i) Satistactory surface finish and high tolerance control can be readily achieved due to ease of post-casting processing.
j) Depending upon design loads and corrosivity of the environment, several copper alloys may be the suitable alternative choices for any given industrial application.
k) It has low cost as compared to other metals due to high yield, less machining cost and minimum requirement for surface coating.

With variations in composition and manufacturing methods, these properties of copper and its alloys can be further enhanced. They can be easily cast, have been successfully used over a long period of time and can be readily available from multitude sources. They have a favorable range of physical and mechanical properties, and are quite suitable for machining, brazing, soldering, polishing or plating operation. Cast copper alloys are quite versatile materials. They are being successfully used in plumbing fixtures, ship propellers, power plant water impellers, and bushing and bearing sleeves. In this example, the machinability performances of eight copper alloys, i.e. CuBe1.7 (Be 1.60-1.80%, Ni + Co 0.20-0.60%, Cu rest), CuBe2 (Be 1.80-2.10%, Ni + Co 0.20-0.60%, Cu rest), CuBe2Pb (Be 1.85-2.10%, Ni + Co + Fe 0.20-0.60%, Pb 0.2-0.6%, Cu rest), CuCo2Be (Be 0.4-0.7%, Co 2.4-2.7%, Cu rest), CuCr1 (Cr 0.4-1.2%, Cu rest), CuCr1Zr (Cr 0.5-1.5%, Zr 0.05-0.25%, Cu rest), CuNiP (Ni 0.47-0.53%, P 0.090-0.115%, Cu rest) and CuNi2Si (Ni 1.6-2.2%, Si 0.4-0.8%, Fe ≤ 0.1%, Zn ≤ 0.50%, Cu rest) are evaluated with respect to five mechanical properties, such as proof strength (in MPa), tensile strength (in MPa), elongation (in %), hardness (in BHN) and thermal conductivity (W/m-K). In metallurgy, hardness is the ability of a specific material to resist plastic deformation. Thermal conductivity of a material is the quantity of heat transmitted due to unit temperature rise in unit time under steady state. Higher values of proof strength, tensile strength and thermal conductivity are always desired. On the other hand, elongation at fracture and hardness being non-beneficial criteria require their lower values. The grey decision matrix for the eight considered copper alloys is developed as presented in Table 8. In Table 9, the grey weights for various criteria are calculated which are subsequently employed for determining the relative closeness values. From Table 10, it is observed that CuCr1Zr is the best machinable copper alloy with respect to the considered mechanical properties. Among the eight copper alloys, CuBe2 is identified as the most difficult one to machine. Although it has the desirable values of proof strength, tensile strength and elongation at fracture, but its high hardness and low thermal conductivity compel it to take the last position in the ranking list. It is also found from Table 10 that the change in greyness in the mechanical properties of copper alloys has no effect on the final rankings of the candidate alloys.

Table 8
Grey decision matrix for copper alloys

Copper alloy	Proof strength (PS)	Tensile strength (TS)	Elongation at fracture (EF)	Hardness (H)	Thermal conductivity (TC)
CuBe1.7	(643.5,656.5)	(841.5,858.5)	(34.95,35.65)	(247.5,252.5)	(29.7,30.3)
CuBe2	(742.5,757.5)	(891,909)	(20,20.4)	(257.4,262.6)	(29.7,30.3)
CuBe2Pb	(742.5,757.5)	(891,909)	(20.2,20.6)	(153.45,156.55)	(44.55,45.45)
CuCo2Be	(514.8,525.2)	(514.8,525.2)	(25.05,25.55)	(158.4,161.6)	(44.55,45.45)
CuCr1	(267.3,272.7)	(356.4,363.6)	(30.5,31.1)	(123.75,126.25)	(79.2,80.8)
CuCr1Zr	(267.3,272.7)	(376.2,383.8)	(35.15,35.85)	(113.85,116.15)	(74.25,75.75)
CuNiP	(425.7,434.3)	(519.75,530.25)	(30.2,30.8)	(158.4,161.6)	(49.5,50.5)
CuNi2Si	(356.4,363.6)	(495,505)	(35.15,35.85)	(148.5,151.5)	(39.6,40.4)

Table 9
Grey weights for mechanical properties of copper alloys

Criteria	PS	TS	EF	H	TC
Grey weight	(0.346,0.447)	(0.648,0.748)	(0.245,0.346)	(0.141,0.245)	(0.573,0.674)

