Compressive Behavior of AISI-416 Stainless Steel at Different Rates of Loading

Ajay K. Behera, Nilamber K. Singh, and Maloy K. Singha

***Abstract* - The mechanical behavior of AISI-416 stainless steel at different rates ($0.001s^{-1}$ - $1500s^{-1}$) of compressive loading is investigated in this paper. Cylindrical specimens of 12 mm thickness and 8 mm diameter have been prepared for experiments. Quasi-static tests are done on *Universal Testing Machine*, whereas, the high strain rate experiments are performed on *split Hopkinson pressure bar setup*. The material parameters of existing Johnson-Cook material model are determined. It is observed that the Johnson-Cook material model can represent the experimentally obtained flow stresses of AISI-416 stainless steel.**

***Index Terms*—Stainless Steel, Strain Rate, split Hopkinson pressure bar setup, Johnson-Cook model**

I. Introduction

Martensitic stainless steel grades, such as AISI-416 are widely used in today's industries because of their high strength, good machinability and low cost. These steels have mild corrosion resistance, ferromagnetic behavior and ability to harden by heat treatment. They are mostly used in gears, shafts, valves, fasteners, some machine parts and even in fusion reactors [1-4]. It is found that the stress-strain behavior of materials depends on the loading rate [5-9]. Quasi-static and dynamic behaviors of materials are often different *i.e.*, the yield and flow stresses of materials under quasi-static condition is different than the corresponding stresses under dynamic condition. Hence, the knowledge of the mechanical behavior of such materials at different strain rates is essential in several fields of engineering in order to improve the safety against crash, impacts and blast loads. By knowing the dynamic behavior at different strain rates one can optimize the design or can develop accurate computational model.

The study of the mechanical properties under dynamic loads needs special experimental techniques to record the stress wave propagation in the materials. The *Kolsky bar*, also known as the *split Hopkinson pressure bar (SHPB)* is one of the widely used experimental techniques for the measurement of the mechanical properties of materials at high loading rates [10] and is used frequently in present days. This setup provides a relatively cheap and simple method for high strain rate materials testing with an acceptable level of accuracy when sufficient care is taken for the proper lubrication of the interfaces and, the correct specimen geometry is chosen. Naghdabadia *et al.* [11] employed a proper pulse shaper technique during *split Hopkinson pressure bar* (SHPB) experiments to achieve dynamic equilibrium condition and to fulfill a constant strain rate condition in the test specimen. Singh *et al.* [12] performed compression tests of a multi-phase steel on SHPB at different strain rates (0.001-$4700s^{-1}$) with pulse shaper and found constant strain rate during plastic deformation of the material.

Several research studies are reported in the literature [13-21] on the mechanical behavior of different grades of stainless steels under dynamic loads. Lee and Yeh [13] have investigated the deformation behavior of AISI 4340 alloy steel at different strain rates (500 - $3300s^{-1}$) and temperatures (25 - 1100°C) by means of a split Hopkinson bar. The results show that the flow stress increases with increase in strain rate and decrease with test temperature. Guo and Nasser [14] reported the experimental results of Nitronic-50 stainless steel at wide range of strain rates (0.001-$8000s^{-1}$) and temperatures (77 - 1000K). It is observed that the material has good ductility (elongation up to 35%) for all considered strain rates. Lee *et al.* [15] studied the high temperature (25-800^0C) deformation and fracture behavior of 316L stainless steel under high strain rate loadings (1000 - $5000s^{-1}$) and found that the flow stress, yield strength and work hardening coefficient increase with increasing strain rate, but decrease with increasing temperature. Odeshi *et al.* [16] studied the effects of high strain rate on the plastic deformation of the low alloy steel, AISI 4340 and observed that the flow stress depends on the strain rates. As deformation proceeds, adiabatic heating occurs along narrow bands and thermal softening begins to dominate the deformation process. Lee *et al.* [17] reported the impact properties (10^{-3} - $7500s^{-1}$) of sintered 316L stainless steel and observed that the true stress, the rate of work hardening and the strain rate sensitivity vary significantly as the strain rate increases. Dynamic impact behavior and ferrite variation of duplex stainless steels and super-austenitic stainless steel are studied by Huang *et al.* [18] at two strain rates $850s^{-1}$ and $5000s^{-1}$. The duplex stainless steels show strain softening, and shear band is revealed at the surface. Austenitic stainless steel, 254 SMO exhibits strain hardening completely and the diffuse Luders bands appear at the surface. The effects of pre-strain (0.15-0.5), strain rate (2000-$6000s^{-1}$) and temperature (300-800^0C) on the impact properties of 304L stainless steel are studied by Lee *et al.* [19]. The results have shown that the deformation behavior of pre-strained 304L stainless steel is highly sensitive to the pre-strain, strain rate and temperature. Fréchard *et al.* [20] studied the mechanical properties of a

