SiC particle reinforced Al matrix composites brazed on aluminum body for lightweight wear resistant brakes

SiC particle reinforced Al matrix composites brazed on aluminum body for light-weight wear resistant brakes

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Keywords: composites; functional applications; wear; joining.

Abstract

Aluminum alloys are well known light-weight alloys and very interesting materials to optimize the strength/weight ratio in order to reduce automotive vehicle weight, fuel consumption and CO_2 emissions; unfortunately, they are also relatively soft and therefore cannot be used for high wear applications.

The aim of this work was to develop an aluminum alloy brake disc with wear-resistant SiC particle reinforced aluminum matrix composites (SiC/Al) joined on to its surface. Different approaches based on brazing or shrink fitting joining technologies were used to join SiC/Al to the aluminum alloy surface.

A functional graded structure was built by brazing thin layers of aluminum matrix composites reinforced with progressively higher amount of SiC particles by using a Zn-Al based alloy as joining material. Several samples were prepared by shrink fitting and brazing: 40 mm x 40 mm x 10 mm samples and a 100 mm diameter brake disc with 68% SiC particle reinforced Al matrix surface and aluminum alloy A365 body.

Tribological tests demonstrated that an aluminum alloy brake disc with wear-resistant SiC particle reinforced aluminum matrix composites (SiC/Al) brazed on its surface is a promising technical opportunity.

Keywords: joining, brakes, metal matrix composites, wear

Introduction

There is a strong interest in transportation industry to obtain lighter components in order to decrease fuel consumption and decrease CO_2 emissions. The amount of aluminum alloys used in passenger cars has risen significantly in the past decades, which resulted in an overall improved energy efficiency [1].

Aluminum alloys are used in many different components like wheels, heat exchangers, transmissions, and other engine components. This is possible because aluminum alloys have several unique properties, in particular, a high strength to weight ratio, an excellent thermal conductivity and corrosion resistance; furthermore, they are easy to machine and recycle [2].

On the other hand, they are relatively soft and offer insufficient wear resistance for applications where high rubbing loads are present. Therefore, passenger car brake discs are currently made of cast iron [3]. Some sport and top luxury cars are also equipped with carbon-based and aluminum based ceramic matrix composite brake discs [4]. Their cost is still too high to extend their use to other cars [5].

A considerable amount of literature has been published on braking systems manufactured using only CMCs ; main issues regard the improving of oxidation resistance [6-9] . In particular, C and SiC based composites show superior friction behavior, especially for ventilated brake disks. Nevertheless, CMCs also suffer from a number of technological limitations, due to the difficulty of their joining to other structural parts (i.e metallic components) [10]

Al alloys have much lower density than cast iron, lower cost than carbon-based ceramic matrix composites, but unfortunately also present lower wear resistance compared when cast iron.

In order to increase the aluminum alloy wear resistance, several ways have been explored: typically, the surface can be reinforced by applying hard and wear resistant coatings such as ferrous coatings by thermal spraying [11], micro-arc oxidation or plasma electrooxidation where a very hard and strong layer of Al_2O_3 can be obtained [12-15].

Recently, new precipitation hardened alloys have been studied [16] or bimetal brake discs with a cast grey iron friction cladding and an aluminum alloy core [17].

Other more exotic materials have been studied and designed for brake systems [18]: ULTALITE® is a low cost aluminium metal matrix composite that uses ceramic particles extracted from fly ash as reinforcement to increase the wear resistance, provide high thermal conductivity and good machinability. Alternatively aluminum can be reinforced with natural fibers (i.e coconut fiber), thus exploiting agricultural waste. The wear behavior of ceramic waste SiC particle-reinforced aluminum matrix composites prepared by powder metallurgy process has been also described. [19]

Researcher at the University of New York, USA [20] reported online about a research project aimed to obtain ceramic-aluminium composite brakes: it consists of an aluminium alloy reinforced with functionally graded ceramic particles and fibers which are located in specific areas of the brakes, where additional strength is needed.

Some attempts with alumina and alumina-based ceramic matrix composites as high wear resistance materials joined on the surface of Al-alloys have been reported in refs [21, 22]: the option initially considered, i.e. to prepare a thin monolithic ceramic disc and to join it to the aluminum alloy brake body was abandoned because of the ceramic brittle behavior.

A second option was tested, with several ceramic inserts joined on the top of the aluminum alloy brake disc to cover it as in a mosaic: several issues related to inserts planarity, brittleness, and the overall mechanical resistance of these joints were discussed in [22].

Recently, Opel et al [23] reported a new concept of metal-ceramic hybrid brake disc; it is based on C/SiC friction segments fixed by screws onto an Al carrier body. This design allows to reduce the amount of CMC material needed for the manufacturing of the brake disc, while screwing the friction segments onto the metallic body ensures easy disassembling and replacement of the segments in case of failure of a single friction element.

The major challenge in brazing ceramics or metal matrix composites to aluminum alloys originates from their different coefficient of thermal expansion (CTE) and consequently different shrinkage after cooling to room temperature. Large thermal stresses are generated, which can compromise the mechanical properties of the final product. The graded structure recently became an interesting solution for brake systems; in order to withstand severe conditions during braking, such as high wear and temperature, functionally graded material (FGM) can be used: the wear resistant material (i.e. SiC) embedded in a metallic matrix can be tailored according to the required performance [24].

Several processes are available [25] for manufacturing functionally graded aluminum matrix composites, such as centrifugal casting, powder metallurgy, spray casting, infiltration, etc.

The idea behind this work is to use aluminum alloys to build the brake disc body and to improve its wear resistance only where needed, i.e. by joining high wear resistance composites on its surface. Two different approaches to obtain these will be discussed in this paper: a graded structure and a specially designed shrink fit joint method.

Experimental

Two typical aluminum alloys were selected, namely A380 and A356, which are widely employed in automotive and other industries: their composition and properties are listed in Table 1. All samples were casted at Fagor Ederlan, Spain, using a low-pressure aluminum casting process.

SiC particle reinforced Al matrix composites with SiC particle volume % ranging from 30 to 68, supplied by Japan Fine Ceramics (Japan) and Ametek Specialty Metal Products (USA) were employed, and their properties are listed in Table 1.

A brazing alloy made of 98 Zn–2 Al ribbons (thickness 300 μm) supplied by Lucas Milhaupt (USA) was used as joining material in Ar at 500 °C; it has a solidus temperature at 377°C and a liquidus one at 385°C. Several layers of different SiC/Al composites with progressively higher amount of SiC particles were stacked and joined by placing the braze ribbons between each layer, to obtain 20 mm x 20 mm x 10 mm samples, with the 30 % vol SiC/Al in contact with the A380 or A356 Al alloys.

In all the samples, 68% SiC/Al or 60% SiC/Al were the top layers. A larger sample of about 40 mm x 40 mm x 10 mm was made with the same method, i.e. by joining SiC/Al composite layers with progressively higher amount of SiC particles on a A365 alloy, with 60% SiC/Al as the top layer. Hereinafter, these samples have been produced and tested to characterize a wear resistant top layer coated FGM.

Other samples were prepared by shrink fitting and brazing: A365 samples were machined with a suitable frame able to shrink-fit the SiC/Al composite (4 mm thick) during cooling to room temperature; ZnAl ribbons were placed inside the A365 frame and heated at 500°C, in Ar flow. Then the SiC/Al composite was placed inside the frame and kept at this temperature for 60 minutes and afterwards cooled to room temperature. Different kinds of SiC/Al composites were brazed in this configuration on the A356 substrate: SiC particle reinforced Al matrix composites with SiC particle volume of 40%, 68%, and 70 %.

The frame size was calculated according to the A365 CTE, in order to shrink fit the SiC/Al composite during cooling to room temperature; hereinafter these samples are indicated as “framed samples”. The same shrink fitting and brazing method was used to prepare a downsized-disc (100 mm diameter) with the whole A356 surface covered by a 68%SiC/Al composite ring. The manufactured samples were cross sectioned, polished and observed by optical and electron microscopy (SEM Philips 525M and Leo 430i) and by energy-dispersive analysis (EDS SW9100 EDAX and Oxford Isis300).

The following samples/prototypes underwent tribological testing:

1. Cast iron, Al_2O_3, SiC specimens as reference materials;
2. 68%SiC/Al specimen as selected material for FGM top layer, henceforth referred to as wear resistant top layer coated FGM;
3. A356- 40% SiC/Al, A356- 68% SiC/Al, A356 –70%SiC/Al framed samples, henceforth referred to as 40 SiC/Al framed samples, 68 SiC/Al framed samples and 70 SiC/Al framed samples, respectively;
4. Reference downsized cast iron disc and downsized A356+68% SiC/Al disc, henceforth referred to as 68 SiC/Al downsized disc.

As counterpart two materials were selected: Normal Production friction material pad provided by CRF (referred to as NP; it is an hard pad) and a special friction material for Al discs provided by Ederlan (referred to as SP; it is a soft pad).

A „pin on disc“ test configuration was selected for specimens used in the cases described in point 1. and 2. listed above and tested at Centro Ricerche Fiat tribology lab CRF, Italy (see Figure 1). Air blowing system was used to simulate car brake cooling in a running vehicle.

Friction coefficient and temperature were measured continuously during the test ; pin and pad wear volume was measured after the test. The tests were repeated at least two times. Wear of the friction pad pins elements was measured by weighting using a

KERN ABT200-5DM an-alytical balance (max weight 220 g, readability 0.1 mg) and the temperature was registered by an IR-tec P500 pyrometer (temperature range -30°C-930°C, accuracy ±1%, emissivity 0.1-1) focused on the disc contact surface. Weight loss in percentage was quantified for each test.

The same type of test was selected for framed specimens as described at point 3, listed above, but a special holder was developed for these samples (Figure 1 c). The test conditions for specimens at points 1., 2. and 3. are reported in Table 2.

Finally, a tribological test was carried out on downsized brake discs (as indicated at point 4): the apparatus test is shown in Figure 2.

In this case a 110 mm diameter disc simulating a brake disc was used to assess the brazed joint strength and a dedicated downscaled testing protocol reproducing the testing conditions of the full-scale brake disc was used.

The applied force was 700N (split on three pad pins) and the rotational speed of sample was 4000 rpm. The environmental condition foresees dry environment and the test temperature was monitored on the sample, measured by a pyrometer.

