Sustainability Analysis of Bimetallic Components

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Abstract

This study deals with the sustainability analysis of bimetallic components putting emphasis on *energy*, *material*, and *component efficiencies*. Energy efficiency deals with the energy consumption of friction welding and material removal processes needed to produce the component. Material efficiency deals with the yield, light-weighting, cost, and CO_2 footprint of primary material production of the materials used in the component. Component efficiency deals with the alternation of functional properties of the component (surface-finish, strength, etc.). Numerical examples are cited based on a case-study of a bimetallic component made from commercial pure Aluminum and Titanium. It is found that the material efficiency is more effective than the energy efficiency in enhancing the sustainability. The outcomes of this study will help make informed decisions in developing sustainable components for automotive/aerospace industry and beyond.

Keywords:
Material Efficiency, Bimetallic Component, Sustainable Manufacturing

1 INTRODUCTION

The concept called energy efficiency (i.e., reduction of greenhouse gas emission by reducing the energy consumption or using cleaner energy sources) has been the main concept for achieving sustainability in different fields including manufacturing. Energy efficiency alone is not enough for solving the problems of sustainability. The concept called material efficiency is needed, in addition [1-3]. Material efficiency means reduction of material use/weight/cost, yield enhancement, and alike [1-3].

In some automotive/aerospace applications, bimetallic components (components consist of two different metal alloys) are preferred over their monometallic counterparts because the bimetallic components help reduce cost/weight [4-11]. This means that the bimetallic components help achieve some of the objectives of the abovementioned material efficiency. To produce a bimetallic component, on the other hand, two metal pieces are first joined employing friction welding [4-11]. A finishing process follows the joining process ensuring the desired shape and surface-finish [11]. The energy and material efficiencies of these manufacturing processes are also important ingredients of sustainability analysis.

Moreover, due to the coexistence of two different metal alloys (say A and B), a bimetallic component may exhibit some unique features. For example, the surface-finish of a segment made from material A might not be the same as the surface-finish of the other segment made from material B. The material properties of the component is not the same as those of its constituent materials. The alternation of the functional properties (surface-finish, strength, etc.) of bimetallic components is referred to as component efficiency. Thus, the sustainability analysis of bimetallic components has three facets: *energy efficiency*, *material efficiency*, and *component efficiency*, as schematically illustrated in Fig. 1. This study sheds some lights on these three facets.

The remainder of this article is organized as follows: Section 2 describes the fabrication of a bimetallic component. Sections 3-5 describe the indices to measure the energy efficiency, material efficiency, and component efficiency, respectively. Section 6 provides the concluding remarks of this study.

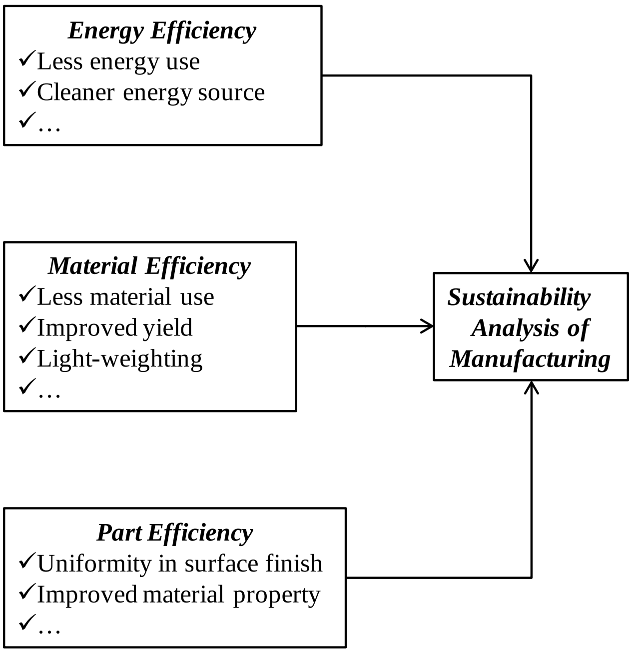

Fig. 1: Sustainability analysis of bimetallic components.