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nitrogen austenitic stainless steel (Uranus B66) at strain rate rage 10^{-3}-$10^{3}s^{-1}$ over a wide range of plastic strain and found that the material has a high-strain hardening rate, a good ductility and high strain rate sensitivity. Bronkhorst *et al.* [21] presented the experimental results of the deformation response of tantalum and 316L stainless steel samples and observed that the tantalum samples do not form shear bands but the stainless steel samples formed a late stage shear band.

As per authors' knowledge, the works on the mechanical behavior of martensitic stainless steel, AISI-416 under dynamic load are scarce in the literature and it still requires more attention to understand the influence of strain rate during large plastic deformation of the material. In this paper, the dynamic compressive behavior of AISI-416, martensitic stainless steel is studied. Quasi-static tests are performed on *Universal Testing Machine* to study the stress-strain behavior under compression, whereas, the dynamic compression tests are conducted on *Split Hopkinson pressure bar apparatus* to understand the effects of different strain rates. The material parameters of existing Johnson-Cook model are determined and the predicted results are compared with the experimental results.

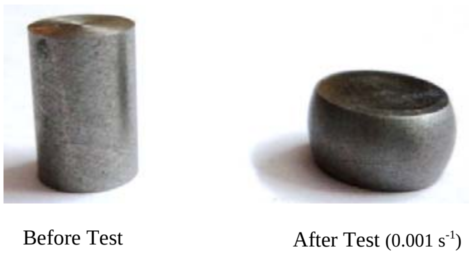

Fig 1. AISI 416 Stainless steel specimen before and after quasi-static test.

II. Material and Specimens

Commercially available AISI-416 stainless steel is used in the present investigation. The chemical composition of this steel in weight % are, C: 0.142, Si: 0.4025, Mn: 0.862, Cr: 13.03, Ni: 0.155, Mo: 0.1756, Cu: 0.0523, Al: 0.0145, V: 0.0449, S: 0.359, P: 0.0134, Co: 0.0184, Fe: 84.72. Cylindrical specimens of thickness 12mm and diameter 8mm are selected for experiments. The variation in thickness and diameter of the cylindrical specimens is less than ±1%. **Fig. 1** shows the specimen, before and after the quasi-static ($0.001s^{-1}$) test.

III. Experimental Setup

Stress-strain behavior of AISI-416 stainless steel specimens under quasi-static load is obtained on *Universal Testing Machine*, whereas, *split Hopkinson pressure bar (SHPB)* setup has been used to study the mechanical properties of the material under dynamic compressive loads. The schematic diagram of SHPB, available at the *Impact Mechanics Laboratory* of *Indian Institute Technology Delhi* is shown in the **Fig. 2**. It consists of an air gun, a striker, an incident bar, a transmission bar, an energy absorber (damper) and a data acquisition system. The specimen is sandwiched between the incident and transmission bars which are 20 mm in diameter and 1.5 m in length. These bars have free axial movement and are aligned to a common axis, which coincides with specimen axis in order to have one-dimensional wave propagation. The air cylinder (air gun) is filled with the help of an Italy based compressor (COLTRI SUB, Model-MCH6/ET). The air gun has the mechanism of releasing a striker of 400 mm length and mass 1.0 kg through a barrel, whose axis coincides with those of the bars and specimen. The velocity of the striker depends on the air pressure developed inside the air gun. There is strain gauge station at the middle of each bar to measure the compressive strain pulses. TML strain gauge of length 5mm and gauge factor 2.12 is used in the present work. The signals of the strain gauges are recorded with the help of a customized signal conditioner and high speed data acquisition system.

