Enhanced yield synthesis of bulk dense \((M_{2/3}Y_{1/3})_2AlC\) (\(M = \text{Cr, W, Mo}\)) in-plane chemically ordered quaternary atomically laminated \(-\text{MAX}\) phases and oxidation of \((\text{Cr}_{2/3}Y_{1/3})_2AlC\) and \((\text{Mo}_{2/3}Y_{1/3})_2AlC\)

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Abstract

Recently, a new family of \(\text{MAX}\) phases with in-plane chemical order, \(-\text{MAX}\), have been discovered which incorporate new elements expanding the family of \(\text{MAX}\) phases. \(-\text{MAX}\) phases remain to be synthesized in single-phase bulk form for characterization. Herein, we show that by reactively hot pressing an intermetallic precursor, \(Y_2.23Al\), instead of elemental \(Y\), in combination with excess overall \(Al\) and a sub-stoichiometric fraction of carbon, we enhance the yield of \((\text{Cr}_{2/3}Y_{1/3})_2AlC\) to \(85 ± 3\) wt\% (\(86 ± 3\) mol\%). Both the fractions of the impurity \(Y_2O_3\) phase and the undesirable ternary \(\text{Cr}_2\text{AlC}\) are reduced. Subsequent isothermal oxidation of \((\text{Cr}_{2/3}Y_{1/3})_2AlC\) in natural air in the \(1000–1400 °C\) temperature range reveals the formation of \(Y_3\text{Al}_2(\text{AlO}_4)_3\) (\(\text{YAG}\)), \(\text{Cr}_2\text{O}_3\) and \(Y_2O_3\), without a continuous \(\text{Cr}_7\text{C}_3\) sub-layer. Additionally, we show that by starting with \(Y_{2.23}Al\) reagent we synthesize dense bulk \((\text{W}_{2/3}Y_{1/3})_2AlC\) and \((\text{Mo}_{2/3}Y_{1/3})_2AlC\) samples with enhanced \(-\text{MAX}\) yields of \(72 ± 3\) wt\% (\(59 ± 2\) mol\%) and \(91 ± 3\) wt\% (\(72 ± 2\) mol\%), respectively. Oxidation of \((\text{Mo}_{2/3}Y_{1/3})_2AlC\) at \(1300 °C\) for \(12\) h leads to formation of a thick, porous oxide of \(Y_2\text{Mo}_3\text{O}_{12}\). © 2021 Elsevier B.V. All rights reserved.

1. Introduction

Atomically laminated \(M_{n+1}AX_n\) (\(\text{MAX}\)) phases - where \(M\) is an early transition metal, \(A\) is an \(A\)-group element (mostly Groups 13 and 14), \(X\) is \(C\), \(N\) or \(B\) and \(n = 1 - 4 \) [1–4] - possess favorable properties hybrid between metallic and ceramic. A number of \(\text{MAX}\) phases (i.e. \(\text{Ti}_2\text{AlC}, \text{Ti}_3\text{AlC}_2, \text{Cr}_2\text{AlC}\)) possess good mechanical strength, damage tolerance, shock resistance, corrosion resistance (i.e. \(\text{Cr}_2\text{AlC}\)), and oxidation resistance [2].

\(\text{Cr}_2\text{AlC}\) specifically presents a good candidate for hot-corrosion resistance, oxidation resistance, erosion resistance and self-healing characteristics as well as low neutron absorption cross section [5–19]. These properties nominate \(\text{Cr}_2\text{AlC}\) phase for accident-tolerant fuel cladding used in light water reactors [20,21]. \(\text{Cr}_2\text{AlC}\) is a known alumina former with excellent isothermal and good cyclic oxidation resistance. However, a \(\text{Cr}_7\text{C}_3\) carbide underlayer forms below the \(\text{Al}_2\text{O}_3\) oxide scale which becomes problematic if the passivating \(\text{Al}_2\text{O}_3\) layer is breached [13]. Moreover, challenges arise at higher temperatures (i.e. >1200 °C) due to possible scale spallation and wrinkle formation of the alumina scale [13,16]. \(\text{Cr}_2\text{AlC}\) is thus less resistant to cyclic oxidation above 1200 °C [19].