2 BIMETALLIC COMPONENT FABRICATION

To fabricate a bimetallic component, first, two objects made of two different metal alloys are joined usually by friction welding [4-11]. A finishing process (e.g., turning) follows the joining process. The finishing process first removes the flash generated during the joining process. This process also ensures the desired shape and surface-finish of the component [11]. The right-hand-side of Fig. 2 schematically illustrates such manufacturing processes. The left-hand-side of Fig. 2 shows pictures of a real bimetallic component made from commercial pure Al and Ti. The existence of flash can be observed from the first picture (Fig. 2) taken after performing the joining process. The second picture in Fig. 2 is the picture taken after performing the finishing process. The last picture is the picture of the surface around the joint interface, which is a magnified view of the surface around the joint interface. From this picture one can identify the difference in surface-finish that exists in the segments of Al and Ti. It is worth mentioning that the joining process affects the material properties, chemical compositions, and crystallographic characteristics of the joint interface [4-9]. As a result, a bimetallic component behaves differently than the constituent materials.

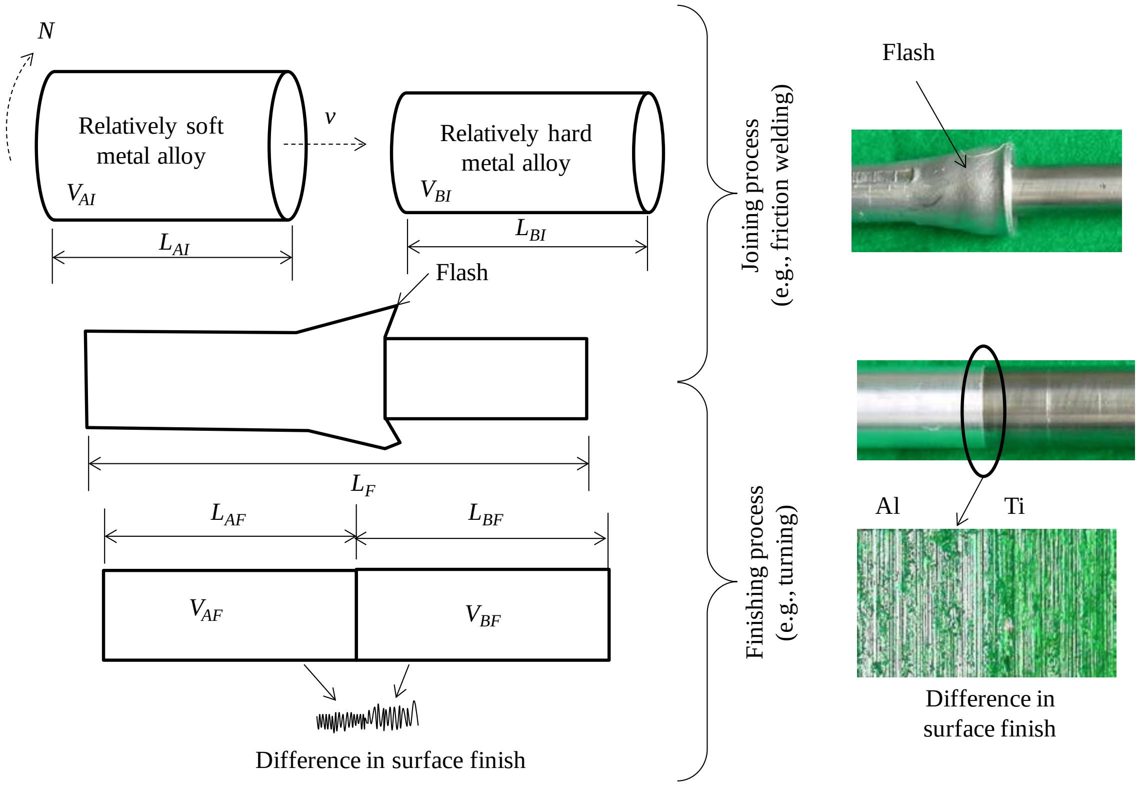

Fig. 2: Producing a bimetallic component.