The striker strikes the input bar at a specified velocity to create a trapezoidal compressive stress wave (incident wave, ε_i). The compressive stress wave travels through the incident bar and reaches to the bar-specimen interface. At this interface, one part of the incident wave (ε_i) gets reflected back into the incident bar as reflected wave (ε_r) and one part gets transmitted as transmitted wave (ε_t) through transmission bar. Small part of the wave reverberates in the specimen. The compression in the specimen is under the load equilibrium as the signals ($\varepsilon_i + \varepsilon_r$) and ($\varepsilon_t$) are equal. These incident, reflected and transmitted stress waves are sensed by the strain gages which are recorded by a data acquisition system at a rate of 1 Mega Samples per second.

In the present work, pulse shaper technique has been employed to minimize wave dispersion, maximize stress equilibrium and to have constant strain rate. The material for the pulse shaper is '*Brass*'. The pulse shaper has thickness 1 mm and diameter marginally more than that of bar diameter. It is attached (in every test) at the impact end of the incident bar with the help of grease. Molybdenum grease is used on both sides of the specimen to minimize friction and to fix up the specimen between the two bars. The friction between the specimen-bar interfaces increases the flow stress in the deformation of specimen.

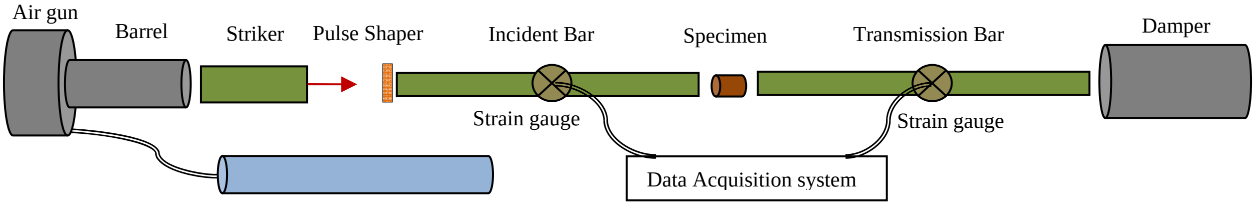

Fig 2. Schematic diagram of *split Hopkinson bar* setup available in Impact Mechanics Laboratory of Applied mechanics department IIT Delhi.

Now by considering the one dimensional wave propagation theory, engineering stress (σ_s), engineering strain (ε_s) and strain rate ($\dot{\varepsilon}_s$) of the specimen are expressed as [10]:

$$\sigma_s = E\frac{A}{A_s}\varepsilon_t$$
$$\varepsilon_s = \frac{-2C_0}{L}\int_0^t \varepsilon_r dt \qquad (1)$$
$$\dot{\varepsilon}_s = \frac{-2C_0}{L}\varepsilon_r$$

Where, E = Modulus of elasticity for the bar material, A = Cross-sectional area of the bar, A_s = Cross-sectional area of the specimen, C_0 = Stress wave speed in pressure bar, L = Gauge length (thickness) of the specimen.

After finding out the engineering stress and engineering strain, the corresponding True stress (σ_T) and True strain (ε_T) can be expressed as:

$$\sigma_T = \sigma_s(1+\varepsilon_s)$$
$$\varepsilon_T = \ln(1+\varepsilon_s) \qquad (2)$$