Results and discussion

The idea behind this work was to use an aluminum alloy to make a lightweight brake disc body and to coat its wear-affected surface with a hard and wear-resistant material. The initial concept is schematically shown in Figure 3. An aluminum alloy is used for the body onto which SiC/Al inserts are brazed.

The selected SiC particle reinforced composites (SiC/Al) and their thermo-mechanical properties are listed in Table 1. As expected, all properties and in particular their coefficient of thermal expansion tend to decrease when increasing the SiC particle amount from 30 % to 68 % volume.

To overcome the coefficient of thermal expansion mismatch, a functionally graded approach was initially designed (as sketched in Figure 4) by brazing layers of different SiC/Al with progressively higher amount of SiC particles with the ZnAl joining material. This protocol guarantees a gradual variation of coefficient of thermal expansion and elastic modulus from the bulk aluminum alloy to the SiC/Al with the highest SiC content.

Several graded structures of about 20 mm x 20 mm x 10 mm, were successfully made with brazing layers of SiC particle reinforced Al matrix composites with different SiC content on A380 aluminum alloy. The cross section is shown in Figure 5a and higher magnification of interfaces are shown in Figures 5 b – d. The joined areas are free of defects, continuous, without cracks and pores. The FGM structure shows continuity and all the brazed structures exhibit sound joined interfaces; 68% SiC/Al is the top layer, (Figure 5 d). With the purpose of testing its feasibility, an alumina layer was brazed as top layer to a 50%SiC/Al composite (Figure 5a): this solution with alumina as top layer will not be discussed here. A larger sample of about 40 mm x 40 mm x 10 mm was made (Figure 6) by joining SiC/Al composite layers on a A365 alloy. Figure 6 c shows the cross section, with 60% SiC/Al as the top layer: the aim of this scaling up was to increase the size up to a prototype brake disc of about 100 mm diameter.

Several attempts were made to increase the size of these samples: unfortunately, partial detachment of one or more layers made this process unsuitable, at least in our laboratory furnaces.

The main reason of the upscaling process failure can be due to larger residual stresses and/or inhomogeneous joined interface than with the smaller samples.

Joining of dissimilar ceramic and metallic materials with differing CTEs via thermal processes such as brazing leads to significant thermal stresses. The stresses can increase with increasing joining temperature as the CTE mismatch between the ceramic and metal partners is increasing with temperature [26]. Ceramics have a low fracture toughness and therefore can fail easily by combination of thermally induced tensile and shear stresses during cooling at the joint interface [26-28]. In addition the size of the ceramic and metal components have also been shown to have a significant impact on the magnitude of these stresses [29]. The residual stresses in components being much larger than those calculated in test samples [29].

Difficulties in terms of upscaling can also arise by the difference in coefficient of thermal expansion of the functional graded structure developed by brazing different MMCs to an Al alloy plate.

The CTE of the Al alloy is 22 $x10^{-6}$ K^{-1} and then lower where the SiC content is increased in the MMC (14.5 $x10^{-6}$ K^{-1} for Al-30%SiC, 11.5 $x10^{-6}$ K^{-1} for Al-40%SiC, 9.5 $x10^{-6}$ K^{-1} for Al-50%SiC, 8.4 $x10^{-6}$ K^{-1} for Al-60%SiC), accordingly to values reported in Table 1.

The coefficient of thermal expansion gradually changes, consequently to the variation in SiC content in the MMC. The gradation reduces the local stress concentration, thermal and residual stresses, which are commonly experienced in traditional composites.

In anycase, the developed component is obtained by brazing and an additional discontinuity in terms of CTE at the interfaces between each MMCs and the MMC close to Al alloy plate (30%SiC/Al) occurs.

Some cracks or voids due to incomplete brazing process or local lack of joining material can lead to detachment of the structure; moreover, controlling the planarity of larger surfaces can be a critical issue in manufacturing of larger joined samples and can lead to unsound joined interfaces.

An alternative approach was then developed, based on shrink fitting and brazing of one layer only of SiC/Al composite in a A365 frame. The ZnAl joining material (ribbons) were used as redundancy joining materials, since the A365 firmly framed the SiC/Al by shrink fitting. This approach was successfully used with all SiC/Al composites, Figure 7 shows a sketch of the process (Figure 7 a) and the samples with 40% and 70% SiC/Al composites framed by the Al-alloy (Figure 7 b, c) . The same shrink fitting and brazing method was used to prepare a downsized disc prototype (100 mm diameter) with the whole A356 surface covered by a 68%SiC/Al composite ring (Figure 8).

The shrinkage of the sample showed in Figure 7 and the resulting clamping stresses need to be recognized as critical feasibility issues. In principle, it can be supposed that geometry shown in Figure 7 leads to higher stresses than in case of the downsized disc prototype (round shape of the disk , without sharp edges, Figure 8), manufactured using the same shrink fitting and brazing method , but further investigations are needed to study this issue.

Even better results are envisaged when the geometry is adopted after a suitable modelling: work is in progress on this point.

Tribological tests (pin-on-disc sketched in Figure 1) were used as an exploratory test on candidate materials for the top layer alone and for the 40 mm x 40 mm x 10 mm framed, according to specification given in the Experimental section. Cast iron, Al_2O_3 and bulk

SiC were also tested as a reference against standard production pads material for cast iron discs (NP) and special pad material for aluminum based discs (SP).

The maximum applicable temperature of the proposed systems is about 400-450°C. According to values reported in Table 1 and to the complex structures of proposed braking systems (brazed FGM and shrink fitted MMC brazed onto an Al alloy plate) the temperature distribution of the brake disc at different stages of braking operation is not predictable at this stage of the investigation.

In any case, the maximum recorded temperature during tribological tests is 300°C; the tests have been stopped after reaching this temperature in order to avoid overheating of the testing equipment. Regardless, no thermally damaged areas have been detected in the sample after testing.

Tribological tests results are reported in Figure 9. In the case of the pad material for Al based discs, the coefficient of friction value for the 68 SiC/Al framed samples falls in the appropriate range for braking application (typical values are from 0.35 up to 0.5), whereas in case of pad material for cast iron disc the coefficient of friction (CoF) results to be above the acceptance limit, when using the SP pad. This behavior is typical since this pad is not designed for cast iron but for aluminum discs. This outcome enforces the consideration that in a tribological system when one of the mating materials changes, the counterpart material also must be accordingly adapted for achieving the same performance.

68%SiC/Al composite moreover shows an excellent heat dissipation behavior, since the temperature increment was very small, comparable to that of allumina.

The maximum reached temperature during the test is higher for alumina than for MMC samples, if SP pad is used, accordingly to thermal conductivity of both materials (15 to 30 W/mK for alumina, 210 W/mK for Al-SiC68%)

Moreover, alumina and Al-SiC68% show comparable specific heat capacity values. As a consequence, the thermal behaviour of the proposed MMC shown in Figure 9 is similar to that of alumina.

Considering the effect of the pad material, wear results were satisfactory specially for the SP pad solution:. In fact, the pad wear values against 68%SiC/Al are comparable with those obtained in case of pure ceramic disc materials and significantly lower in comparison with cast iron disc counterpart.

In Figure 10 the experimental data obtained by tribological tests on SiC/Al framed samples (40 SiC/Al framed samples, 68 SiC/Al framed samples and 70 SiC/Al framed samples) are shown; three SiC percentages from different suppliers were considered according to data reported in Table 1. Based on previous results the customized pad material for Al discs (SP) was used as the counterpart.

The maximum temperature measured on the surface varied accordingly to thermal conductivity of the composite materials (see Table 1) and values are aligned for the two suppliers. The higher the thermal conductivity, the lower is the surface temperature, due to the faster heat dissipation effect. Coefficient of friction values are in the expected range for all the three framed samples . The smallest pin weight loss was obtained for 40SiC/Al samples. Similar values were obtained for 40 SiC/Al and 70 SiC/Al framed samples, even if characterized by different SiC content, while wear of the pad material is higher in case of 68 SiC/Al: these friction and wear results can be attributed to a different surface characteristic roughness of the material plates provided by different suppliers rather than to the difference in reinforcement content. Materials supplied by the same company show the same surface finish due to the proprietary manufacturing process; this leads to the same behavior in terms of pad wear, independently from the SiC content of the composites.

Accordingly, since the thermal exchange is related to the SiC content in the composites and does not show significant differences for the three composite materials and the wear is low (even if it depends on the surface roughness) for all the tested samples, it was decided to select for the upscaling the 68% SiC particle reinforced Al matrix composites in combination with lining material for Al disc. This choice was also justified by the availability of this last material in size and dimension suitable for larger component manufacturing.

The conditions and the parameters under which the tests were conducted on the 68 SiC/Al downsized disc are reported in Figure 11; the basic idea was to use developed test procedures based on automotive dyno testing protocols. The full scale system values of applied loads and rotational sliding velocities were downscaled to be adapted to the reduced disc dimension.

Three test procedures were developed to evaluate 68 SiC/Al downsized disc performance in comparison with downsized cast iron normal production disc:

- Braking at constant load: duration max 300s at following loads: 100N, 210N, 300N, 500N, 700N when running at 2000rpm; in the case of 500N and 700N a shorter drag time was applied (about 50s) to avoid system overheating; these series of tests were performed with different material couples:
    - downsized cast iron disc vs NP lining material (reference)
    - downsized cast iron disc vs SP lining material

- 68 SiC/Al downsized disc vs SP lining material

- Braking in Wet Conditions Simulation: 1800s @ 300N and 2000rpm, including 10 water spray events (10s each) to simulate braking in wet conditions;

- Repetitive Braking Drags Series: for a total length of 600s @ 4 load/speed combinations (2000-4000rpm, 200-300N) to simulate a sequence of alternate abrupt stops and slowing down braking conditions.

The results of these tests have been summarized in Figure 12, 13, 14.

Analyzing the results of the three procedures the following conclusions can be made:

- Test procedure 1 (Figure 12):

In case of downsized cast iron disc /NP pad in tests up to 300N the temperature increase was smooth until reaching a stable value and CoF was in the appropriate interval. For the case of downsized cast iron disc /SP pad too high CoF values and higher temperatures were measured even at low loads. Finally for 68 SiC/Al downsized disc /SP pad test, the tribocouple worked properly: appropriate values of CoF and temperatures resulted within a reasonable interval.