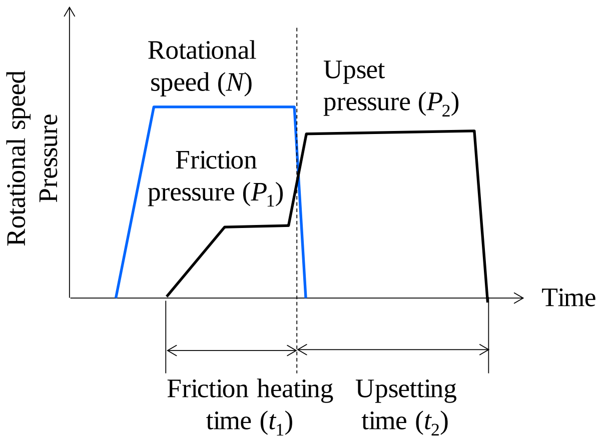

Fig. 3: Important parameters of friction welding

The process parameters of friction welding are schematically illustrated in Fig. 3. Some of the parameters are already shown in Fig. 2. As seen from Figs. 2-3, friction welding undergoes two stages: *friction heating* and *upsetting* [4-9]. In friction heating, one of the objects first approaches the other at a velocity (v) until a physical contact being established. Simultaneously, the approaching object rotates at a rotational speed (N). The other object remains standstill. Just after establishing the physical contact, the objects are pressed against each other. A pressure (P_1) is maintained. As a result, heat is generated in the interface of the objects due to excessive friction. This causes a great deal of plastic deformation. After a period, the rotational speed is stopped and the next stage called upsetting starts. In this stage, one of the objects is moved toward the other while maintaining a pressure (P_2). As a result, joining between two objects takes place. Note that P_2 is greater than P_1. An amount of flash is generated at the joint interface as a result of joining. Later the finishing process removes the flash and ensures the desired shape and surface-finish.

3 ENERGY EFFICIENCY

Energy efficiency of a bimetallic component is the energy intensiveness of joining and finishing processes. In this study joining process means friction welding and finishing process means turning.

It is worth mentioning that although there are comprehensive studies on different issues of friction welding [4-9], there is no study on the energy intensiveness of it. Therefore, it is important to a theoretical model of energy intensiveness of friction welding. On the other hand, energy efficiency of material removal processes (e.g., turning, milling, drilling, etc.) has been studied by many authors [12-17].

However, it is found that the theoretical minimum energy consumption of a manufacturing process [12-13] is about 10-30% of the total energy needed to perform the same process in the real context because most of the energy is consumed by the peripheral devices (heating, cooling, and lighting equipments), not by the process itself [14-17]. Thus, it is not unlikely that real energy consumption of a manufacturing process is ten times greater than the theoretical energy consumption.

Let t_1 and t_2 be the durations of friction heating and upsetting, respectively. Let r be the radius of the interface; μ be the coefficient of friction; L be the distance travelled during upsetting. As such, the theoretical energy consumption of friction welding (E_J) is the summation of friction heating energy (E_F) and upsetting energy (E_U):

$$\begin{aligned} E_J &= E_F + E_U \\ &= \int_0^r \mu\left(P_1 2\pi r dr\right)\left(2\pi r N\right)t_1 \\ &\quad + P_2\left(\pi r^2\right)L \\ &= \pi r^2\left[4.2\mu r N P_1 t_1 + P_2 L\right] \end{aligned} \tag{1}$$

Equation (1) can be modified for objects having cross-sections other than the assumed cross-section (circular cross-section). Note that the coefficient of friction μ might vary during t_1. It has been reported that at the time of initiation of friction heating (when the temperature is low), μ is quite high (about 0.8). With the increase in temperature μ goes down significantly (about 0.3) [10]. Thus, for the sake of estimation μ is considered to be 0.5, a value about the average.

The component shown in Fig. 2 corresponds to P_1 = 50 MPa, P_2 = 100 MPa, N = 1500 rpm, v = 20 mm/sec, r = 9 mm, t_1 = 2 sec, t_2 = 6 sec, $L \cong 10.5$ mm (L is calculated from $L_A + L_B - L_F$). This yields E_J = 12290.85 J or 0.0034 kWh. As a result, CO_2 footprint of this amount of energy is about 2 g-CO_2 (588 g-CO_2 per kWh of energy [18-19]), which is not a significant amount.