Oxide scale wrinkling phenomenon is recognized for other alumina-forming materials [22–26]. There are two main theories explaining the formation of wrinkles; namely due to compressive stresses through lateral oxide growth within the grain boundaries [27], or due to the formation of a volatile gaseous phase which bubbles outside of the oxide scale. Wrinkling has been addressed in \(\text{FeCrAl}\) and other alloys through the addition of reactive elements (RE) (e.g. \(\text{Hf}, \text{Y}, \text{Zr}\)) which modifies oxide growth rate and improves scale adhesion and thus spallation resistance [22,28–33].

Oxidation improvement mechanism by RE additions is suggested to be due to: prevention of S impurity segregation at grain boundaries in the case of \(\text{FeCrAl}\) alloys, or segregation of reactive-element ions to the oxide scale grain boundaries and the metal-oxide interface [27,32,34–38]. It is argued that Y-doping in alumina-forming alloys (e.g. \(\text{FeCrAl}\)) transforms early oxidation mechanism into predominantly inward growth, and it is suggested that this promotes scale adhesion by avoiding the porous scale/alloy interface typical for outward grown scales [39]. Furthermore, Y-additions can improve the high-temperature steam tolerance of \(\text{FeCrAl}\) alloys [40,41]. For the \(\text{Cr}_2\text{AlC}\) MAX phase, Y-doping has been shown to promote favorable oxidation behavior, improve oxide scale adherence and
affect oxide scale morphology and growth [42–44]. This supports the idea that doping some alumina-forming MAX phases (e.g. Cr2AlC) with Y element could enhance oxidation resistance and high-temperature steam tolerance in similitude to FeCrAl alloys [22,28–33]. In a relevant attempt to introduce secondary elements in MAX phases, recently, in-plane chemically ordered quaternary (Mo2/3Sc1/3)2AlC, (Mo2/3Y1/3)2AlC, (V2/3Zr1/3)2AlC have been both predicted and synthesized from elemental precursors [45,46]. The chemical ordering in the case of i-MAX is within the M layers. They are reported to crystallize in both C2/c monoclinic and/or Cmcm orthorhombic space groups. An attempt to take advantage of Zr small neutron absorption cross-section was made through synthesis of (Cr2/3Zr1/3)2AlC by Chen et. al [47]. Samples were sintered using ZrH2 precursor instead of elemental Zr [47]. Chen et. al argues that it is essential to use non-elemental Zr for the synthesis of Zr-based MAX phases.

Interest in potential nuclear applications also motivated work on synthesis of (Cr2/3Sc1/3)2AlC and (Cr2/3Y1/3)2AlC i-MAX phases using elemental precursors [48]. However, the previous yields of the main i-MAX phase were insufficient for undertaking necessary bulk characterization work for service applications.

Otherwise, little work has been conducted on (Cr2/3Y1/3)2AlC i-MAX phase bulk synthesis and properties. This phase was found to crystallize mostly with orthorhombic Cmcm space group with a minority phase in monoclinic C2/c space group, as reported by Lu et. al. [48]. The samples were prepared from elemental precursors and composed of 60.8 wt% (Cr2/3Y1/3)2AlC (space group Cmcm), with impurity phases of 24.6 wt% Y2O3, 8.5 wt% (Cr2/3Y1/3)2AlC (space group C2/c) and 6.1 wt% Cr2AlC phase (space group P63/mmc), as determined by X-ray diffraction (XRD) Rietveld refinement. It is not particularly clear why orthorhombic symmetry is more favorable than monoclinic in the Cr-Y-Al-C system but Tao et. al showed energetically comparable DFT stability calculations for both symmetries [1,45].

We note in passing that substitution of Cr in out-of-plane ordered quaternary α-MAX phase compounds has also been realized in synthesized phases of (Cr2/3Ti1/3)2AlC2 and (Cr5/8Ti3/8)4AlC3 showing the possibility of tailoring of various properties [49]. Several other out-of-plane quaternary MAX phases have since been discovered [11].

To better understand the properties of the i-MAX phases in general and (Cr2/3Y1/3)2AlC, in particular, as well as pave the way for practical application, herein we attempted to maximize phase content of (Cr2/3Y1/3)2AlC, (W2/3Y1/3)2AlC and (Mo2/3Y1/3)2AlC in fully dense polycrystalline samples. This was accomplished via reactive hot-pressing. HPing, of mixtures of Y2.23Al, elemental Al, and C combined with Cr, W, and Mo, respectively. Phase formation is confirmed using XRD; phase compositions and morphologies are investigated using Scanning Electron Microscopy (SEM), and Energy Dispersive Spectroscopy (EDS). Isothermal oxidation behavior is investigated in the range of 1000–1400 °C for 12–24 h for (Cr2/3Y1/3)2AlC and 1300 °C for 12 h for (Mo2/3Y1/3)2AlC. Similar protocols are repeated to produce dense bulk (W2/3Y1/3)2AlC and (Mo2/3Y1/3)2AlC i-MAX phases, with varying success.