IV. RESULTS AND DISCUSSION

The mechanical behavior of AISI-416 stainless steel specimens under quasi-static and dynamic compressive loads is investigated in this section. The stress-strain curve under different rates of compressive loading is compared in **Fig. 3.** The yield stress in the curves is measured at 0.2% offset strain. The engineering and true yield stresses under quasi-static ($0.001s^{-1}$) condition are 550 MPa and 554 MPa respectively. The engineering yield stresses at strain rates $350s^{-1}$, $750s^{-1}$, $1050s^{-1}$, $1300s^{-1}$ and $1500s^{-1}$ are 882 MPa, 1033 MPa, 844 MPa, 857 MPa and 857 MPa respectively, whereas, the true yield stress are respectively 890 MPa, 1048 MPa, 852 MPa, 865 MPa and 866 MPa. It is found that the yield stress increases when strain rate increases from $0.001s^{-1}$ to $750s^{-1}$ and then the yield stress decreases in the range $1050\text{-}1500s^{-1}$ due to rise in adiabatic temperature. The yield stress is almost same at high strain rates $1300s^{-1}$ and $1500s^{-1}$. The compression in specimen increases with increasing strain rate and it reaches up to 25% at $1500s^{-1}$. It is observed from **Fig. 3** that the strain hardening and the flow stress increase with increasing strain rate. Hence, the material may be considered as moderate strain rate sensitive.

There is smooth yielding of the material at quasi-static condition. The material deforms horizontally first at the yield during dynamic loadings and then it regains strength, a strain hardening peak is observed. After achieving this peak, the flow stress decreases due to thermal softening and again increases with slow rate during deformation of the specimen. The engineering stress and strain rate versus time curve at $1500s^{-1}$ is shown in **Fig. 4**. The strain rate is constant during the plastic deformation of the material as the pulse shaper is used during the SHPB experiments. **Fig. 5** shows the specimens before and after dynamic tests at different strain rates.

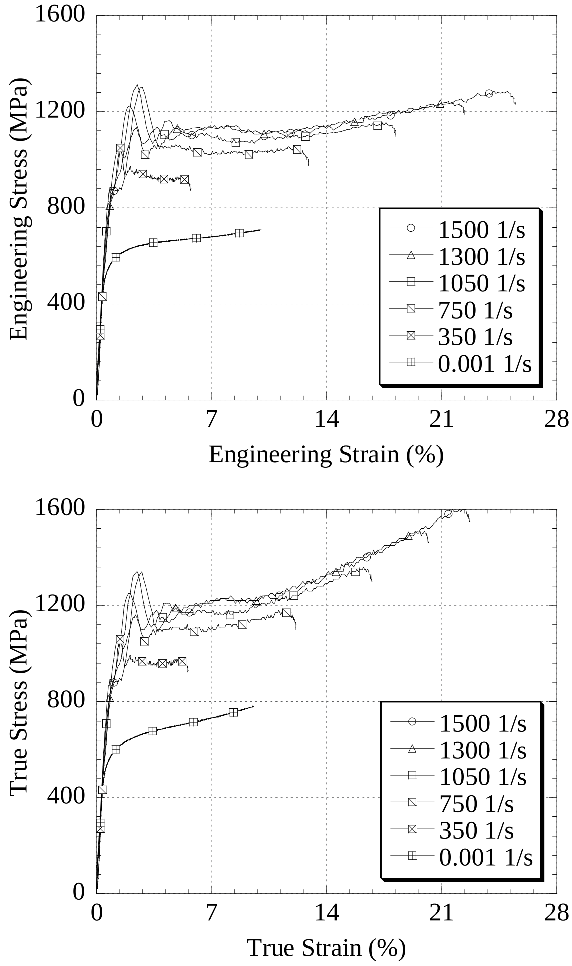

Fig. 3. Comparison of stress-strain curves at different strain rates (a) Engineering stress-strain (b) True stress-strain