In addition to E_J, a theoretical amount of energy denoted as E_T is consumed during the finishing process (turning). Thus, energy efficiency of a bimetallic component denoted as E_P is given as:

$$E_P = E_J + E_T \tag{2}$$

One of the recommended ways to estimate E_T is given as:

$$E_T = F_c V_c T \tag{3}$$

In Equation (3), F_c denotes the cutting force; V_c denotes the cutting velocity; and T denotes the machining time. It is assumed that the cutting force is directly proportional to hardness/strength of the material to be machined. In case of a bimetallic component, a great deal of variability in F_c is observed. In addition, F_c does not correspond to hardness/strength of the materials as expected [14-15]. This is best explained by the cutting force signals shown in Figs. 4-5. The signals shown in Figs. 4-5 are the signals of Fc when the bimetallic component shown in Fig. 2 is turned under the following conditions: carbide cutting tool; cutting tool nose radius = 0.4 mm; depth of cut = 0.5 mm; feed rate = 0.051 mm/rev; cutting speed = 50 m/min.

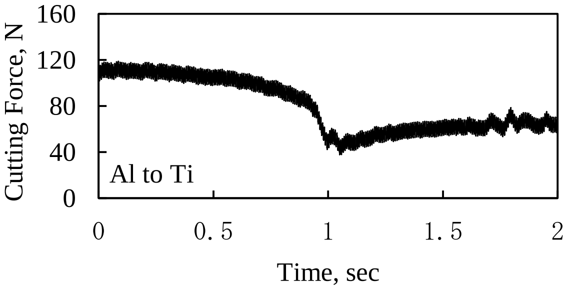

Fig. 4: Cutting force (turning direction Al to Ti).

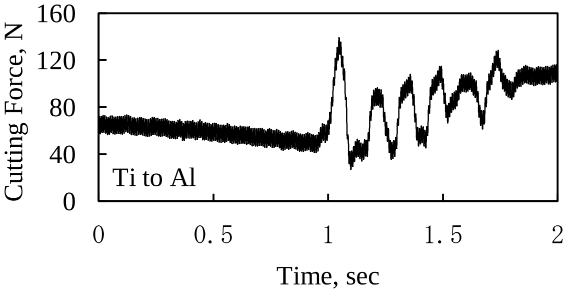

Fig. 5: Cutting force (turning direction Ti to Al).

The cutting force signals shown in Fig. 4 correspond to the turning direction Al to Ti (i.e., turning from softer material to harder material). The cutting force signals shown in Fig. 5 correspond to the other possibility, i.e., turning direction Ti to Al (i.e., turning from harder material to softer material). In Figs. 4-5, the time point equal to 1 sec represents the joint interface. When a cutting tool starts to cut the softer material (i.e., starts to cut Al) the cutting force remains unstable (see the left segment of cutting force signals in Fig. 4). This instability disappears soon, but a degree of unwanted friction among the cutting tool, work-piece, and chip persists. Therefore, softer material (in this case Al) exhibits a higher cutting force than that of the harder material. This can be realized by comparing the force signals shown in Figs. 4-5. Thus, to estimate E_T of a bimetallic component, the following expression can be used:

$$E_T = V_{cf} F_{cA} T_f + V_c \left[F_{cA} T_A + F_{cB} T_B \right] \quad (4)$$

In Equation (4), V_{cf} denotes the average cutting velocity during the flash removal process; V_f denotes the average cutting velocity during finishing; F_{cA} denotes the average cutting velocity while removing metal alloy A; F_{cB} denotes the average cutting velocity of metal alloy B; T_f denotes the machining time of flash removal; T_A denotes the machining time of metal alloy A; and T_B denotes the machining time of metal alloy B. Note that in Equation (4), it is assumed that metal alloy A forms the flash. It is true if metal A is the softer material. In this study, A means Al and B means Ti, i.e., the above proposition is true for this study. However, referring to Figs. 4-5, F_{cA} = 110 N and F_{cB} = 70 N.

