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High temperature single impact studies on material deformation and fracture behaviour of metal matrix composites and steels

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ABSTRACT

To exploit the full potential of materials used at elevated temperatures, it is crucial to understand their deformation and fracture mechanisms. High Temperature Single Impact Studies were performed to evaluate deformation mechanisms at different energy and momentum levels and their correlation to temperature. The limitations of materials regarding their impact resistance, the resulting deformation and fracture mechanisms were investigated. NiCrBSi based Metal Matrix Composites (MMC), reinforced with TiC–NiMo or Cr_3C_2–Ni particles, manufactured by Plasma Transferred Arc Cladding along with two different types of steels were tested and compared to study different types of deformation and fractures. Results indicate more ductile deformation behaviour of the investigated steels, while the MMCs show brittle behaviour at several temperatures. Critical impact loadings were determined at elevated temperatures to limit the range of use in impact dominated high temperature environment. Results show that the influence of different momenta at constant impact energy levels cannot be neglected.

1. Introduction

Deformations due to single impacts at different temperature levels are a crucial failure criterion for materials and, subsequently, for machine components [1]. To prevent material failure at high temperatures, it is important to understand the underlying mechanisms at single impact loading on diverse materials, their relation to different microstructures and their resulting deformation [2]. Different mechanisms can be examined on different microstructures. It is well known that the microstructure of steel with a defined chemical composition can be changed by heat treatment, which leads to different forming and impact behaviour [3–5]. Martensitic structure in steels results in good ductility at higher hardness; grain refinement leads to good material behaviour in impact loading conditions [6–9]. With increased amounts of hardphases, e.g. carbides or borides, brittle material behaviour can be detected. Cracks or outbursts may occur due to the distinction of hardness levels present in different phases of the material [10–13]. Deformation mechanisms can change due to different influences. At constant impact energy, a higher momentum leads to bigger impacts, which can cause critical deformations and lead to cracks or outbursts; a change from elasto-plastic to plastic deformation can be detected. Low energies and momenta mostly lead to elasto-plastic deformation processes, while higher loads engender plastic deformation [10,14]. Temperature has a large influence on the forming behaviour of materials. Thermal activated processes start at elevated temperatures and materials may soften or recrystallise [15–20]. Often metal matrix composites lose their good anti-wear properties, because of matrix softening and the concomitant loss of mechanical support of the hardphases. Optimal bonding between hardphases and matrix is crucial [21–24]. To investigate different material behaviours under the influence of single impacts, the materials were chosen to evaluate their range of application at elevated temperature correlated with various impact energies. The dominating failure mechanisms were analysed in different loading regimes. Two different steels, which are expected to reveal ductile material behaviour [25–27], were investigated. Additionally, two promising NiCrBSi based Metal Matrix Composites (MMCs) with high amount of different hardphases (Cr_3C_2–Ni and TiC–NiMo), which should reveal brittle behaviour [10,13,21–24], were chosen for the present study. The aim of this work are High Temperature Single Impact studies to determine limits in the range of application for different materials and to understand high temperature deformation, cracking and wear mechanisms at different energy and momentum levels up to 700 °C.

2. Experimental

2.1. Materials data

In the present study, four different materials were examined in the HT-SIT to investigate their behaviour at various temperatures,

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momenta and energies. Two materials were steels with different hardness and microstructure, while the other two were MMCs with the same matrix but different hardphases. Material A was carbon steel (1.1191 or AISI 1045), whereas Material B was a High Speed Steel (1.3554 or AISI M2). Material A was normalised at 860 °C for 4 h in protective gas atmosphere and slowly cooled in air. Material B is a standard High Speed Steel tested in tempered condition: hardened at 1210 °C in a protective gas atmosphere and quenched in oil with afterwards, tempering at 520 °C and slow cooling in air. Materials C and D are NiCrBSi-based hardfacings reinforced with Cr_3C_2–Ni particle and TiC–NiMo, respectively. Both were produced from a mixture of 40 wt% hardphase powder and 60 wt% NiCrBSi matrix powder in a similar PTA cladding process using an EuTronic® Gap 3001 DC apparatus with optimised welding parameters previously presented by Zikin et al. [11,24,28]. Initial welding powder data is given in Table 1.