- Test procedure 2 (Figure 13):

Downsized cast iron disc /NP pad coefficient of friction shows a uniform value of around 0.5 along the test; temperature rises in the first 300s up to about 180°C, and maintains a uniform value. 68 SiC/Al downsized disc /SP pad couple shows a lower value of coefficient of friction, still in the acceptable interval, slightly decreasing over time, whereas temperature shows a sharp increase in the first 200s up to about 260°C, and then continuously decreases demonstrating the ability of the 68 SiC/Al downsized disc to reach a good equilibrium in thermal exchange over time.

- Test procedure 3 (Figure 14):

Each of the two downsized discs was tested against the most appropriate pad lining material; for both of them, and the CoF was in the proper range. The highest variability of temperature was measured for 68 SiC/Al downsized disc with significantly low values for min load/min velocity combination that demonstrated a higher sensitivity of the disc to abrupt variation of loading conditions.

Conclusions

SiC particle reinforced Al-based composites (SiC/Al) were used as a wear resistant protection layer for aluminum alloy car brake discs. Two approaches to join SiC/Al to aluminum alloys, brazing and shrink fitting, were investigated. SiC/Al composites were proven to have good tribological and thermal properties for this application.

The disc manufactured by using SiC/Al composites showed very promising results: the 68 SiC/Al downsized disc was able to bear the applied loads, the CoF was in the correct range and the heat dissipation behaviour was satisfactory.

By summarizing the experimental activity carried out on all samples (wear resistant top layer coated FGM, framed samples and downsized discs) it can be concluded that the coefficient of friction, which is the most important property for friction resistant materials and qualifies the braking safety of vehicles, was measured in the typical CoF ranges, for all samples. In particular, for composite materials, it is known that temperature is the most influential parameter on the CoF, due to the interfacial thermomechanical behavior which is affected by friction heating during braking and associated with the temperature rise: all the tested samples showed a certain increase in temperature which was comparable or even lower than that measured on more traditional friction materials, i.e. cast iron. The overall experimental screening activity conducted by pin on disc on all samples and by using counterpart "pins" really used in the production of brake pad lining materials, gave very promising results for a future application of brakes of this kind, specifically when an important weight reduction is needed.

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Captions

Table 1 Selected materials used in the experimental activity and their relevant properties

Table 2 Parameters for tribotesting on different materials

Figure 1 a) Sketch of a pin on disc tribological test b) photograph of the tribological test apparatus at CRF (Italy) c) fixture for framed joined samples (Horizontal pin-on disc)

Figure 2 Sketch of the device for tribological testing of downsized brake discs

Figure 3. Sketch of an aluminum alloy braze disc protected by wear-resistant SiC particle reinforced Al matrix composite.

Figure 4 Sketch of functionally graded material for braking system: bulk Al alloy brazed to different SiC/Al composites with increasingly higher amount of ceramic particles

Figure 5 SEM micrographs of polished cross-sections of SiC particle reinforced Al matrix composites with different content of ceramic particles (a); higher magnification images of : the interfaces between the Al alloy and 30%SiC /Al MMC (b); interfaces between 30%SiC /Al MMC and 40%SiC /Al MMC (c); interfaces between 50%SiC /Al MMC and 68%SiC /Al MMC (top layer) (d).

Figure 6 FGM sample manufactured by joining SiC/Al composite layers on A356 alloy (size 40 x40 x 40 mm^3) (a); sketch of the FGM structure (b) ; Low magnification SEM micrograph of joined interfaces (c)

Figure 7 Sketch of the shrink fitting and brazing assembly of SiC/Al composite on A356 frame (a) ; manufactured samples with 40% SiC/Al composite (b) and with 70%SiC/Al composites (c) framed by Al alloy

Figure 8 Downsized disc (100 mm diameter) manufactured by brazing the Al alloy to 68%SiC/Al composite ring

Figure 9 Friction coefficient and temperature for tribological tests made on wear resistant top layer materials ; C.I.= cast iron (data supplied for comparison purpose)

NP= normal production friction material pad, hard pad

SP= special friction material for Al discs, soft pad

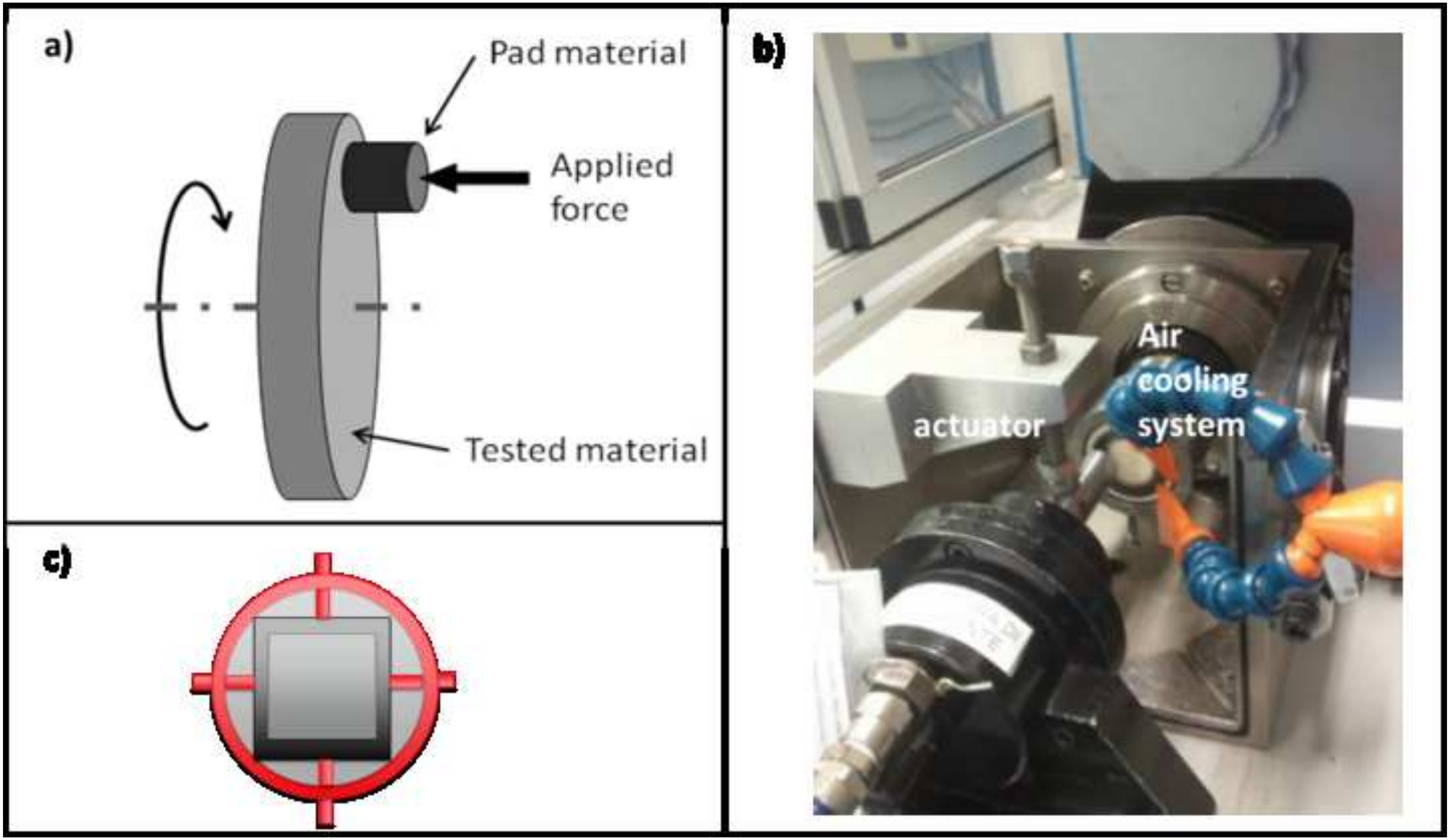
Figure 10 Friction coefficient and temperature for tribological tests made on framed samples

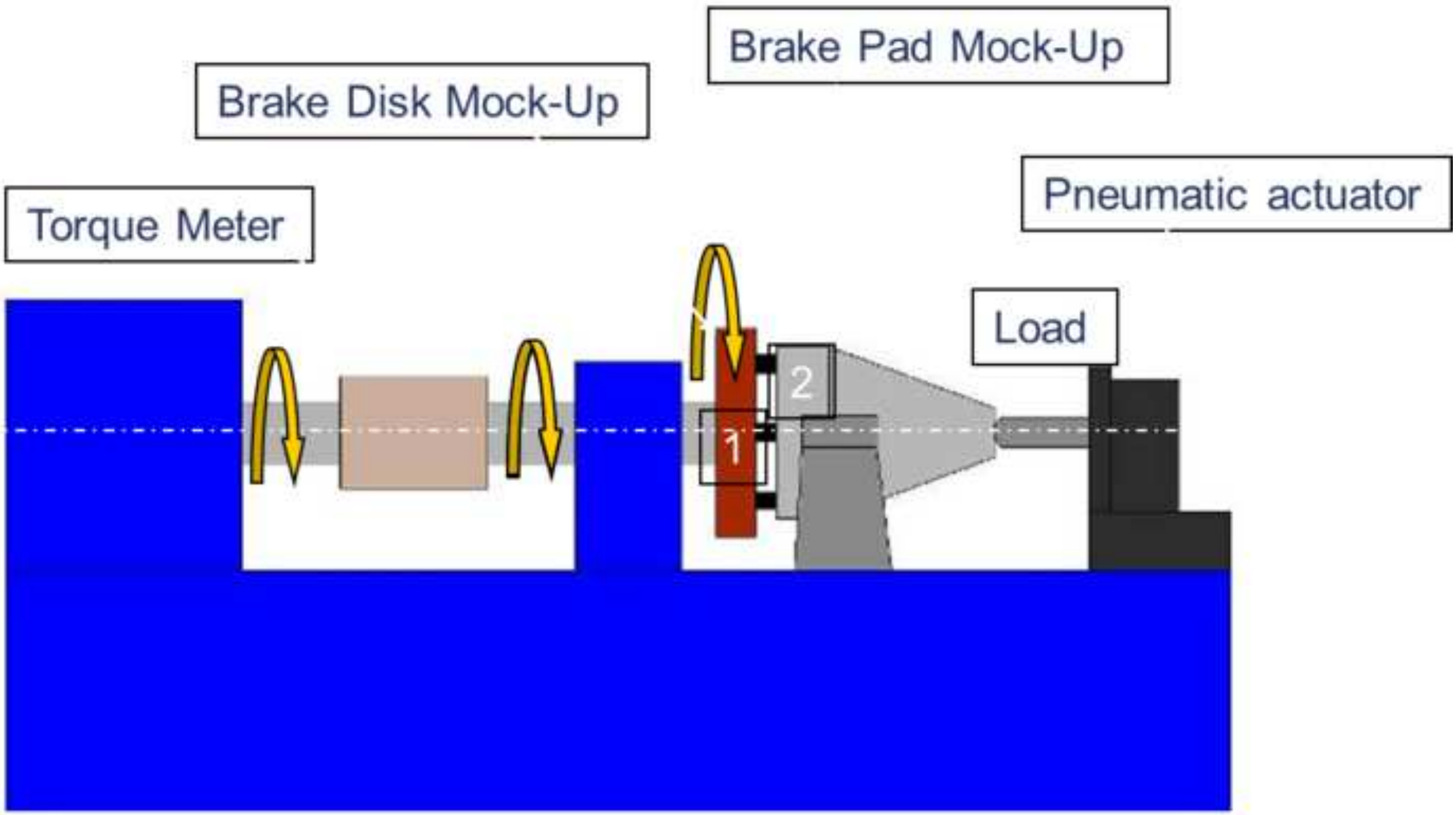
Figure 11 Tribological testing parameters for 68 SiC/Al downsized disc characterization