4 MATERIAL EFFICIENCY

This section describes some parameters to measure the material efficiency of a bimetallic component. In particular, the parameters called volumetric yield, weight reduction coefficient, CO_2 footprint diminution, and cost reduction coefficient are considered, as follows:

4.1 Volumetric yield

Volumetric yield (Y_V) measures how much material has been utilized (or how much material has been wasted) during manufacturing processes (joining and finishing) in terms of volume. The expression of Y_V is as follows:

$$Y_V = \frac{V_{AF} + V_{BF}}{V_{AI} + V_{BI}} \quad (5)$$

In Equation (5), V_{AI} denotes the volume of blank made of metal alloy A; V_{BI} denotes the volume of blank made of metal alloy B; V_{AF} denotes the volume of metal alloy A in the finished component; and V_{BF} denotes the volume of metal alloy B in the finished component. A value of Y_V close to 1 is desirable, indicating the fact that there is no significant loss of material due to joining/finishing.

Recall the bimetallic component shown in Fig. 2. The component is made by joining two cylindrical objects (both 80 mm long) made from commercial pure Al and Ti. The diameter of Al blank is 18 mm whereas the diameter of Ti is 16 mm. (This is a common scenario in friction welding–the object made from relatively softer material has larger cross-sectional area so as to avoid any unwanted deformation/buckling.) The flesh is removed and the diameter is adjusted to 16 mm. The overall length of the bimetallic component after finishing is equal to 149.5 mm ($L_{AF} + L_{BF}$ = 70 mm + 79.5 mm = 149.5 mm). Thus, for this case: $V_{AI} = \pi*9^2*80$ mm^3, $V_{BI} = \pi*8^2*80$ mm^3, $V_{AF} + V_{BF} = \pi*8^2*149.5$ mm^3. This yields Y_V = 0.82 (or 82%). This means that 18% of the material in terms of volume is not utilized, which is not desirable, however.

4.2 Weight reduction coefficient

Let ρ_A and ρ_B be the density of metal piece A and B, respectively and A is lighter than the other, $\rho_B > \rho_A$. Let m_{AF} and m_{BF} be the masses of metal piece A and B in the finished product. Also, let m_M be the mass of the monometallic counterpart of the bimetallic component.

Weight reduction coefficient (W_L) thus measures the degree of weight reduction of the bimetallic component compared to its monometallic counterpart, as follows:

$$W_L = \frac{m_{AF} + m_{BF}}{m_M} = \frac{\rho_A V_{AF} + \rho_B V_{BF}}{\rho_B \left(V_{AF} + V_{BF} \right)} \quad (6)$$

Recall the bimetallic component shown in Fig. 2. For this case, ρ_A = 2.7 g/cm^3 and ρ_B = 4.52 g/cm^3 [20]. Thus, $V_{AF} = \pi*8^2*70$ mm^3 and $V_{BF} = \pi*8^2*79.5$ mm^3. This yields W_L = 0.82, i.e., 18% weight reduction has taken place. Note that from the density viewpoint the expected weight reduction should have been 60% (2.7/4.52), whereas in reality it is about 18%, only. The reason is that the segments of Al and Ti are unequal in length (L_{AF} = 70 mm, L_{BF} = 79.5 mm). The weight reduction coefficient can be enhanced by keeping two lengths equal (i.e., by keeping $L_{AF} = L_{BF}$). This might reduce the volumetric yield Y_V because the blank size of the lighter (or less stronger metal piece) is larger than that of finished component ($L_{AI} = L_{AF} + \Delta L_A$, and ΔL_A is larger enough). Thus, a trade-off is needed to get an optimal solution in terms of weight-reduction coefficient.

4.3 CO_2 footprint diminution

CO_2 footprint diminution measures CO_2 emission reduction of the bimetallic component compared to its monometallic counterpart. The formulation is as follows:

$$C_P = \frac{m_{AI} C_A + m_{BI} C_B}{m_M C_B} = \frac{\rho_A V_{AI} C_A + \rho_B V_{BI} C_B}{\rho_B \left(V_{AF} + V_{BF} \right) C_B} \quad (7)$$