2.2. Hot hardness data

The Hot Hardness Test rig is based on the Vickers method at elevated temperatures [23], developed at the Austrian Centre of Competence for Tribology (AC^2T research GmbH). The test rig is used to determine materials hardness up to 800 °C. To prevent oxidation at higher temperatures, the testing chamber is kept under vacuum conditions. The testing method is similar to Vickers-Hardness HV 10. All indents are measured by means of optical microscopy (OM) to calculate the hardness regarding the dimension of the indent diagonals. As OM a Leica MEF4A microscope with a Leica DFC 450 camera was used. For statistical reasons, three indents per temperature were performed on Materials A and B; due to the high diversity of the hardness values of Materials C and D, eight indents at each temperature were performed. Temperature–hardness curves of Material B were previously presented by Winkelmann et al. [23]. Zikin et al. presented those of Materials C, D and the NiCrBSi based matrix [24].

2.3. High temperature single impact test (HT-SIT)

The HT-SIT, as seen in Fig. 1a, was recently developed at AC^2T for determining the high temperature impact behaviour of materials at several impact energies (0.25–100 J) and momenta (1.11–44.72 Ns) in a temperature range between 20 and 1000 °C. The test principle is based on potential energy turned kinetic energy by free fall, which leaves a defined wear mark. The test principle is given in Fig. 1b and consists essentially of a dropping head with changeable weights hauled by a horizontally arranged impact edge with an angle of 5°. The testing parameters can be chosen with a defined potential energy $E_{pot}=m\cdot a\cdot s$ or with a defined momentum $p=m\cdot v$, where m is the mass, a the gravitational acceleration, s the initial height (so the dropping distance) and v the velocity. In this experiment the energy was defined and the momentum was calculated. The conversion from the energy into the momentum is calculated according to

$$2mE=p^2 \tag{1}$$

The initial value for the distance and the velocity is 0. The velocity of the dropping head can be calculated, dependent on the time t, by

$$v=v_0+\int a\,dt=v_0+at \quad v_0=0 \quad v=at \tag{2}$$

Here the initial velocity v_o is zero. Therefore the dropping distance s is

$$s=s_0+\int v\,dt=s_0+\frac{at^2}{2} \tag{3}$$

and the time can be followed according to

$$s=\frac{at^2}{2}\rightarrow t=\sqrt{\frac{2s}{a}} \tag{4}$$

The momentum can be calculated as a function of the distance:

$$p=mv=mat=ma\sqrt{\frac{2s}{a}}=m\sqrt{2sa} \tag{5}$$

Combining Eqs. (4) and (5) leads to the relation between energy and momentum according Eq. (1).

After defining the parameters, the weight is adjusted in the sledge and set to the right drop height. The specimen is fixed in the inductively heated specimen holder and heated to the testing temperature. To unleash the sledge for the drop, the trigger is turned. The sledge impacts the specimen surface leaving an impact mark; the specimen is taken out of the sample holder and cooled to room temperature. Now the impact mark length can be measured by means of microscopy, which gives a correlation between the deformation and the impact energy or momentum (Fig. 1c). In this first microscopic investigation with the stereo microscope (SM), the forming behaviour of the materials was investigated. If there are no cracks or outbursts, a valid measurement of the length can be made; at the appearance of cracks or breakouts, the mark length cannot be measured correctly. However, the deformation behaviour switches from elasto-plastic to plastic, which indicates some energy is used to fracture the material. The subcritical energy $E_{subcrit}$ is defined as the energy where cracks start to form. Once failures become significant, which means cracks running down the substrate of the coating, outbursts or displacement of a coating against the substrate occurs, the impact energy can be considered critical for the material. In bulk materials, this happens if deep cracks or massive material deflection occur. The threshold energy beyond which these failures occur is defined as E_{crit}. Impact loads should not exceed this critical energy in applications; failure free applicability is not given when exceeding this load. At this point it shall also be mentioned that E_{crit} is a function of momentum and temperature $E_{crit}(p,T)$.

For both steels (Materials A and B), the focus was set on the influence of the forming behaviour at different energy levels, momenta and temperature. This was to reveal the influence of the momenta, which is often neglected. Test parameters of the energy and momentum sensible measurements are given in Table 2. Materials C and D focused on the determination of critical energies and their change with elevated temperatures. Test parameters for determining the critical impact energies are given in Table 3. For statistical reasons, three impacts at every energy level and material were performed. For a detailed understanding

Table 1
Initial welding powder data.

Powder	Source	Grain size (μm)	Chemical composition, (wt%)
Ni-based matrix	Castolin 16221	−50+150	0.2% C, 4% Cr, 1% B, 2.5% Si, 2% Fe, 1% Al, rest Ni
TiC–NiMo (hard phases)	Recycled from bulk	−150+310	80% TiC, 20% Ni:Mo 2:1
Cr_3C_2–Ni (hard phases)	Recycled from bulk	−150+310	80% Cr_3C_2, 20% Ni