2. Materials and methods

2.1. Synthesis

Quaternary (Cr2/3Y1/3)2AlC was synthesized by mixing reagent powders of Y2.23Al, Cr, Al, and C (Table 1) with different starting nominal compositions (Table 2) in polyethylene jars with ZrO2 balls for 9 h. Mixed powders were loaded in 1” diameter graphite dies
wrapped with graphite foil and hot-pressed (HPed) to temperatures of 1450–1500 °C for 4 h with 400 °C/h ramp rate (Table 2).

In starting compositions and processing conditions attempted herein (Table 2), we use excess Al reagent. Excess Al is necessary to compensate for evaporation at high processing temperature and aluminothermic reduction of metallic powders. XRD patterns (Fig. 1) of HPed samples and Rietveld refinement (Fig. 2) are used to confirm \(\text{(Cr}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) synthesis while back-scattered electron (BSE) micrographs are analyzed by image contrast analysis through ImageJ software to estimate final phase fractions. SEM micrographs used herein for phase analysis were captured at 100–300x magnification 15–25 kV at 11 mm WD, to quantify impurities and hence optimize reagent starting composition for enhanced \(\text{(Cr}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) phase yield (illustrated in Fig. 3).

The HPing conditions and starting reagent compositions that produced the highest \(\text{(Cr}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) yield were tailored for synthesis of dense bulk \(\text{(W}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) and \(\text{(Mo}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) using reagents of Table 1 and compositions of Table 2. Although Meshkian et. al [50] previously synthesized \(\text{(W}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) at 1450 °C, herein we chose 1550 °C for 3 h. \(\text{(Mo}^{2/3}\text{Y}^{1/3})_2\text{AlC}\) was HPed herein at 1550 °C for 5 h, compared to 1500 °C for 20 h by Tao et. al [45].

As-sintered HPed samples were polished using 240–1200 grit sized silicon-carbide paper (SiC) prior to characterization. When polished with water, the samples appeared to deteriorate in the form of pullouts. Therefore, dry polishing was used instead.

2.2. Characterization

To obtain powders, a mortar and pestle was used. XRD diffractograms of powders crushed from bulk HP samples were collected on powder diffractometers (SmartLab, Rigaku Corp., Tokyo, Japan) and (Rigaku MiniFlex 600, Japan) using 40 kV, 15–30 mA Cu-K\(\alpha\) radiation in a Bragg-Brentano scan mode. Scans were in the 10–80° 2\(\theta\) range with a step size of 0.02° and dwell time of 1–1.8 s per step.

Rietveld refinement (Match-FullProf integrated software [51]) was carried out on XRD patterns obtained in Bragg-Brentano scanning mode in the 10–80° 2\(\theta\) range and 1 s dwell time per step. A pseudo-Voigt model was used, and the refined parameters were scale factors, unit cell lattice parameters (LPs), Caglioti half-width parameters, specimen displacement, profile shape parameters and overall isotropic displacement parameters. Statistical uncertainties in estimated parameters are included in parentheses after each value. Phase distribution and impurities could not be reliably quantified solely from XRD. To estimate the impurity type and content, phase analysis was performed using a scanning electron microscope (SEM) micrographs in combination with energy-dispersive X-ray spectroscopy, EDS.

Oxidation samples (~5 mm radius × 2 mm thick) were electro-discharge machined out of HPed bulk discs and polished down to 1200 grit using SiC paper prior to testing. The samples were weighed and then oxidized in the 1000–1400°C temperature range under...
natural air for 12–24 h in a box furnace at a heating/cooling rate of 5 °C/min.