In Equation (7), m_{AI} and m_{BI} are the masses of the blank of metal pieces A and B, respectively; and C_A and C_B are the CO_2 footprints of primary material production of metals A and B, respectively. CO_2 footprints of primary material production of Al and Ti are 9.5 kg-CO_2/kg and 40 kg-CO_2/kg, respectively, [20] i.e., C_A = 9.5 g-CO_2/g and C_B = 40 g-CO_2/g. This yields C_P = (522 + 2908)/5434 = 0.63. This means that 37% reduction in CO_2 footprint has been achieved. However, it would be beneficial to see the absolute reduction in CO_2 footprint of primary material production. The formulation is as follows:

$$C_{PA} = m_M C_B - \left(m_{AI} C_A + m_{BI} C_B \right) \quad (8)$$

In Equation (8), C_{PA} denotes the absolute reduction in CO_2 footprint of primary material production. For the case shown in Fig. 2, C_{PA} = [5434 - (522 + 2908)] g-CO$_2$ = 2004 g-CO$_2$.

It is worth mentioning that increase in CO$_2$ burden due to friction welding is insignificant (2 g-CO$_2$, see the previous section) compared to CO$_2$ footprint reduction (2004 g-CO$_2$) as a result of material efficiency. However, $C_{PA} < 0$ means that the bimetallic component does not help reduce the CO$_2$ burden.

4.4 Cost reduction coefficient

Cost is an important component of sustainability and material cost is many folds higher than manufacturing cost. Therefore, cost increment due to manufacturing (friction welding, turning) is assumed to be well compensated by material cost saving. To measure the degree of cost reduction, a coefficient is proposed, as follows:

$$P_P = \frac{m_{AI}P_A + m_{BI}P_B}{m_M P_B} = \frac{\rho_A V_{AI} P_A + \rho_B V_{BI} P_B}{\rho_B (V_{AF} + V_{BF}) P_B} \qquad (9)$$

In Equation (9), P_P denotes the cost reduction coefficient; P_A and P_B are the cost of metal alloys A and B, respectively. For the case shown in Fig. 2, P_A = 2.4 USD/kg (Al) and P_B = 53 USD/kg (Ti) [20]. This yields P_P = (0.132 + 3.85)/7.2 = 0.553. This means that the bimetallic component helps reduce the material cost by 44%.

4.5 Material efficiency index

The measures called volumetric yield, weight reduction coefficient, CO2 footprint diminution, cost reduction coefficient can be aggregated into a single measure called material efficiency index (M_I), as follows:

$$M_I = \frac{Y_V W_L}{C_P P_P} \qquad (10)$$

For the case shown in Fig. 2, M_I = (0.82*0.82) / (0.63*0.553) = 1.93. The more the value of M_I is the better the material efficiency is.

5 COMPONENT EFFICIENCY OF BIMETALLIC COMPONENTS

As mentioned before, due to the coexistence of two different metal alloys and alternation of material characteristics in the joint interface, a bimetallic component may exhibit some unique features (e.g., may exhibit a significant difference in surface-finish at different segments, a significant difference in material properties compared to those of constituent materials, and alike). This is referred to as component efficiency. To quantify the component efficiency, two quantities are proposed. One of the quantity deals with the surface-finish and the other deals with strength.

5.1 Surface-finish coefficient

Surface-finish coefficient measures the degree of difference in surface-finish of metals A and B in the finished component. Figures 6-7 show the surface profiles of the bimetallic of Fig. 2 for cutting directions Ti to Al and Al to Ti, respectively. As seen from Figs. 6-7 surface-finish in the segment of Al is not the same compared to that of in the Ti segment.

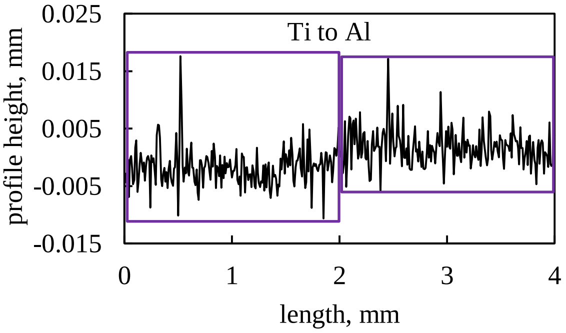

Fig. 6: Variability in the surface-finish (Ti to Al).