Table 10
Effect of change in greyness on ranking of copper alloys

Copper alloy	1%	2%	3%	5%	10%	Rank
CuBe1.7	0.209138	0.209226	0.209310	0.209910	0.209892	6
CuBe2	0	0	0	0	0	8
CuBe2Pb	0.219310	0.219479	0.219553	0.219951	0.220771	7
CuCo2Be	0.561381	0.561323	0.561264	0.561185	0.560880	5
CuCr1	0.946531	0.946453	0.946496	0.946226	0.945841	2
CuCr1Zr	0.970654	0.970612	0.970570	0.970491	0.970289	1
CuNiP	0.664228	0.664140	0.664053	0.663927	0.663471	4
CuNi2Si	0.739131	0.738893	0.738656	0.738235	0.737077	3

3.3 Alloy steels

Alloy steel is a type of steel with a variety of alloying elements in total amounts ranging between 1.0% and 50% by weight to improve its certain mechanical properties. In alloy steel, carbon is the common alloying element. Apart from carbon, it also contains other major alloyants, like manganese, nickel, chromium, molybdenum, vanadium, silicon and boron. Aluminum, cobalt, copper, cerium, niobium, titanium, tungsten, tin, zinc, lead and zirconium are also added in it in less proportion. Alloy steels can be divided into two main groups, i.e. low alloy steels and high alloy steels. Alloy steel usually refers to low alloy steels. Low alloy steels have better hardenability, which in turn, influences its other mechanical properties. They have increased corrosion resistance in certain environmental conditions.

Low alloy steel with medium to high carbon content is difficult to weld. When the carbon content is reduced to a range of 0.10% to 0.30%, along with some change in other alloying elements, the weldability and formability of steel can be substantially increasd while maintaining its strength. This type of steel is known as high strength low alloy steel. Alloy steels may also be divided into four classes, i.e. a) structural steels, which are subjected to stresses in machine parts, b) tool and die steels, c) magnetic alloys, and d) stainless and heat-resisting steels.

When chromium, molybdenum, nickel, manganese and silicon are added, hardness, corrosion resistance, temperature and material strength can be maximized in the basic mix of iron and carbon. Addition of each material must be carefully controlled if the desired result needs to be achieved. From household utensils to buildings to modern art, steel alloys, especially stainless steel have become ubiquitous materials. This alloy has many useful attributes, like bright shine, corrosion and rust-free surface, and durability under harsh weather conditions. Depending on contents of various alloying elements, its specific properties can be enhanced. Alloy steels have wide uses in exotic and highly-demanding applications, like turbine blades in jet engines, landing gear of aircraft and in nuclear reactors. Because of iron's ferromagnetic properties, some steel alloys find important applications in electric motors and transformers where their responses to magnetism are very important.

While selecting the best machinable steel alloy employing grey TOPSIS method, eight candidate alternatives, i.e. AISI 4130 (Fe 97.03-98.22%, Cr 0.80-1.10%, Mn 0.40-0.60%, C 0.28-0.33%, Si 0.15-0.30%, Mo 0.15-0.25%, S 0.04%, P 0.035%), AISI 4340 (Fe 95.195-96.33%, Ni 1.65-2.99%, Cr 0.7-0.9%, Mn 0.6-0.8%, C 0.37-0.43%, Si 0.15-0.30%, Mo 0.2-0.3%, S 0.04%, P 0.035%), AISI 5140 (Fe 97.395-98.07%, Cr 0.7-0.9%, Mn 0.7-0.9%, C 0.38-0.43%, Si 0.15-0.30%, S ≤ 0.04%, P ≤ 0.035%), AISI 6150 (Fe 97.095-97.72%, Cr 0.80-1.10%, Mn 0.7-0.9%, C 0.48-0.53%, Si 0.15-0.30%, V ≥ 0.15%, S ≤ 0.04%, P ≤ 0.035%), AISI 8650 (Fe 96.54-97.67%, Cr 0.4-0.6%, Mn 0.75-1.00%, C 0.48-0.53%, Ni 0.4-0.7%, Si 0.15-0.30%, Mo 0.15-0.25%, S ≤ 0.04%, P ≤ 0.035%), AISI 8620 (Fe 96.895-98.02%, Cr 0.4-0.6%, Mn 0.7-0.9%, C 0.18-0.23%, Ni 0.4-0.7%, Si 0.15-0.35%, Mo 0.15-0.25%, S ≤ 0.04%, P ≤ 0.035%), AISI 4150 (Fe 96.745-97.67%, Cr 0.80-1.10%, Mn 0.75-1.00%, C 0.48-0.53%, Si 0.15-0.30%, Mo 0.15-0.25%, S ≤ 0.04%, P ≤ 0.035%) and AISI 8740 (Fe 96.595-97.72%, Cr 0.4-0.6%, Mn 0.75-1.00%, C 0.38-0.43%, Ni 0.4-0.7%, Si 0.15-0.30%, Mo 0.2-0.3%, S 0.04%, P 0.035%) are considered whose performances are evaluated with respect to five mechanical properties, such as tensile strength (in MPa), yield strength (in MPa), elastic modulus (in GPa), elongation at fracture (in %) and hardness (in BHN). Among these, tensile strength, yield strength and elastic modulus are beneficial criteria, and the remaining two are non-beneficial in nature. Table 11 exhibits the mechanical properties of the considered alloy steels expressed in grey numbers. The grey weights as calculated for the five mechanical properties of alloy steels are given in Table 12. It is found from Table 13 that AISI 5140 outperforms the other alternatives from the machinability characteristic point of view. With respect to all the five mechanical properties, its performance is satisfactory. AISI 4340 is the most difficult alloy to machine. AISI 5140 has a machinability index of 65 as compared to 50 of AISI 4340. Again, it is observed that the rankings of the alloy steels remain unaltered with the variations in greyness of the considered mechanical properties of the alloys.

Table 11
Grey decision matrix for alloy steels

Alloy steel	Tensile strength (TS)	Yield strength (YS)	Elastic modulus (EM)	Elongation at fracture (EF)	Hardness (H)
AISI 4130	(554.4,565.6)	(455.4,464.6)	(198,202)	(15.84,16.16)	(214.83,219.17)
AISI 4340	(737.55,752.45)	(465.3,474.7)	(207.9,212.1)	(21.78,22.22)	(214.83,219.17)
AISI 5140	(564.3,575.7)	(292.05,297.95)	(188.1,191.9)	(19.8,20.2)	(165.33,168.67)
AISI 6150	(663.3,676.7)	(410.85,419.15)	(217.8,222.2)	(22.77,23.23)	(195.03,198.97)
AISI 8650	(707.85,722.15)	(381.15,388.85)	(188.1,191.9)	(22.27,22.72)	(209.88,214.12)
AISI 8620	(524.7,535.3)	(381.15,388.85)	(193.05,196.95)	(24.75,25.25)	(147.51,150.49)
AISI 4150	(723.69,738.31)	(376.2,383.8)	(212.85,217.15)	(19.99,20.40)	(195.03,198.97)
AISI 8740	(688.05,701.95)	(410.85,419.15)	(207.9,212.1)	(21.98,22.42)	(198.99,203.01)

Table 12

Grey weights for alloy steels

Criteria	TS	YS	EM	EF	H
Grey weight	(0.648,0.748)	(0.573,0.674)	(0.141,0.245)	(0.245,0.346)	(0.346,0.447)

Table 13

Effect of change in greyness on ranking of alloy steels

Alloy steel	1%	2%	3%	5%	10%	Rank
AISI 4130	0.385168	0.385028	0.384888	0.384613	0.383950	3
AISI 4340	0.239423	0.239581	0.239737	0.240044	0.240782	8
AISI 5140	0.751607	0.751447	0.751288	0.750976	0.750225	1
AISI 6150	0.424285	0.424401	0.424516	0.424742	0.425288	4
AISI 8650	0.413256	0.413306	0.413357	0.413455	0.413693	5
AISI 8620	0.689647	0.689689	0.689732	0.689815	0.690015	2
AISI 4150	0.379471	0.379526	0.379581	0.379689	0.379948	6
AISI 8740	0.369715	0.369823	0.369929	0.370140	0.370646	7

4. Conclusions

In this paper, the machinability characteristics of some alloys of three different metals are studied while employing grey TOPSIS method. The adopted methodology helps the manufacturers to identify the most easily machinable alloys from a list of considered alternatives so that proper machining conditions can be set beforehand. The grey TOPSIS method is found to be quite suitable for this type selection and evaluation problem where the criteria (mechanical properties) values are expressed in grey numbers. It is easily comprehensible and applicable under conflicting decision-making environment. The derived results are observed to be in good agreement with the opinions of the metallurgists and machining professionals. It is also found that the variation in greyness of the mechanical properties of the alloys has no influence on the ranking performance of the adopted methodology. It can be applied to study the machinability characteristics of other alloys too.

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