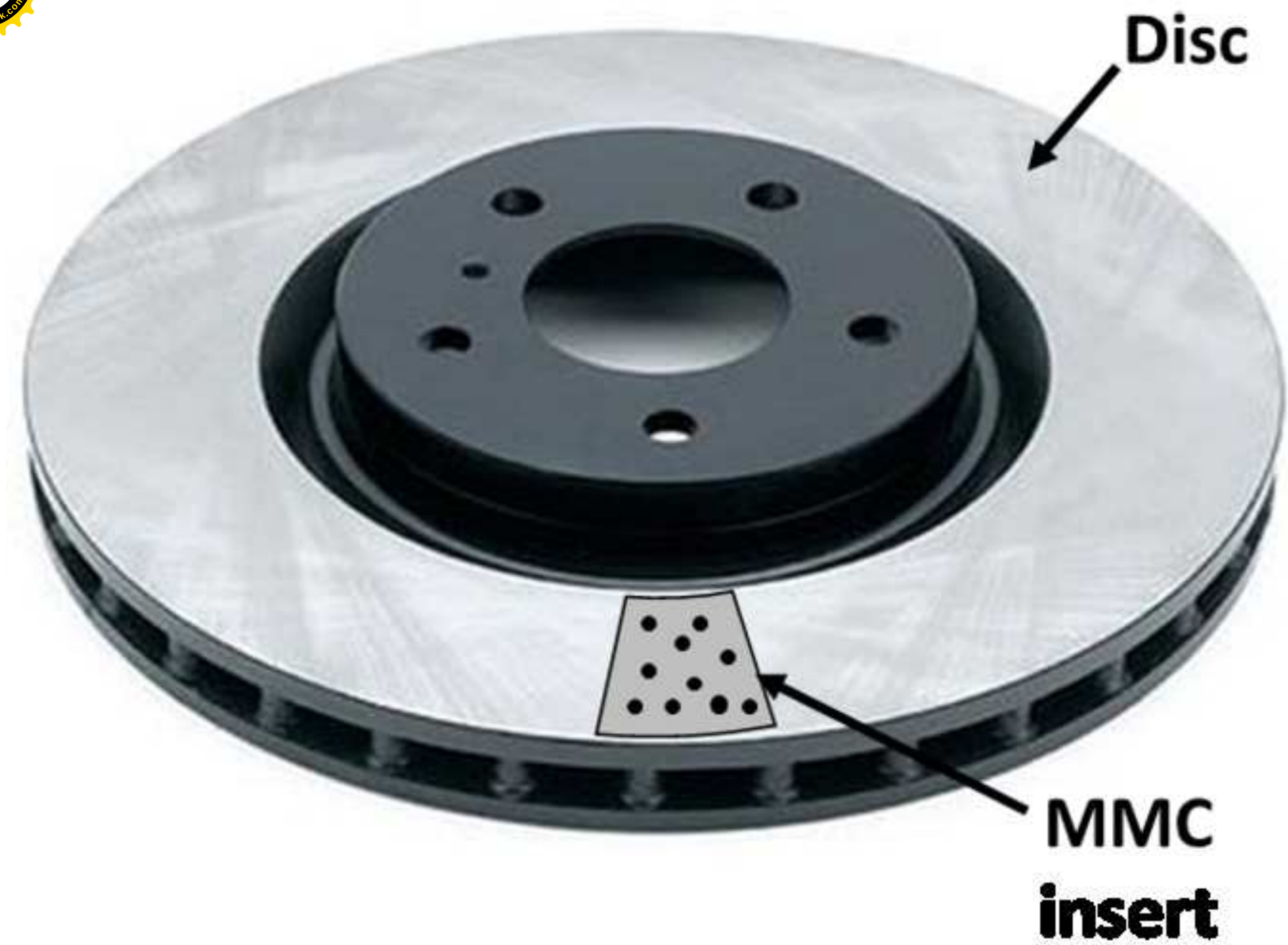
Figure 12 Results of the tribological testing with SP pad against 68 SiC/Al downsized disc (a); results of the tribological testing with NP (b) and SP (c) pad against downsized cast iron disc are given for comparison purpose

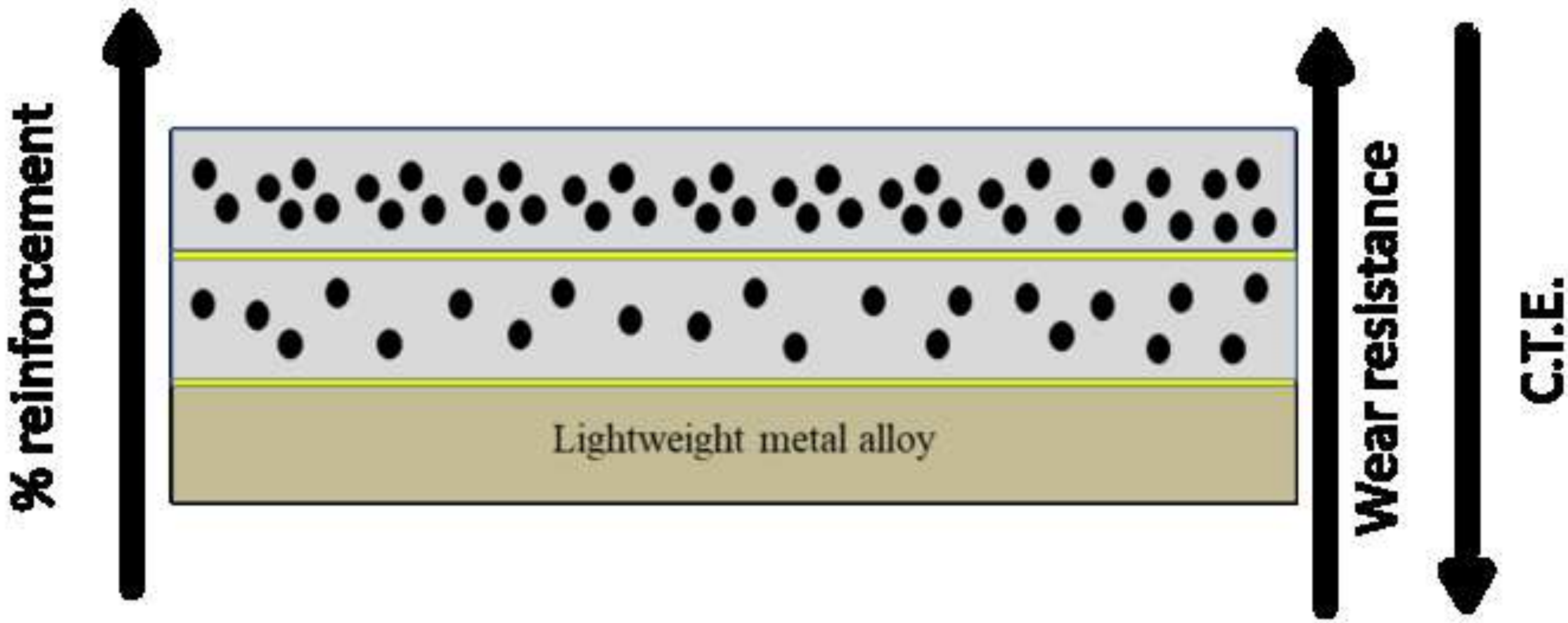
Figure 13 CoF and temperature trend of 68 SiC/Al downsized disc in wet conditions (load and speed are constant) ; cast iron data are given for comparison purpose