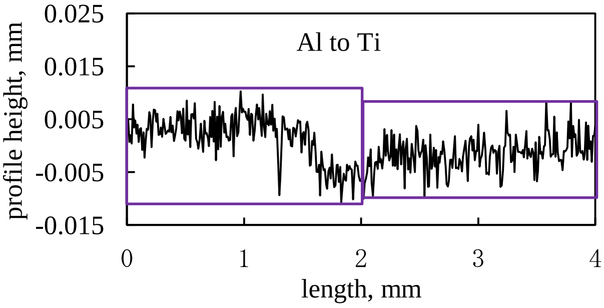

Fig. 7: Variability in the surface-finish (Ti to Al).

To measure the difference the following coefficient denoted as S_P can be used:

$$S_B = \frac{|R_{aA} - R_{bB}|}{\max(R_{aA}, R_{bB})} \qquad (11)$$

In Equation (11), R_{aA} and R_{aB} are the arithmetic average surface roughness of the segments of A and B, respectively. Instead of using the coefficient defined by Equation (11), one may use the entropy-based parameters [11], however.

5.2 Joint efficiency

The strength of the bimetallic component is not the same compared to that of its constituents A and B. This evolves a parameter called joint efficiency (J_P), given as:

$$J_P = \frac{\sigma_P}{\min(\sigma_A, \sigma_B)} \qquad (12)$$

In Equation (12), σ_A, σ_B, and σ_P are the strengths of A, B, and bimetallic component, respectively. Usually, J_P = 1 is desirable. In reality it is difficult to achieve this [4-9]. The parameters of friction welding, as explained in Section 2, needed to be adjusted to achieve keep J_P around unit.

6 CONCLUDING REMARKS

Sustainable manufacturing should incorporate the aspects of energy, material, and process related issues [18-19, 21] to make it more meaningful. This study is one of the examples of such a comprehensive analysis of sustainability. Particularly some aspects of material efficiency, i.e., weight/cost reduction, might affect other aspects such as yield and energy efficiency as shown in this study. Nevertheless, the indices introduced in this study can be used a fair analysis of sustainability of a bimetallic component, in particular, and a component made from different materials, in general. However, the material efficiency of cutting tools is not considered in this study. In fact, cutting tools are nowadays made from very hard materials, which, on one hand creates a favorable condition for achieving sustainability by reducing the machining time and tool wear [22], but, on the other hand, might left a significant amount of environmental burden [23-24]. This issue remains open for further research.

REFERENCES

[1] Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E. (2011). Material efficiency: A white paper, *Resources, Conservation and Recycling*, 55(3), 362-381.

[2] Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E. (2013). Material efficiency: providing material services with less material production, *Philosophical Transactions of the Royal Society A*, 371(1986), 20120496, doi:10.1098/rsta.2012.0496.

[3] Milford, R.L., Pauliuk, S., Allwood, J.M. and Muller, D.B. (2013). The Roles of Energy and Material Efficiency in Meeting Steel Industry CO_2 Targets, *Environmental Science and Technology*, 47(5), 3455-3462.

[4] Fuji, A., Kokawa, H., and Kim, Y.-C. (2000). A Study of Stress-strain, Acoustic Wavevelocity and Hardness Across Joint Interface of Pure Ti/Pure Al Friction Weld Joint, *Quarterly Journal of the Japan Welding Society*, 18(1), 617-627.

[5] Kim, Y.-C., and Fuji, A.(2002). Factors dominating joint characteristics in Ti-Al friction welding, *Science and Technology of Welding and Joining*, 7(3), 149-154.

[6] Kimura, M. Utsumi, D., Kusaka, M. and Kaizu, K. (2011). Strength enhancement of autocompleting medium and high carbon steels friction welded joints, *Journal of Materials Processing Technology*, 211(2), 256-262.

[7] Sahin, M. (2004). Simulation of friction welding using a developed computer program, *Journal of Materials Processing Technology*, 153-154(10), 1011-1018.

[8] Meshram, S.D., Mohandas, T. and Madhusudhan G.R. (2007). Friction welding of dissimilar pure metals, *Journal of Materials Processing Technology*, 184(1-3), 330-337.

[9] Sathiya, P., Aravindan, S., Noorul Haq, A. and Paneerselvam, K. (2009). Optimization of friction welding parameters using evolutionary computational techniques, *Journal of Materials Processing Technology*, 209(5), 2576-2584.