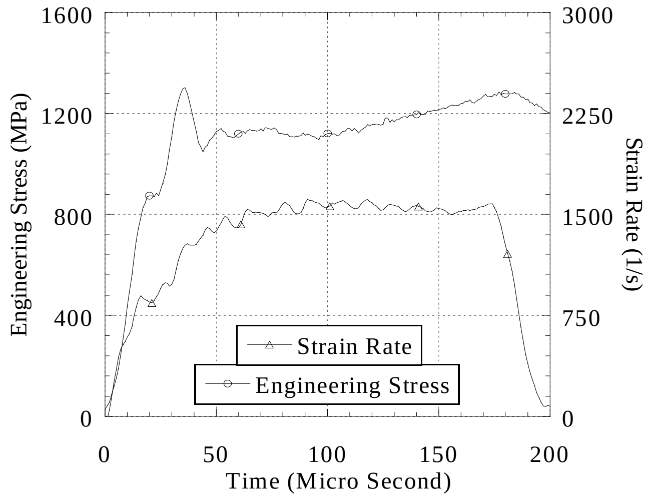

Fig. 4. Engineering stress and strain rate *versus* time curve

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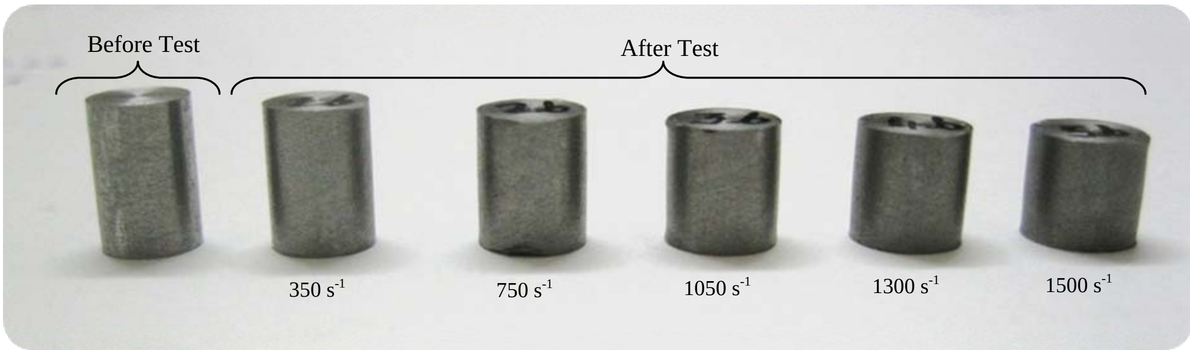

Fig. 5. AISI 416 Stainless Steel specimen before and after *split Hopkinson bar test* test.