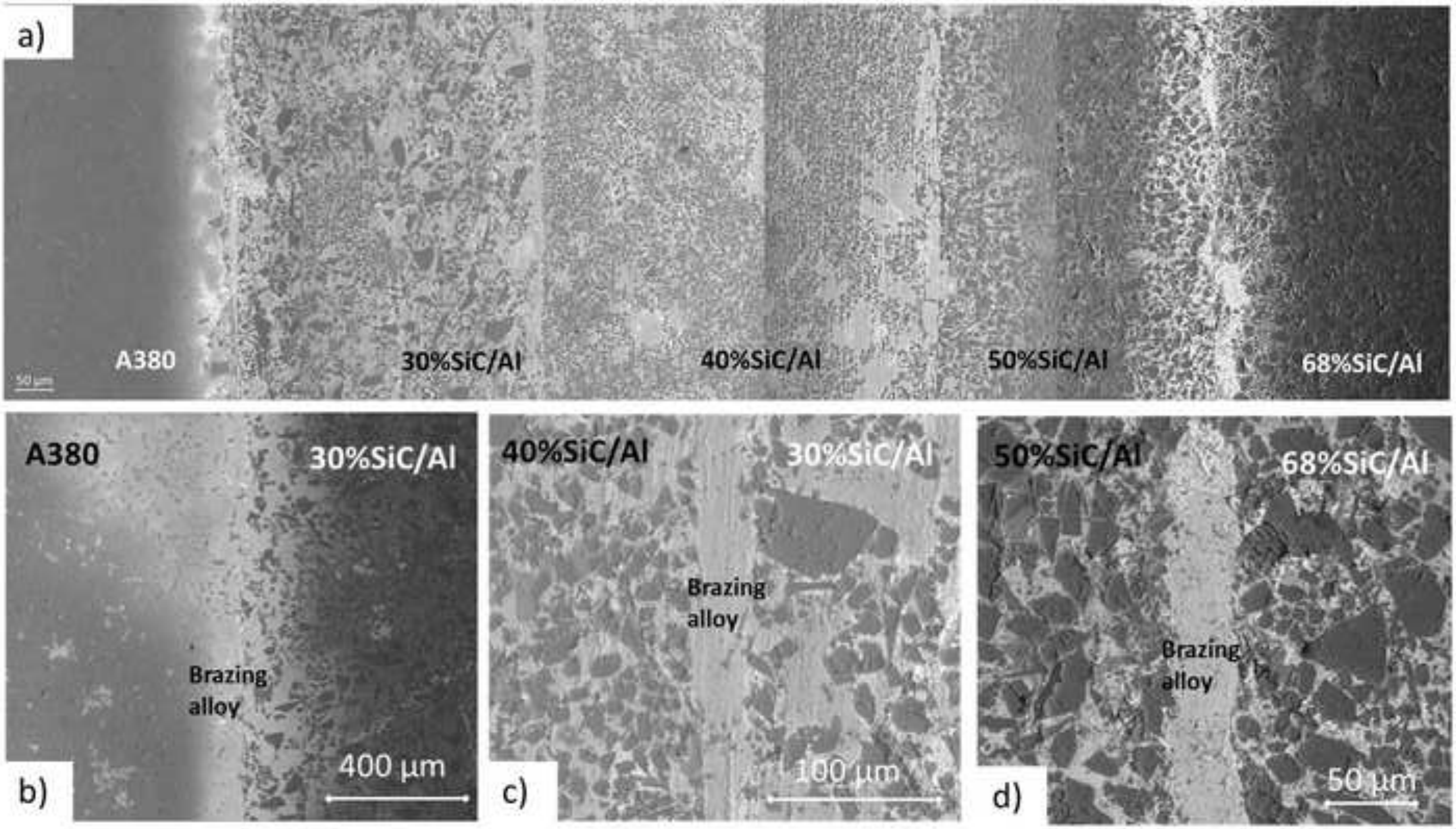
Figure 14 CoF and temperature trend of 68 SiC/Al downsized disc in repetitive braking drags series (repeated stops results); cast iron data are given for comparison purpose

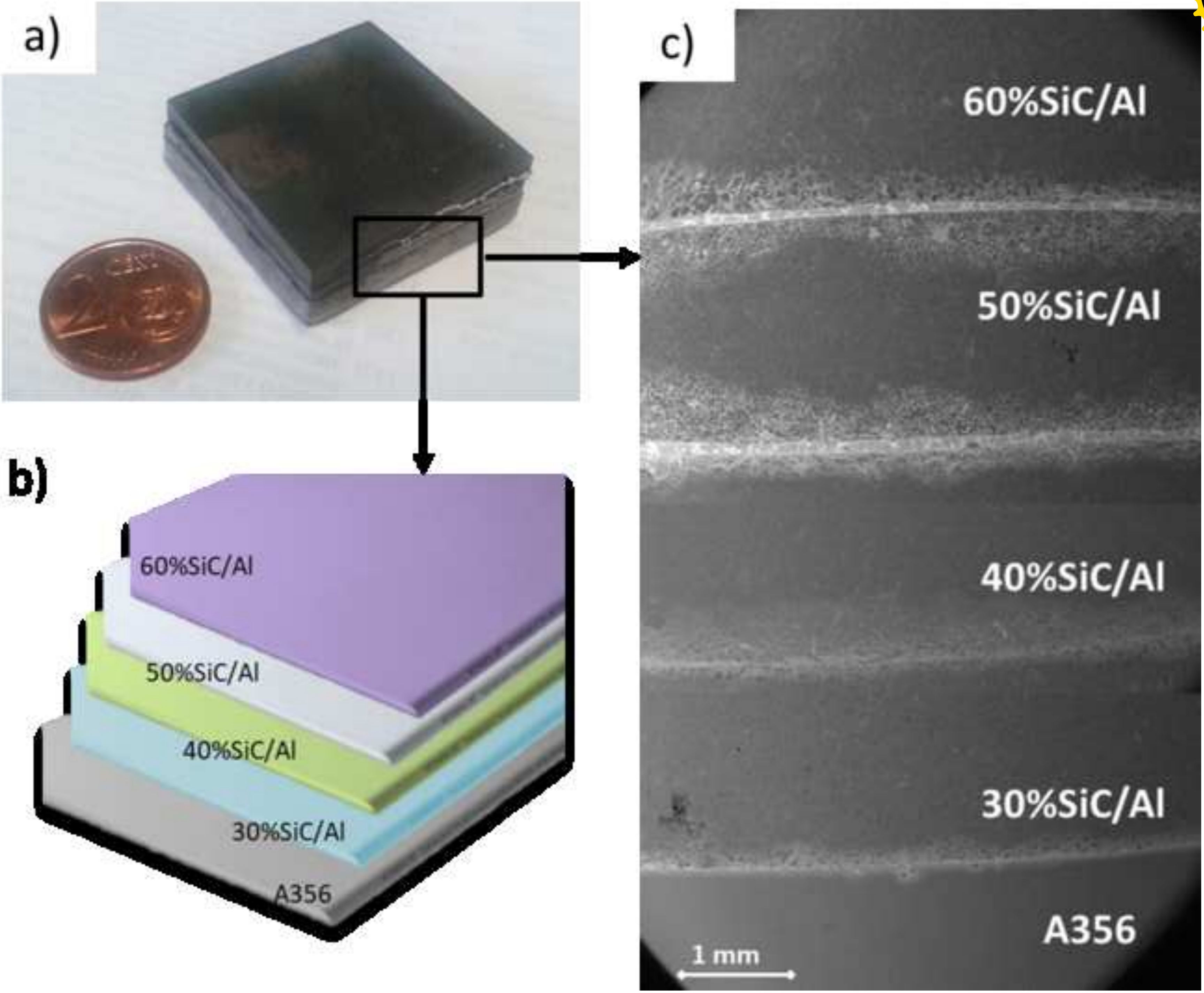

a)
Pad material
Applied force
Tested material
b)
Air cooling system
actuator
c)


Brake Disk Mock-Up
Brake Pad Mock-Up
Pneumatic actuator
Torque Meter
Load
2
1

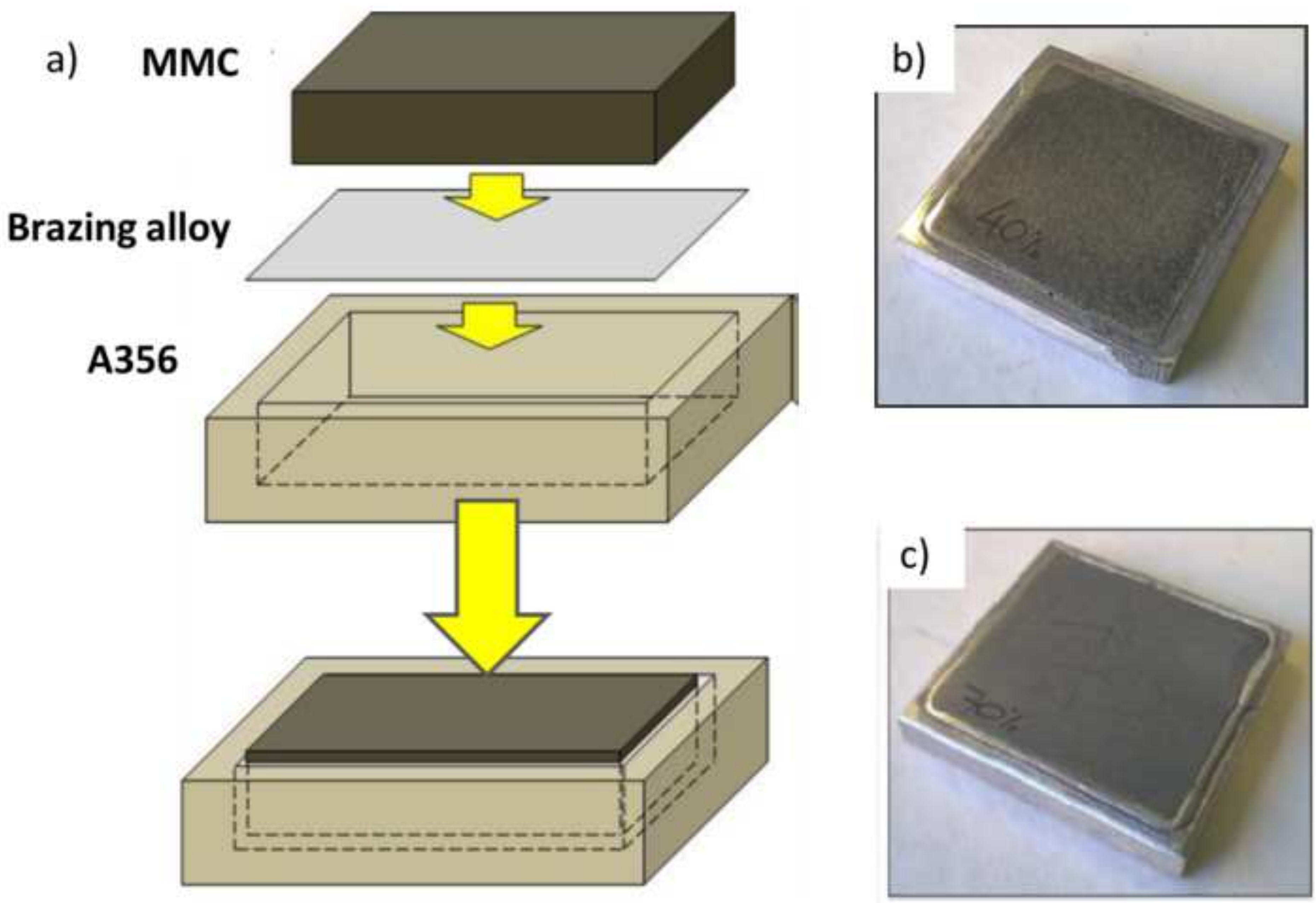

Disc
MMC
insert


% reinforcement
Lightweight metal alloy
Wear resistance
C.T.E.