3. Results and discussion

3.1. Synthesis and structure of (Cr$_{2/3}$Y$_{1/3}$)$_2$AlC

Powder XRD patterns of the 5 compositions HPed in this work (Table 2) are compared in Fig. 1. (A sixth is shown in Fig. 2). HP1 to 3 were significantly less single phase and are not shown. In all cases, the major peaks belong to the i-MAX phase in the Cmcm orthorhombic crystal structure [48]. A (110) peak at 18.99° is noted, indicating in-plane chemical order [52]. In addition, all patterns show peaks belonging to one, or more, of the following impurity phases: Y$_2$O$_3$, YAl$_2$ and Cr$_x$Cy (i.e. Cr$_3$C$_2$, Cr$_7$C$_3$, or Cr$_{23}$C$_6$). Rietveld refinement was performed on XRD pattern of the HP4 sample (Fig. 2) because this run resulted in one of the highest i-MAX yields (see Fig. 6). The refined lattice parameters, LPs, are $a = 9.3360(1)$ Å, $b = 5.3540(2)$ Å and $c = 13.2100 (4)$ Å in Cmcm space group. The $\chi^2$ for this refinement is 5.0, the deviation from the $a$, $b$ and c LPs, reported by Lu et. al [48], are $-0.008\%$, $-0.018\%$, $-0.06\%$, respectively. We note in passing that in the i-MAX structure the Y atoms are closer to Al layer than Cr atoms, forming a staggered M layer which distinguishes i-MAX from traditional MAX phases (see inset in Fig. 2) [48]. The impurity phases were not quantified from XRD refinement due to; overlap between i-MAX and impurity peaks, relatively small quantities of some impurities and limited scan resolution. Instead image contrast analysis was carried out on BSE SEM micrographs to estimate phase fractions.

3.2. Microstructures and phase compositions

SEM micrographs and EDS maps of samples HP1 and HP4 are shown in Figs. 3–5. In all cases, the samples appear to be fully dense. The slight porosity observed is most probably due to polishing pullouts. In general, these two microstructures were comprised of five phases, confirmed by EDS. The phases are, i) the majority i-MAX matrix, ii) Cr$_x$Cy (light gray in Fig. 4a,d), iii) Y$_x$Al$_y$ intermetallic (dark gray) (Fig. 4b,e), and iv) Y$_2$O$_3$ (brightest white regions) (Fig. 4c,f). v) Al$_4$C$_3$ (not seen). No peaks corresponding to the latter phase were conclusively found in XRD patterns.

This is typical of Al$_4$C$_3$ since it tends to be poorly crystallized and/or found at the grain boundaries [53]. Initially, we hypothesized that the dark gray Al-containing regions in contact with Cr$_x$Cy impurity regions shown in Fig. 4d,e and Fig. 5c was the Al$_4$C$_3$ phase, however, EDS maps in Fig. 5c revealed this phase to be Y$_x$Al$_y$ intermetallic. Attempts of identification of Al$_4$C$_3$ phase, which is hygroscopic, in the EDS were not conclusive but the sensitivity of samples to water-based polishing procedure highlights its presence as discussed by Agne et. al [53] and explains why many of the samples disintegrated to powders with time [54]. Degradation and/or subsequent disintegration had been previously attributed to volume expansion due to interaction of Al$_4$C$_3$ with moisture in SiC/Cr$_2$AlC [54] and Ti$_2$AlC-B$_4$C-Al [53] phase systems, respectively.

Fig. 6 summarizes the results of the image contrast analysis of BSE SEM micrographs of all the HPed runs. Not surprisingly, in all cases the i-MAX phase was the majority phase. It is worth noting here that our goal is to try to minimize the fractions of impurity phases. Samples with high yields; HP4, HP6 and HP8 (Fig. 6) were selected for oxidation work. HP5 and HP7 possessed high i-MAX
Fig. 4. BSE SEM micrographs of impurity phases in HP1 & HP4 samples surrounding i-MAX main phase, respectively. (a) HP1 Cr$_2$C$_{y}$ impurity (mild gray); (b) HP1 Y$_2$Al$_x$ intermetallic phase (dark gray); (c) HP1 Y$_2$O$_3$ impurities (white) (d) HP4 Cr$_2$C$_{y}$ impurity (mild gray); (e) HP4 Y$_2$Al$_x$ intermetallic phase (dark gray); (f) HP4 Y$_2$O$_3$ impurities (white).

Fig. 5. SEM and EDS maps for sample HP4 showing, (a) BSE micrograph. (b) Cr map with Cr-containing regions, attributed to the Cr$_2$C$_{y}$ phase in the 10–50 µm size range. (c) Al map showing Al-containing, Y$_2$Al$_x$ in the 5–50 µm size range. (d) Y map showing bright small Y-containing regions identified as Y$_2$O$_3$ in the 10–15 µm size range.
yields but were not used as they had deteriorated into chunks (see Table 2) with the suspected culprit probably being Al₄C₃. The molar percentage of the i-MAX phase in the HP4, HP6 and HP8 samples were 84 ± 2 mol%, 86 ± 3 mol% and 76% ± 3 mol% of i-MAX phase, respectively.