[10] Ambroziak, A., Winnicki, M., Laska, P., Lachowicz, M., Zwierzchowski, M. and Leśniewski, J. (2001). Examination of Friction Coefficient in Friction Welding Process of Tubular Steel Elements, *Archives of Metallurgy and Materials*, 56(4), 975-980.

[11] Nagara, Y., Sharif Ullah, A.M.M. and Fuji, A., Tamaki, J. and Kubo, A. Surface finish characteristics of bimetallic parts, *Proceedings of The 5th International Conference on Manufacturing, Machine Design and Tribology* (ICMDT2013), 22-25 May 2013, Busan, South Korea, pp. 93-94.

[12] Gutowski, T.G., Branham, M.S., Dahmus, J.B., Jones, A.J. and Thiriez, A. (2009). Thermodynamic Analysis of Resources Used in Manufacturing Processes, *Environmental Science and Technology*, 43(5), 1584-1590.

[13] Gutowski, T.G., Sahni, S., Allwood, J.M., Ashby, M.F. and Worrell, E. (2013). The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand, *Philosophical Transactions of the Royal Society A*, 371(1986), 20120003, doi:10.1098/rsta.2012.0003.

[14] Rajemi, M.F., Mativenga, P.T. and Aramcharoen, A. (2010). Sustainable machining: selection of optimum turning conditions based on minimum energy considerations, *Journal of Cleaner Production*, 18(10-11), 1059-1065.

[15] Narita, H., Kawamur, H., Chen, L., Fujimoto, H., Norihisa, T. and Hasebe, T. (2008). Development of Prediction System of Environmental Burden for Machine Tool Operation (2nd Report, Proposal of evaluation indicator for eco-efficiency), *Journal of Environmental and Engineering*, 3(2), 307-315.

[16] Salonitis, K. and Ball, P. (2013). Energy Efficient Manufacturing from Machine Tools to Manufacturing Systems, *Procedia CIRP*, 7, 634-639.

[17] Branham, M.S. and Gutowski, T.G. (2011). Deconstructing Energy Use in Microelectronics Manufacturing: An Experimental Case Study of a MEMS Fabrication Facility, *Environmental Science and Technology*, 44(11), 4295-4301.

[18] Sharif Ullah, A.M.M., Hashimoto, H., Hayashi, F., Omori, R., Nagara, Y., Kubo, A., Tamaki, J. (2012). *Comparison between wooden and conventional prototyping: An eco-manufacturing perspective*. In: Design for Innovative Value Towards a Sustainable Society (Editors: Matsumoto, M., Umeda, Y., Masui, K. and Fukushige, S.), pp. 877-881, doi:10.1007/978-94-007-3010-6_179.

[19] Sharif Ullah, A.M.M., Hashimoto, H., Kubo, A. and Tamaki, J. (2013). Sustainability analysis of rapid prototyping: material/resource and process perspectives, *International Journal of Sustainable Manufacturing*, In Print.

[20] -.CES Selector, Eco-module, Version 5.1.0, Granta Design Limited, UK (http://www.grantadesign.com).

[21] Yuan, C., Zhai, Q. and Dornfeld, D. (2012). A three dimensional system approach for environmentally sustainable manufacturing, *CIRP Annals - Manufacturing Technology*, 61(1), 39-42.

[22] Diaz, N., Ninomiya, K., Noble, J. and Dornfeld, D. (2012). Environmental Impact Characterization of Milling and Implications for Potential Energy Savings in Industry, *Procedia CIRP*, 1, 518-523.

[23] Rashid, M.M., Sharif Ullah, A.M.M., Tamaki, J. and Kubo, A. (2011). Evaluation of Hard Materials using Eco-Attributes, *Advanced Materials Research*, 325, 693-698.

[24] Sharif Ullah, A.M.M., Kitajima, K., Akamatsu, T., Furuno, M., Tamaki, J., and Kubo, A. (2011). On Some Eco-indicators of Cutting Tools, P*roceedings of the ASME MSEC 2011*, pp. 105-110. doi: 10.1115/MSEC2011-50071.