a)
A380
30%SiC/Al
40%SiC/Al
50%SiC/Al
68%SiC/Al
A380
30%SiC/Al
Brazing alloy
400 µm
b)
40%SiC/Al
30%SiC/Al
Brazing alloy
100 µm
c)
50%SiC/Al
68%SiC/Al
Brazing alloy
50 µm
d)



a)
b)
c)
60%SiC/Al
50%SiC/Al
40%SiC/Al
30%SiC/Al
A356
60%SiC/Al
50%SiC/Al
40%SiC/Al
30%SiC/Al
A356
1 mm


a)
MMC
Brazing alloy
A356
b)
40%
c)
30%

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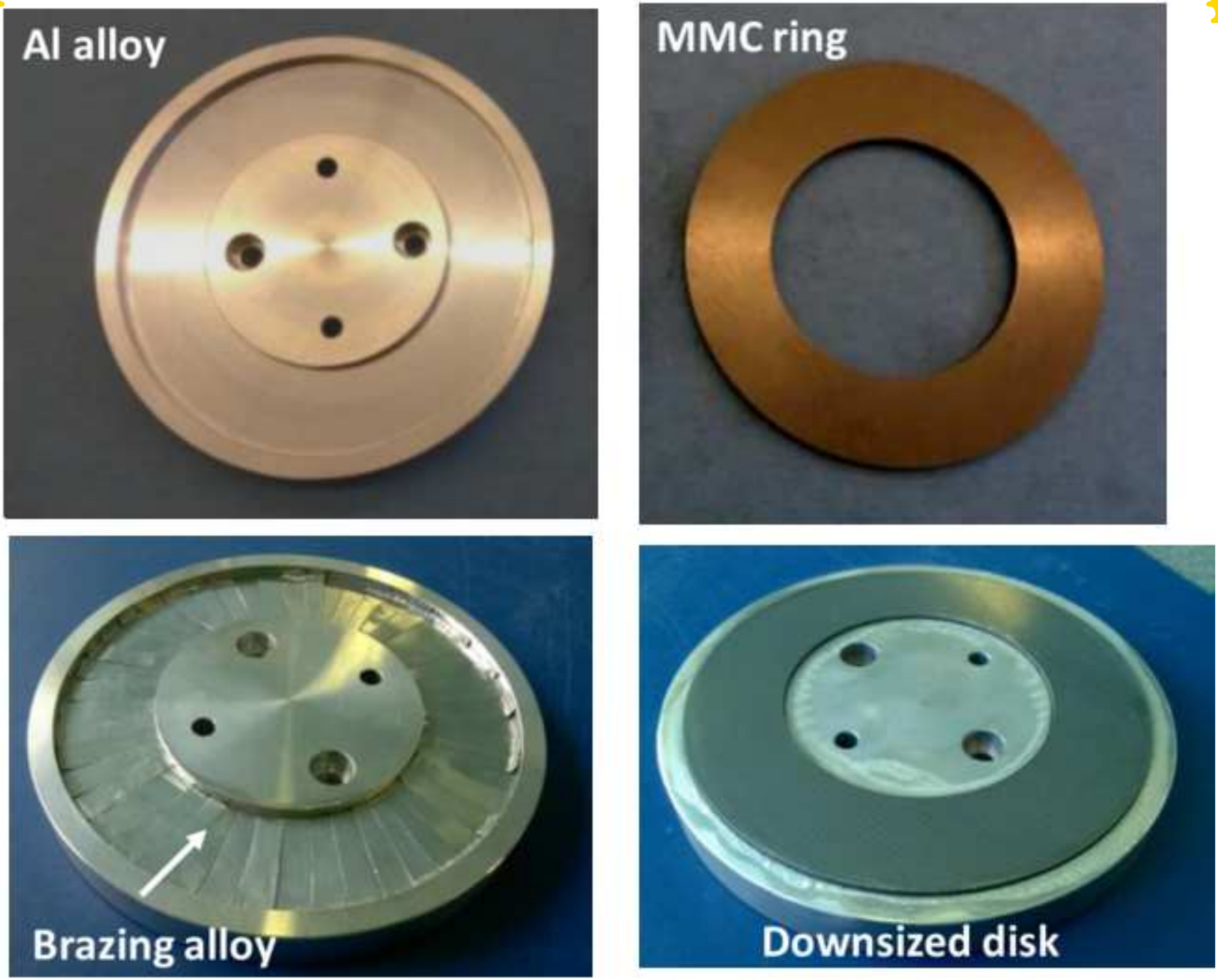
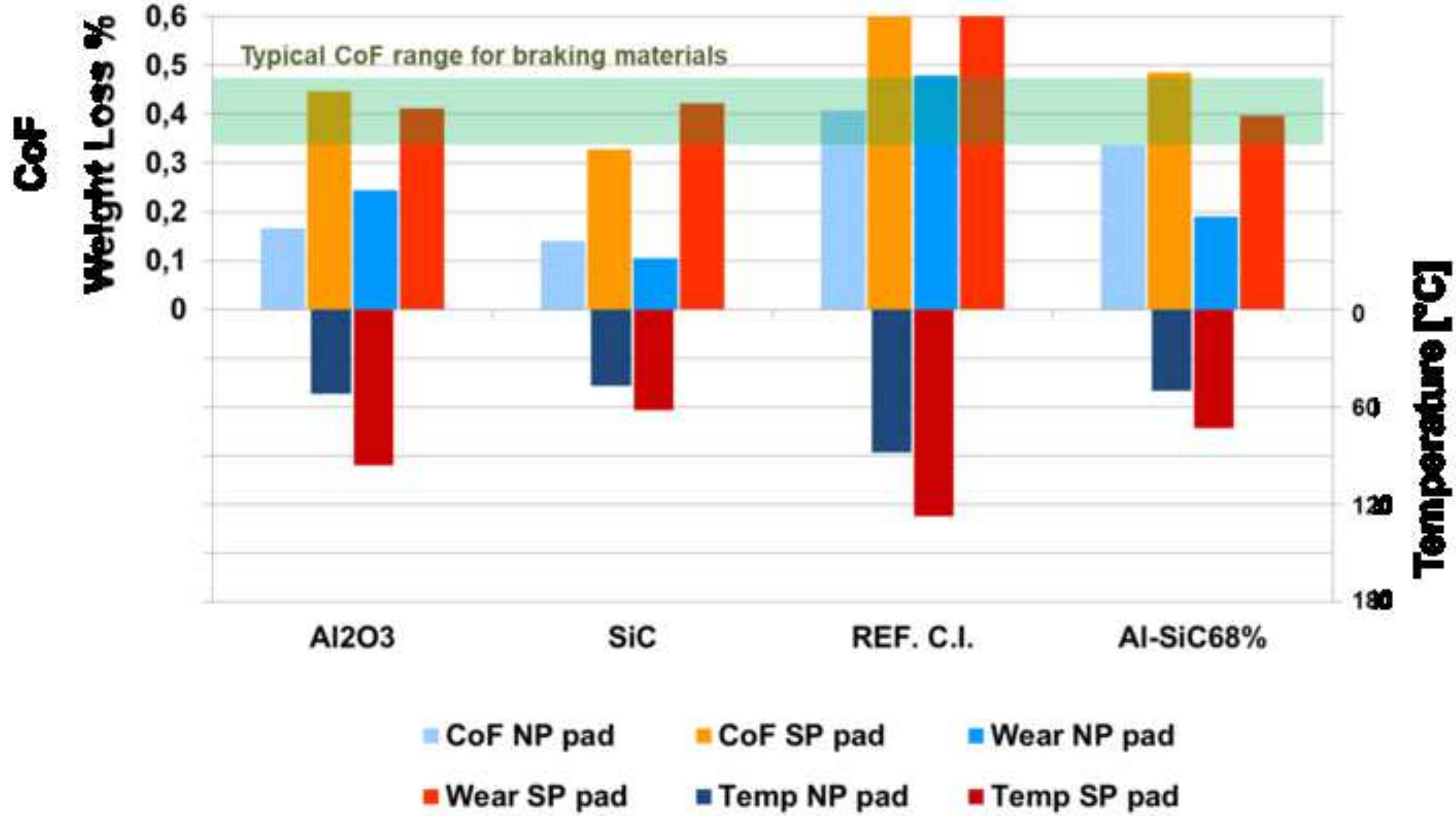
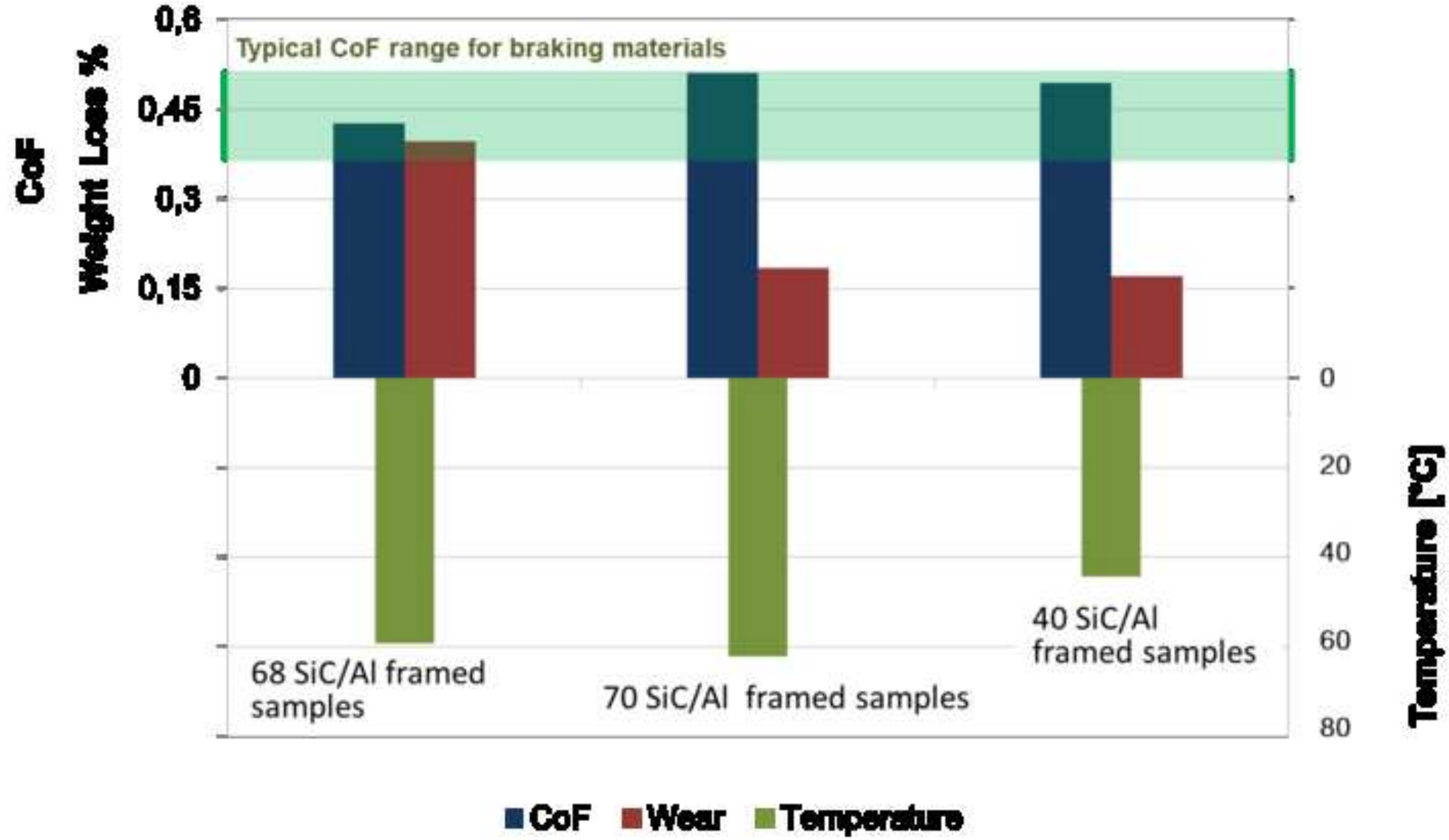
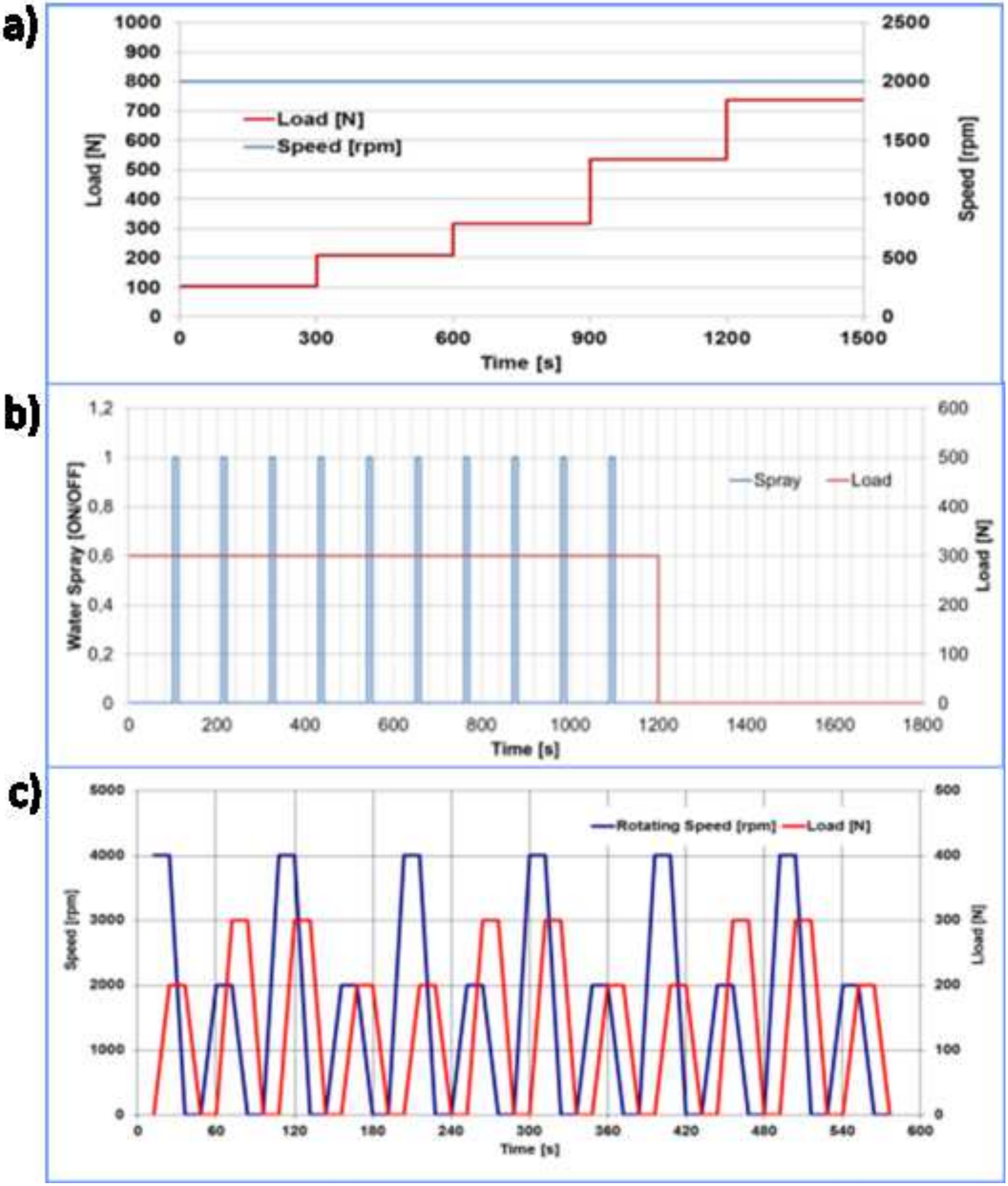
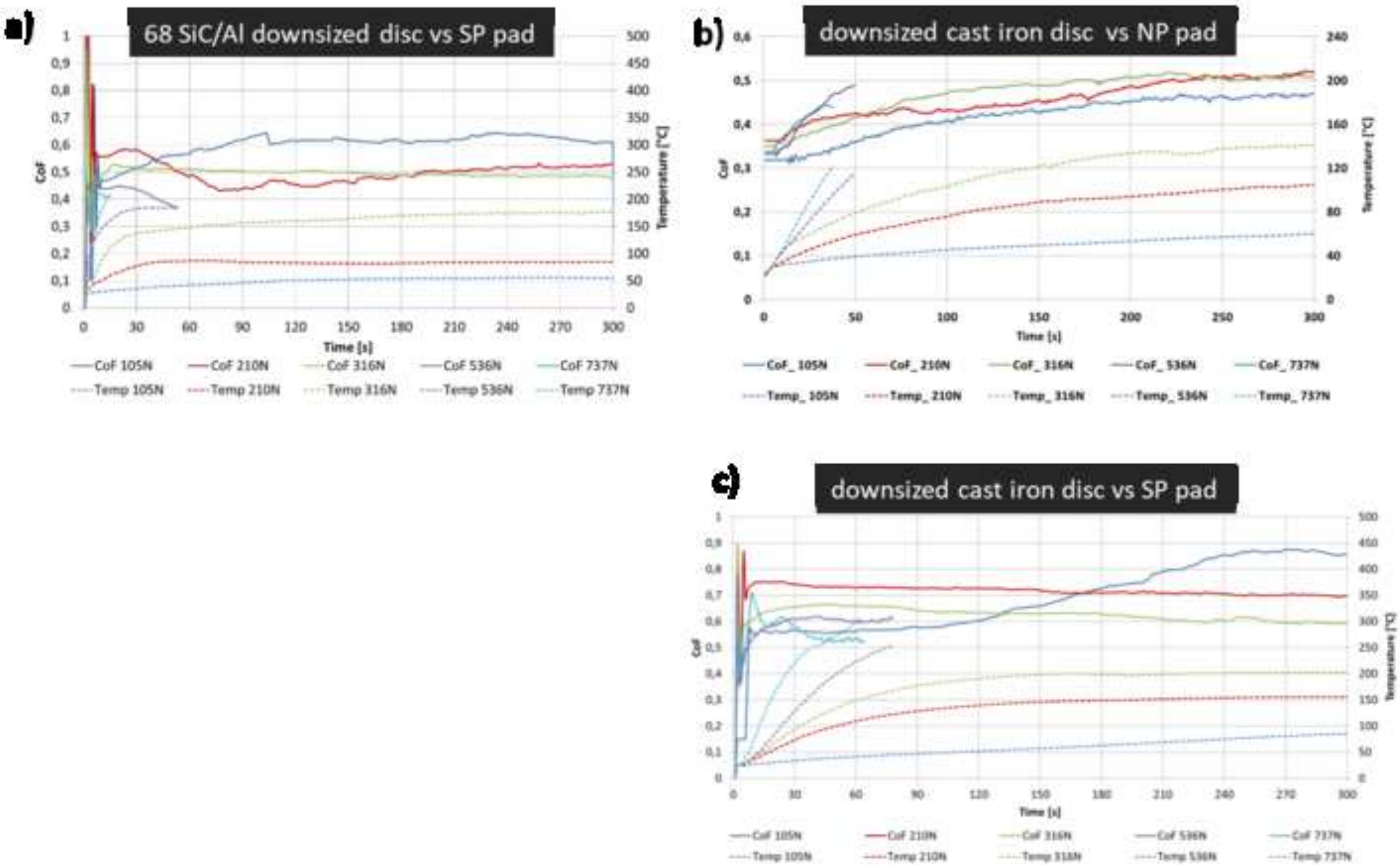