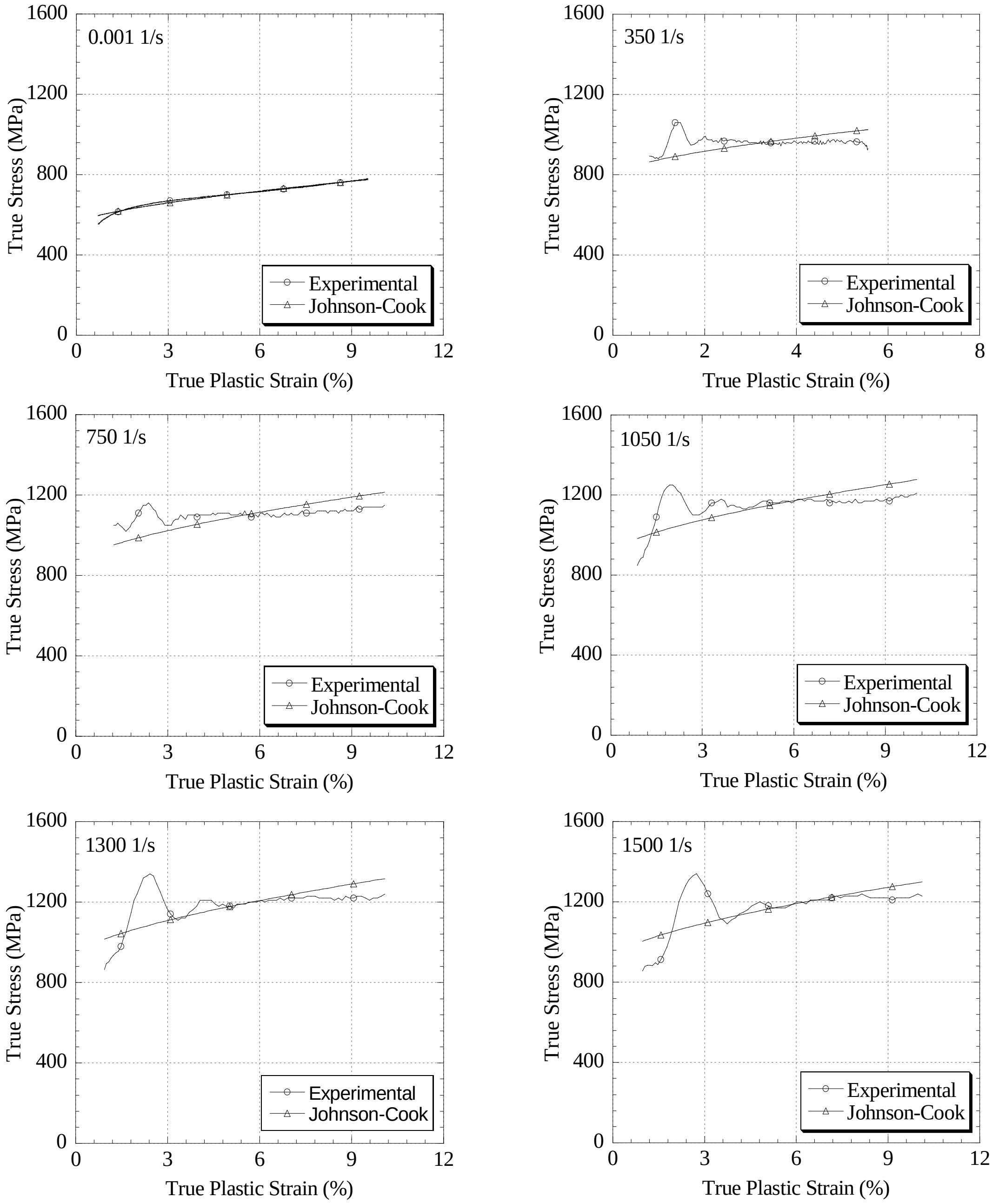

Fig. 6. Comparison of predicted results with the experimental results

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V. Material Model

The Johnson-Cook material model can be expressed as [22-23]:

$$\sigma = \left[A + B\varepsilon_p^{\ n}\right]\left[1 + C\ln\dot{\varepsilon}^*\right] \tag{3}$$

Where, ε_p is the equivalent plastic strain; $\dot{\varepsilon}$ is the strain rate; $\dot{\varepsilon}_0$ (= 0.001s^{-1}) is the reference strain rate, $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate. The material constant *A* is the quasi-static (0.001s^{-1}) true yield stress at 0.2% offset strain in room temperature; *B* and *n* represent the effects of strain hardening under quasi-static condition and are determined by curve fitting method up to maximum 10% deformation of the specimens; C is the strain rate sensitivity parameter and is obtained by curve fitting method at different strain rates

All the four material parameters are determined here from the experimentally obtained true stress *versus* true strain curves. The parameters *A*, *B* and *n* are 554 MPa, 995 MPa and 0.64 respectively. The *C*-parameter at strain rates, 350s^{-1}, 750s^{-1}, 1050s^{-1}, 1300s^{-1} and 1500s^{-1} are 0.035, 0.041, 0.046, 0.0484 and 0.0463 respectively.

After substitution of the obtained material parameters in equation (3), the final relationship (4) of the Johnson-Cook material model is expressed as:

$$\sigma = \left[554 + (995)\varepsilon_p^{\ (0.64)}\right]\left[1 + C.\ln\dot{\varepsilon}^*\right] \tag{4}$$

The '*C*' parameter can be used here at different strain rates. The Johnson-Cook model results are compared with the experimental results in **Fig. 6** at each strain rate. It is observed that the Johnson-Cook model with the estimated material parameters (*A*, *B*, *n* and *C*) has good agreement with the experimental results.

VI. Conclusions

Experimental investigation on the mechanical behavior of commercially available AISI-416 stainless steel under dynamic compression is reported here in the strain rate range (0.001-1500s^{-1}). High strain rate experiments are performed on split Hopkinson pressure bar setup. The material is observed to be moderately sensitive to strain rate. The Johnson-Cook material model with appropriate material parameters estimates the flow stress well. The results reported here will be useful for the designers working on the dynamic behavior of structures made of stainless steel.

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