3.3. Isothermal oxidation of (Cr₂/₃Y₁/₃)₂AlC

Optical photographs of HP samples before and after oxidation are shown in Fig. 7. Oxidation at 1000 °C for 24 h, results in an adherent green oxide scale that covers the entire sample surface (Fig. 7b). The oxide layer, at this magnification, does not show evidence for spallation. After oxidation at 1200 °C for 24 h (Fig. 7c), the oxide scale appearance is not different than that after oxidation at 1000 °C but some spallation of oxide was noted. Oxidation for 12 h at 1400 °C, resulted in a relatively thick microcracked layer (Fig. 7d). Moreover, this sample was deformed compared to samples tested at lower oxidation temperatures with apparent white discoloration in the oxide scale.

By comparison of sample weight gains per unit area (ΔW/A) (Table 3) to previous work on Cr₂AlC and MoAlB [7,55], it is clear that the oxidation resistance of the i-MAX phase is worse within the range of oxidation conditions examined herein.

XRD patterns of the oxidized samples at 1000 °C and 1200 °C shown in Fig. 8a and b, respectively, reveal peaks belonging to Y₃Al₂(AlO₄)₃ (YAG), Cr₂O₃ and Y₂O₃. The small peaks at 26.30°, 32.78°, 39.24°, and 48.07° could not be identified and are marked by “?” label. Comment notwithstanding, more work is needed to reveal the exact nature of oxide composition. At 1400 °C, the sample disintegrated after oxidation during handling and is omitted from XRD.

Polished cross-section SEM micrographs of sample oxidized at 1000 °C for 24 h (Fig. 9) indicate the presence of an outer 15 ± 4 µm thick Cr₂O₃ oxide scale layer and a 25 ± 11 µm thick inner Y₃Al₂(AlO₄)₃ (YAG) layer. The inner layer appears to be well adhered to the substrate, while the outermost layer seems less so. These oxide species could nominate (Cr₂/₃Y₁/₃)₂AlC i-MAX phase for in-situ fluorescence decay temperature sensing, and coating lifetime detection applications as in the case of Cr³⁺ doped YAG [56,57]. This comment notwithstanding, more work would be needed in that regard.

Remarkably, no evidence for formation of a continuous Cr₇C₃ underlayer was found, an important distinction from oxidation in Cr₂AlC MAX phase. In the case of Cr₂AlC, a passivating Al₂O₃ forms upon oxidation with a continuous Cr₇C₃ underlayer. The Cr₇C₃ underlayer becomes problematic in the case of passivating Al₂O₃ scale breach as Al₂O₃ will not reform. It follows that the addition of Y in the i-MAX structure appears to disrupt binary Cr₇C₃ layer formation during isothermal oxidation.

Post-oxidation sample integrity and thick oxide scale formed during oxidation indicates that (Cr₂/₃Y₁/₃)₂AlC may be susceptible to failure in fuel cladding applications of light water nuclear reactors (LWR) in the case of loss of coolant conditions. However, at lower temperatures (i.e. 1000 °C), the oxide scale integrity is relatively adequate, the thickness of oxide formed is a limiting factor for use in fuel cladding applications. This comment notwithstanding, investigation of corrosion resistance, neutron interaction cross-section and oxidation behavior in steam or steam-H₂ environments would provide better insight into the use of (Cr₂/₃Y₁/₃)₂AlC for fuel cladding nuclear application. We note in passing that Y₃Al₂(AlO₄)₃ shows high dimensional and good neutron irradiation stability nominating it as a candidate for inert-matrix candidates for nuclear actinide fuels [61].

3.4. Synthesis of (W₂/₃Y₁/₃)₂AlC

The XRD pattern of the HPed sample (Fig. 10) confirms the formation of the (W₂/₃Y₁/₃)₂AlC phase with (110) peak at 18.75°
signifying in-plane chemical order of i-MAX [50]. XRD patterns also contain peaks corresponding to YAl₂ and Y₂O₃, possibly from the starting reagent. It is further suggested from XRD that either some unreacted W remains, or that binary W₂C forms. i-MAX phase yield determined from phase fraction image contrast analysis of BSE SEM micrographs (e.g. Fig. 11) is 72 ± 3 wt% (59 ± 2 mol%). This value is higher than that obtained by Meshkian et. al (50 wt%) [62], who started with elemental reagents.

BSE SEM micrographs (Fig. 11) indicate the existence of either unreacted W or binary W₂C in the HPed sample. In future work, to
reduce this W-based impurity, higher temperatures, longer times and/or fine-grained W powder are suggested.

3.5. Synthesis and oxidation of (Mo2/3Y1/3)2AlC

XRD of the HPed samples (Fig. 12) signify that the majority phase is the i-MAX with (110) peak at 18.61° indicative of in-plane chemical order of i-MAX, confirming phase formation in the structure previously reported by Dahlqvist et al. [46].

XRD patterns show the existence of impurity peaks from Mo3Al and Y2O3. The presence of Y2O3 is likely due to the presence of native oxides in the starting powders.

Interestingly, phase fraction image contrast analysis of BSE SEM micrograph (Fig. 13) indicates a highly single phase structure with 91 ± 3 wt% (72 ± 2 mol%) of (Mo2/3Y1/3)2AlC i-MAX phase (predominant gray phase). It is also evident from micrograph (Fig. 13b) that Mo2.74Al intermetallic (bright gray) phase is present, confirming XRD results. However, EDS spot analysis gives indication of substoichiometric Mo in Mo3Al intermetallic present. There are also traces of circularly-shaped Y2O3 (dark gray) grains uniformly distributed in the main i-MAX phase.

Oxidation of (Mo2/3Y1/3)2AlC-HP1 at 1300 °C for 12 h (see Fig. 14) results in a porous white oxide with some deviation from original dimensions on the sample. Sample ΔW/A was 0.62 ± 0.02 kg/m², around 40 fold that of MoAlB [55]. XRD pattern (Fig. 15) of oxidized sample surface at 1300 °C for 12 h indicates that the major oxidation product is Y2Mo3O12. There are two unidentified peaks at 36.44° and 57.65°. Given the poor oxidation resistance of this phase at this stage it is an unlikely choice for high temperature applications. Whether making cleaner samples will result in better oxidation resistance is a research goal very much worth pursuing.

![Fig. 9. BSE SEM cross-sectional micrographs of HP4 sample oxidized at 1000 °C for 24 h in air at (a) sample corner (b) lower magnification and c) at higher magnification. Cr2O3 outer oxide layer (15 ± 4µm thick) covers a YAG inner layer (25 ± 11 µm).](image)

![Fig. 10. XRD pattern of HPed (W2/3Y1/3)2AlC sample (blue). Calculated i-MAX patterns [62] for monoclinic C2/c and orthorhombic Cmcm structures are shown in black and red, respectively.](image)
4. Conclusions

Through reactive hot-pressing of Y\textsubscript{2.23}Al, Cr, Al and C powders we produced fully dense (Cr\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC polycrystalline samples with highest phase content of 85 ± 3 wt% (86 ± 3 mol%). By starting with Y\textsubscript{2.23}Al, the content of Y\textsubscript{2}O\textsubscript{3} and the undesirable ternary Cr\textsubscript{2}AlC were reduced. Isothermal oxidation of (Cr\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC produces a continuous oxide layer at 1000 °C for 24 h consisting of YAG, Cr\textsubscript{2}O\textsubscript{3} and Y\textsubscript{2}O\textsubscript{3}. The formation of YAG could potentially nominate the use of (Cr\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC for in-situ fluorescence decay temperature sensing applications. Sample weight gain at 1000 °C is around 20 times that reported Cr\textsubscript{2}AlC. At higher temperatures of 1200–1400 °C, oxide scale integrity decreases with evidence of spallation and cracking in oxide scale.

The ternaries (W\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC and (Mo\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC were synthesized with yields of 72 ± 3 wt% (59 ± 2 mol%) and 91 ± 3 wt% (72 ± 2 mol%), respectively. Oxidation of (Mo\textsubscript{2/3}Y\textsubscript{1/3})\textsubscript{2}AlC at 1300 °C for 12 h reveals formation of a thick, porous layer of Y\textsubscript{2}Mo\textsubscript{3}O\textsubscript{12} with a weight gain was around 40 times that reported for bulk MoAlB.

CRediT authorship contribution statement

Tarek Ali ElMelegy: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization
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Declaration of Competing Interest

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.
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