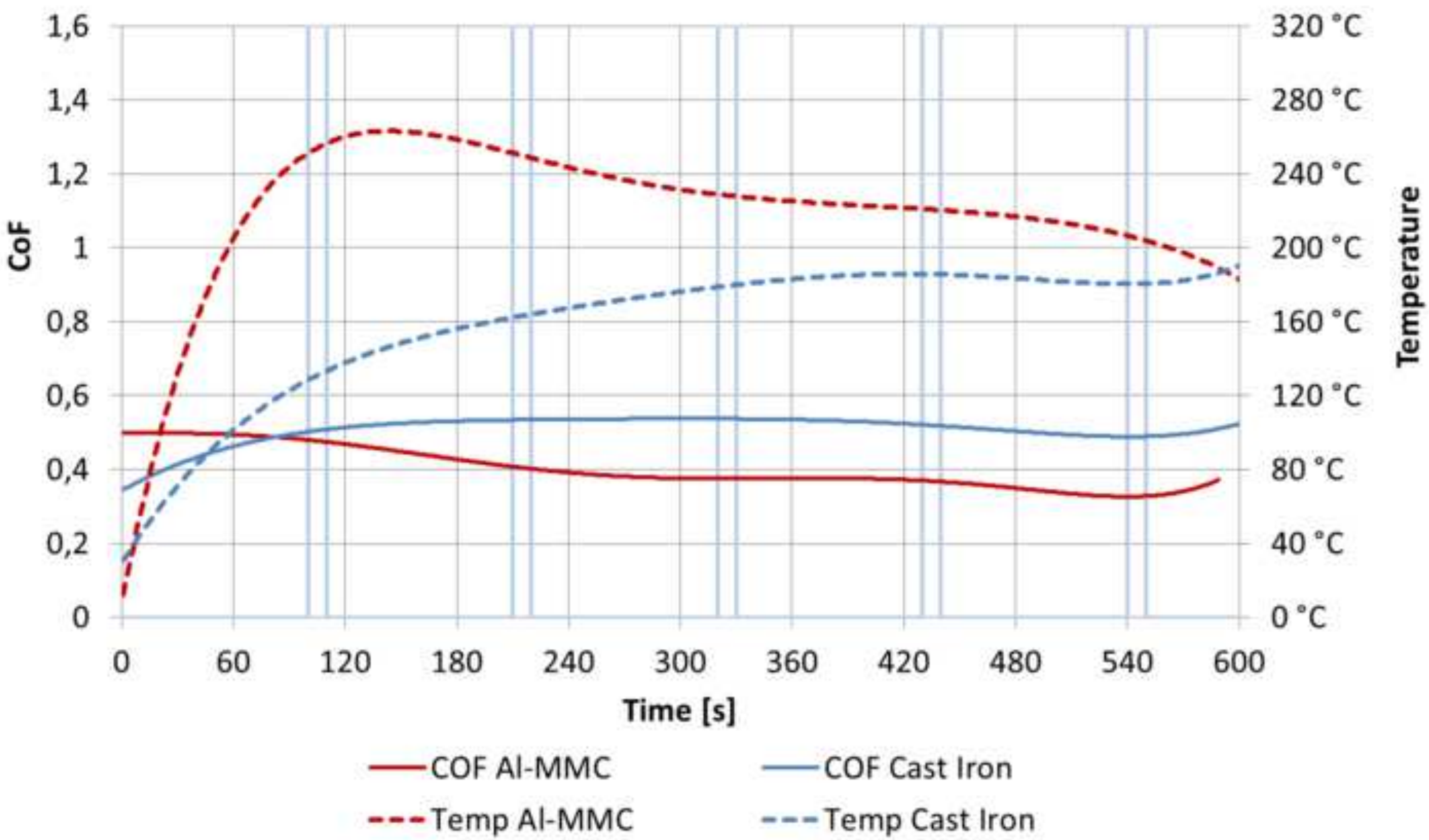

CoF
Weight Loss %
0,6
0,5
0,4
0,3
0,2
0,1
0
Typical CoF range for braking materials
0
60
120
180
Temperature [°C]
Al2O3
SiC
REF. C.I.
Al-SiC68%
CoF NP pad
CoF SP pad
Wear NP pad
Wear SP pad
Temp NP pad
Temp SP pad


0,6
0,45
0,3
0,15
0
CoF
Weight Loss %
Typical CoF range for braking materials
68 SiC/Al framed samples
70 SiC/Al framed samples
40 SiC/Al framed samples
0
20
40
60
80
Temperature [°C]
CoF
Wear
Temperature

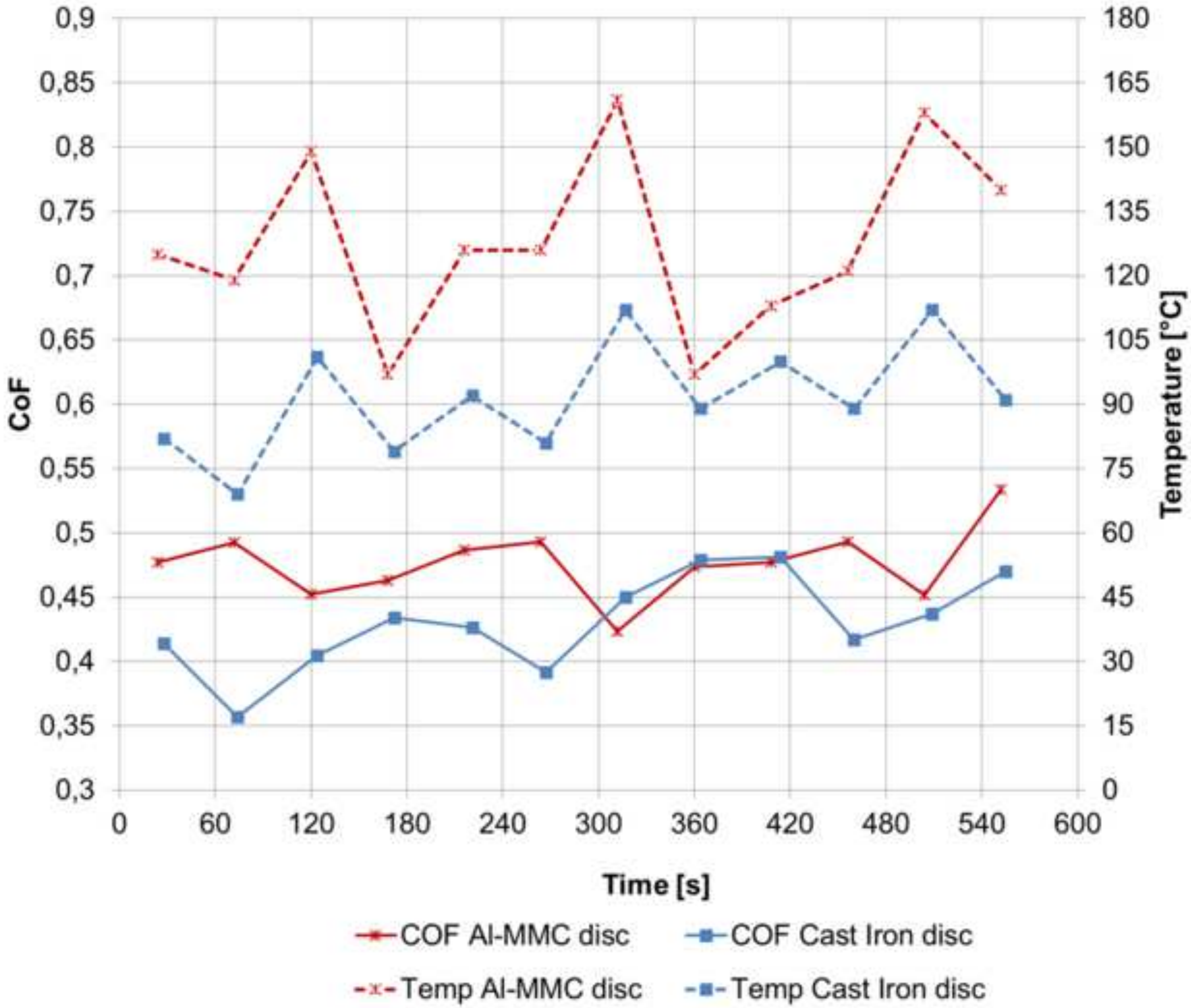


a)
Load [N]
Speed [rpm]
Time [s]
b)
Water Spray [ON/OFF]
Spray
Load
Load [N]
Time [s]
c)
Rotating Speed [rpm]
Load [N]
Speed [rpm]
Time [s]


a)
68 SiC/Al downsized disc vs SP pad
CoF
Temperature [°C]
Time [s]
CoF 105N
CoF 210N
CoF 316N
CoF 536N
CoF 737N
Temp 105N
Temp 210N
Temp 316N
Temp 536N
Temp 737N
b)
downsized cast iron disc vs NP pad
CoF
Temperature [°C]
Time [s]
CoF_105N
CoF_210N
CoF_316N
CoF_536N
CoF_737N
Temp_105N
Temp_210N
Temp_316N
Temp_536N
Temp_737N
c)
downsized cast iron disc vs SP pad
CoF
Temperature [°C]
Time [s]
CoF 105N
CoF 210N
CoF 316N
CoF 536N
CoF 737N
Temp 105N
Temp 210N
Temp 316N
Temp 536N
Temp 737N



1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
CoF
320 °C
280 °C
240 °C
200 °C
160 °C
120 °C
80 °C
40 °C
0 °C
Temperature
0
60
120
180
240
300
360
420
480
540
600
Time [s]
COF Al-MMC
COF Cast Iron
Temp Al-MMC
Temp Cast Iron



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Material	Supplier	Type	Composition %	Density [g/cm^3]	HV (GPa)	CTE [10^{-6}/K]	Thermal conductivity [W/mK]
A380	Fagor Ederlan	Al alloy	Al 8.5Si 3.5Cu (wt%)	2.71	0,7	22	96
A356	Fagor Ederlan	Al alloy	Al 8.5Si 0.3Mg (wt%)	2.69	0,8	22	160
NPX30	Japan Fine Ceramics	SiC/Al composite	Al + 30 SiC (vol%)	2.78	1.8	14.5	140
NPX40	Japan Fine Ceramics	SiC/Al composite	Al + 40 SiC (vol%)	2.85	2	11.5	167
NPX50	Japan Fine Ceramics	SiC/Al composite	Al + 50 SiC (vol%)	2.90	2.5	9.5	167
NPX60	Japan Fine Ceramics	SiC/Al composite	Al + 60 SiC (vol%)	2.97	3.8	8.4	180
Ametek 68	Ametek	SiC/Al composite	Al + 68 SiC (vol%)	3.03	4	8.75	210
SA701	Japan Fine Ceramics	SiC/Al composite	Al + 70 SiC (vol%)	3.0	4	7.0	190

Table 1 Selected materials used in the experimental activity and their relevant properties

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Pin on disc Test	Value
Velocity	850rpm
Load	200N
Test duration	15 min
Compressed air cooling	ON
Pin	• Normal pad (Hard pad)=NP • Special pad (Soft pad)= SP
Test output	CoF/Pad Wear /Temperature

Table 2 Parameters for tribotesting on different materials

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Declaration of interests

x The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: